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Deformation monitoring and analysis using Victorian regional CORS data

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Abstract. This paper investigates 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 reliability of the GPSnet solution are investigated using geological information. Appropriate strategies for GPS data processing and deformation analysis are investigated. The absolute and relative displacement of selected GPSnet stations are analysed using chronological GPS CORS data and dedicated high precision scientific GPS data processing software packages. The latest International Terrestrial Reference Frame is used for deformation analyses. Detailed data-processing strategies and results of deformation analyses are presented and some useful conclusions are drawn.

Results show that the methodology of deformation analysis and data processing based on the regional CORS network data is feasible and effective. 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. By mining the data from the GPSnet, not only reliable and high precision deformation information can be potentially obtained, but also high expenditure required for establishing dedicated deformation monitoring networks in this area can also be spared.

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

1 Introduction

Natural disasters are of a problem of global concern and may cause significant social, environmental and human losses and sometimes, threaten geopolitical stability. Natural hazards that impact on Australian communities include earthquakes, landslides, floods, storm surges, severe winds, bushfires, and tsunamis. In Australia, natural hazards are estimated at an average annual cost of $1.25 billion (Geoscience Australia, 2004a). Victoria is one of the regions where earthquake epicentres are relatively concentrated. There is potential risk of earthquakes 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 (see Figure 9). The Earth's surface deformation due to human activities such as mineral mining may also cause hazards.

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 monitoring ground movement, deformation and subsidence (He et al., 2004; King et al., 1995; Kogan et al., 2000). 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 extracted, 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 (Dawson et al., 2004) on-line scientific data-processing engine. The feasibility and effectiveness of the methodologies put forward are discussed and some useful conlusions are given.

2 Victorian GPSnet

In 1994, Land Victoria, the Department of Sustainability and Environment (DSE) of the 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. 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. GPSnet currently consists of 19 operating base stations and will contain approximately 24 primary stations upon completion. Table 1 lists the chronological developments of the GPSnet stations.

The nominal design spacing of GPSnet stations is approximately 50km in the Melbourne metropolitan region and 100km in rural Victoria, but in remote areas the separations can range up to 200km (see Figure 1). The Melbourne observatory base station has been connected to International GPS Service (IGS) network. The network records, distributes and archives GPS data for accurate position determination with post-processing techniques. Seven 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. Real-time transmission of networked GPSnet data to enable near instantaneous network RTK positioning services using a single GPS receiver is currently under consideration by DSE (Hale, 2004).

GPSnet uses a variety of receivers including Trimble 4000SSE/SSI, 4700 and Leica SR9500 dual-frequency receivers. The receivers use dual-frequency 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 the most stable locations free of multipath. Data

Tab. 1 Chronological developments of the Victorian GPSnet stations

GPSnet stations (date of operation)	Year of operation	No of Stations (Total)
Ballarat (01/12)	1995	1 (1)
Epsom (01/07) (relocated in 2002) Melbourne RMIT (01/08)	1996	2 (3)
Geelong (03/09)	1998	1 (4)
Benalla (13/07) Irymple (relocated in 2003) (26/01)	1999	2 (6)
Colac (30/10) Mt Buller (19/12)	2000	2 (8)
Swan hill (05/03) Hamilton (19/03) Shepparton (06/04) Walpeup (14/05) Horsham (02/06) Yalllourn (21/06) (relocated in 2003)	2001	6 (14)
Cann River (01/09) Melb obs (IGS station) (18/11)	2002	2 (16)
Clayton (12/02) Bairnsdale (31/10)	2003	2 (18)
Albury (11/02)	2004	1 (19)

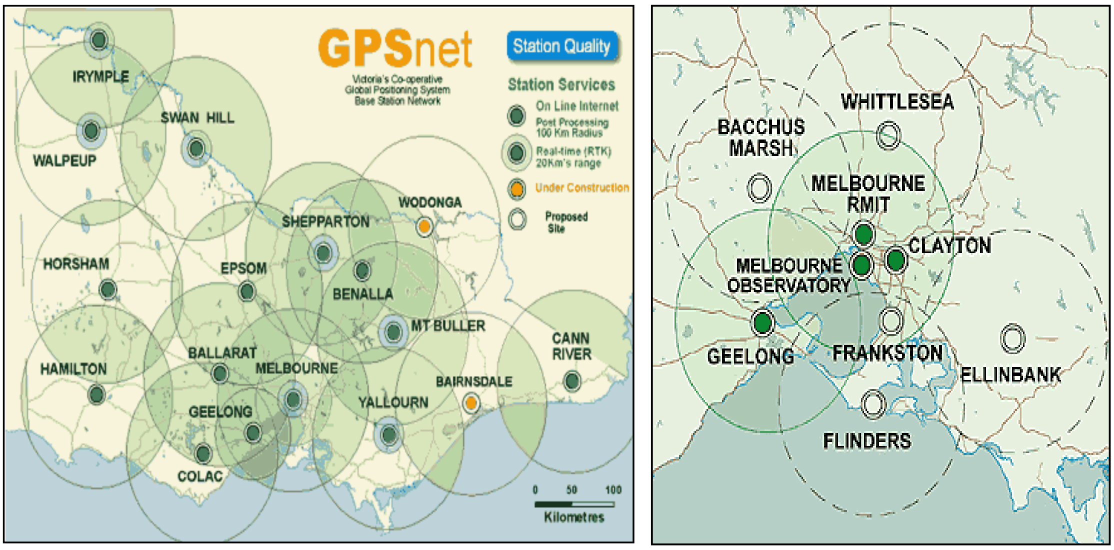

Fig. 1 Victorian rural/regional (left) and Melbourne (right) GPSnet base station network locations and their development status (Land Victoria, 2003)

processing is performed in the International Terrestrial Reference Frame (ITRF) 97 and then transformed to geocentric datum of Australian (GDA) 1994. Preliminary 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 and Roberts, 2003).

Land Victoria has also developed a mechanism for data quality check of the GPSnet measurements. This is measured through visual indications of cycle slips in carrier phases, multipath effects and data completeness respectively. Figures 2-4 show cycle slips occurred, multipath effects and data completeness for Ballarat station from 7 October to 6 November 2004 (Land Victoria, 2004).

This information provides a rough idea on the quality of the data measured in a particular station and this is very valuable for GPSnet users.

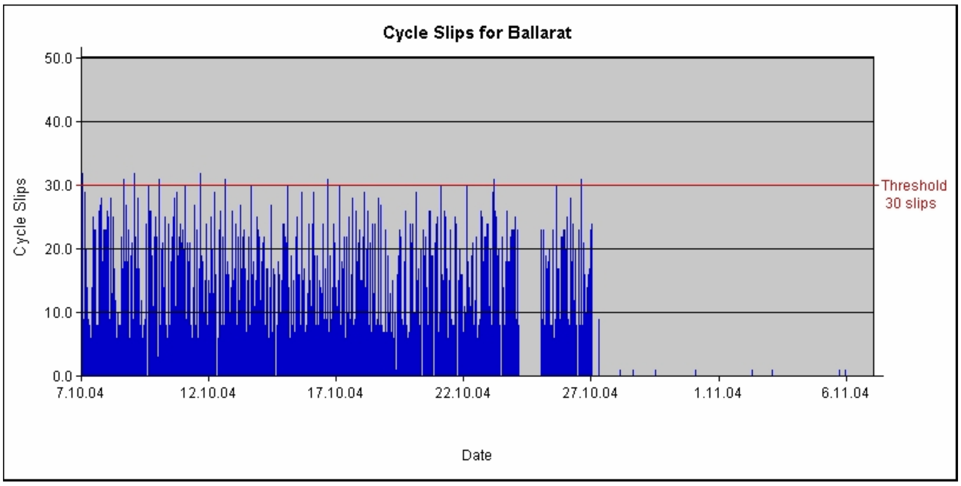

Fig. 2 Cycle slips detected for Ballarat station during October 2004

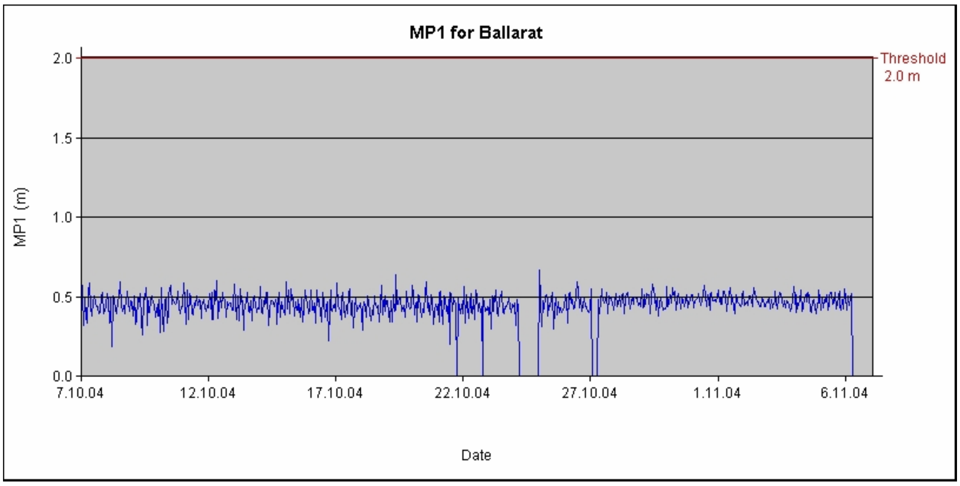

Fig. 3 Multipath effects detected for Ballarat station during October 2004

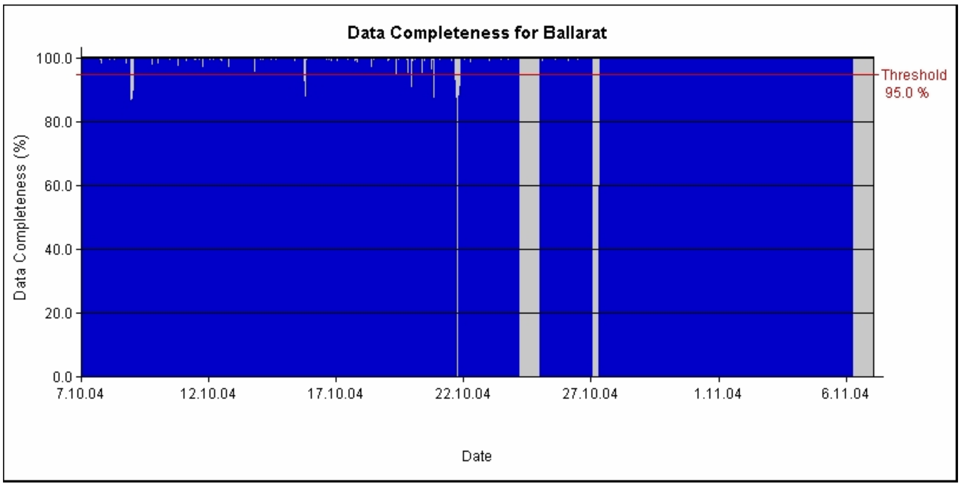

Fig. 4 Data completeness results for Ballarat station during October 2004

3. Method of deformation analysis

Victorian GPSnet is of high precision (mm level in horizontal position), and most 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 5 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 Selection of deformation analysis datum

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

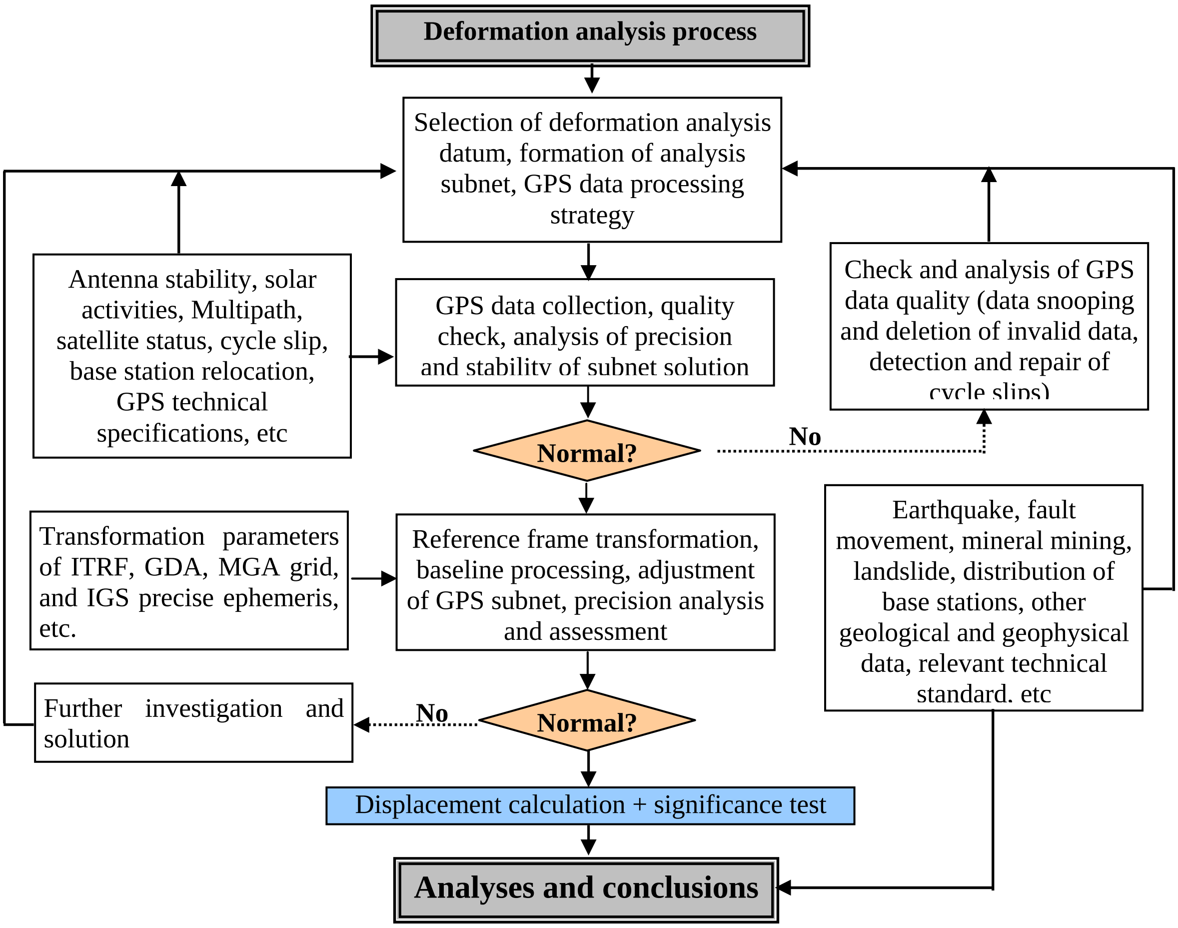

Fig. 5 Flowchart of GPSnet data processing and stability analysis

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 more 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 Observatory" 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, ie the GPS network for displacement analysis is adjusted using the free network adjustment method with no fixed datum.

3.2 Formation of deformation analysis subnet

There are a number of different deformation analyses 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 different deformation analysis, GPSnet stations should be chosen to form an optimal deformation analysis network - "subnet" for a particular corresponding purpose.

The subnet used for a certain deformation analysis purpose should use the same network shape, same deformation analysis datum and compatible precision whenever the subnet data is 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 at one time per year or one time per 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 properly increased or the session interval can even 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 precise enough and stable. 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 precise enough and stable 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 (e.g. multipath, solar activities, satellite status), and cycle slip, etc. Among these, many 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.

In GPS data processing, analysis of 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 the three packages give very similar baseline solution. AUSPOS is chosen due to its automation and access to the solutions in different reference frames (details see below). 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 6). GPS data pre-processing 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.

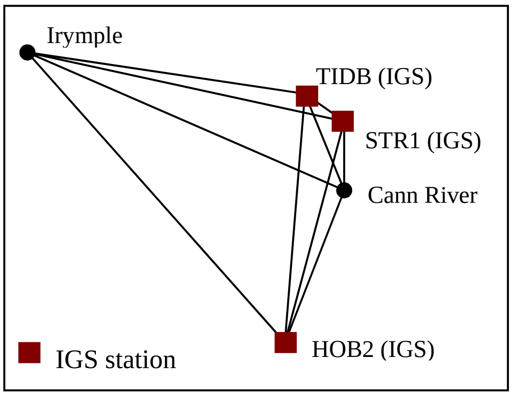

Fig. 6 An experimental network for precision analysis of GPSnet solution (not to scale)

AUSPOS allows users to submit their data via the Internet. The RINEX data needs to be static and geodetic quality (i.e. dual frequency) and the turn-around time of the processing results is very short. The quality of the coordinates with 6 hours of data is: horizontal precision is better than 10 mm and vertical precision is better 20 mm (Dawson, 2002). AUSPOS processing report provides coordinates in ITRF, GDA94 and MGA Grid, precision of coordinates, RMS of observations, 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 (IERS) computation standards.

The experimental network data recorded on 14 April 2004 is used for precision and stability analysis of solutions. Figure 7 shows the relation between precision (s_X, s_Y, s_Z) of coordinates computed (in ITRF2000) and the amount of data used. Figure 8 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-hour data.

From Figures 7 and 8, we can conclude that:

(1) Overall the accuracy of the coordinates derived from different lengths of observations varies and their differences can be upto one decimetre level. The accuracy can be improved when more data is used and the solution is pretty 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 for a high precision deformation monitoring. In addition, the solution is not stable enough, particularly when the session length is less than 2 hours. Figures 7 (b) and 8 (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 most likely due to the fact that the 2-hour data is too noisy and there exists a large random error (see Figures 2-4 for example).

(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, which means that the solution is relatively stable. When the session length is close to 24 hours, such as more than 20 hours, the precision of coordinates is 3~5mm, and the coordinate differences can be less than 5mm, which mean that the solution becomes quite stable.

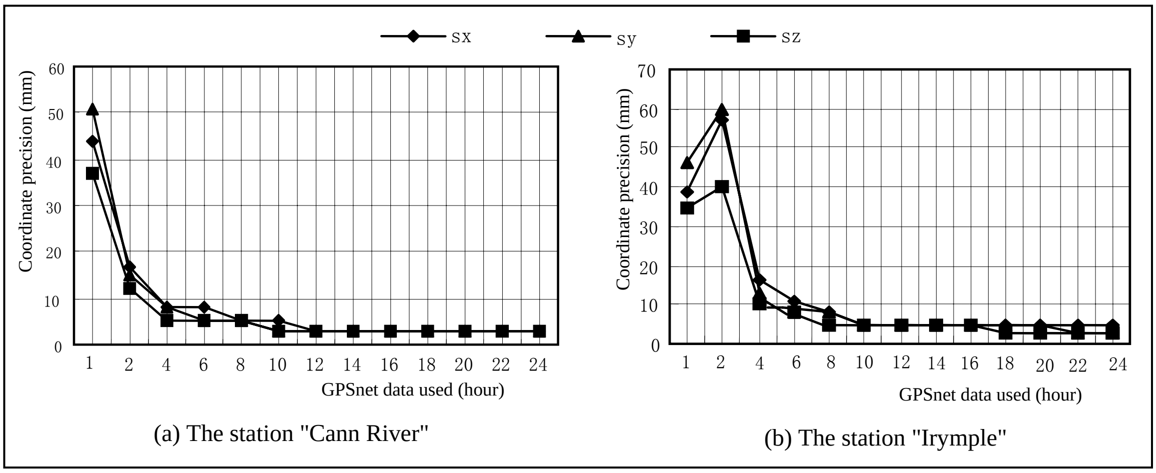

Fig. 7 Precision evaluation of GPSnet solution in ITRF2000 using different session lengths of data at stations (a) "Cann River" and (b) "Irymple" respectively

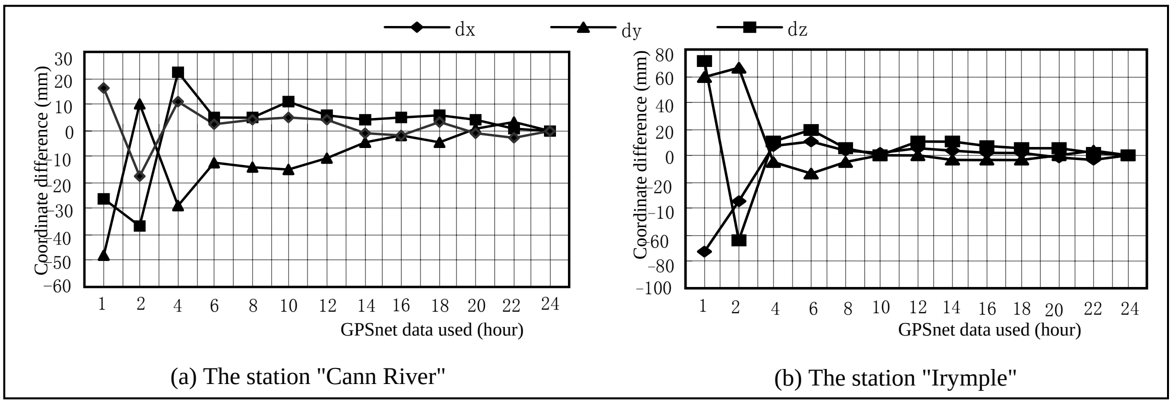

Fig. 8 Differences of the coordinate solutions in ITRF2000 using different session lengths of GPSnet data in comparison with the solution from 24 hours data

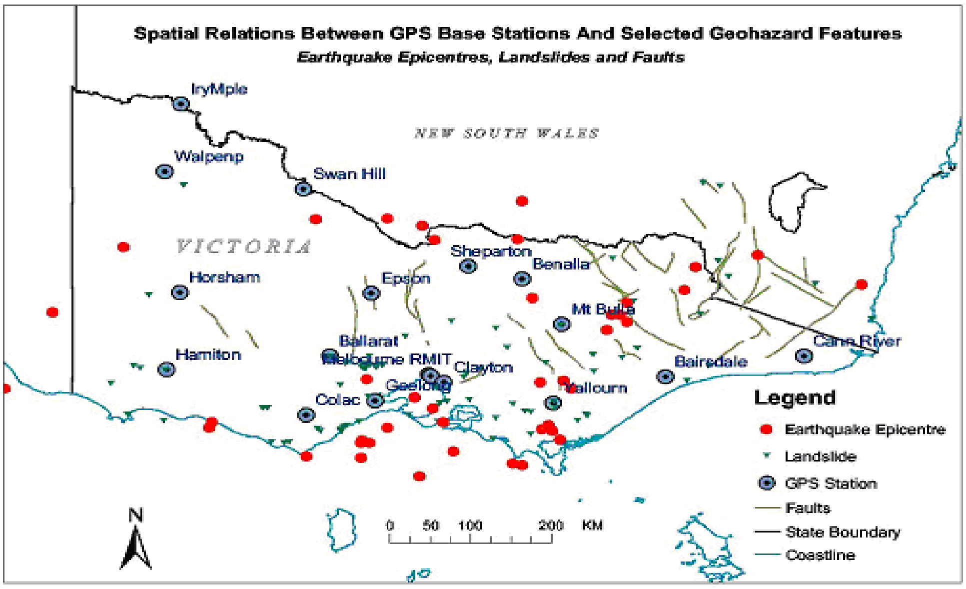

Fig. 9 Schematic figure of the displacement vector at selected stations and spatial relations between GPSnet stations and geological features

Thus it can be seen that daily GPSnet solution (24 hours of data) is of high precision and sufficient stability. It is, therefore, possible to use this data for high precise regional deformation monitoring and 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 within Victoria and some stations are close to faults and/landslide sites (eg Epson). Victoria, in particular south-eastern Victoria, 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, according to the result of displacement analysis of GPSnet stations, the regional deformation of the Earth's surface and the stability of some faults and landslide sites can be inferred.

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.

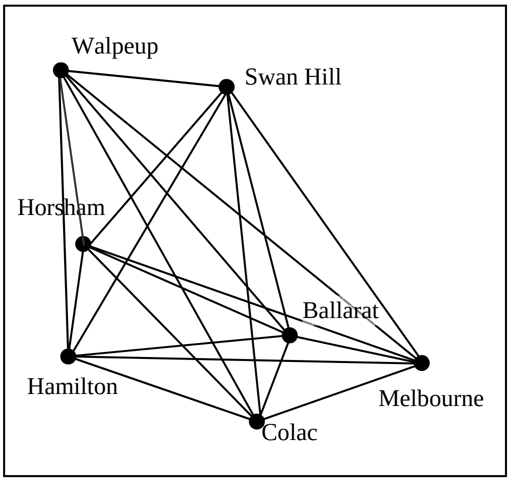

Fig. 10 A seven-station GPSnet subnet selected for displacement analysis (not to scale)

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 (ΔE=Easting, ΔN=Northing) and vertical direction (ΔU=up direction) of the subnet stations (derived from the transformation of ITRF2000 to Australian Map Grid) are shown in Table 2.

Tab. 2 Absolute and relative displacements of the GPSnet subnet stations

station	Absolute displacement (mm) and velocity (mm/yr)						relative horizontal displacement (mm)		
	ΔE	ΔN	ΔU	V	V/2	significance test	ΔE_r	ΔN_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	×

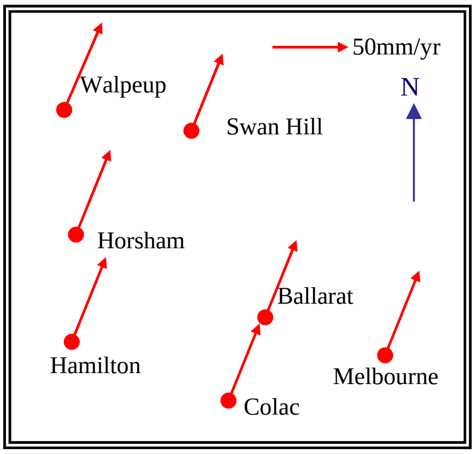

Fig. 11 Amplitude and direction of the absolute

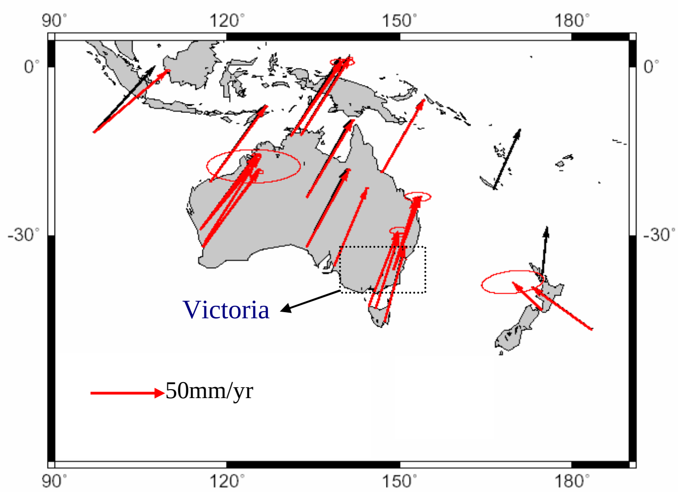

Fig. 12 Australian tectonic motion vector from IGS

The total displacement magnitude "*V*" is calculated by the following formula: $V = \sqrt{(\Delta E)^2 + (\Delta N)^2 + (\Delta U)^2}$. "*V/2*" is the mean annual velocity of the displacement. "ΔE_r" and "ΔN_r" are relative horizontal displacements and are free from the systematic horizontal displacement of the whole subnet.

5.2 Deformation Analysis

The significance of both absolute and relative displacements in Table 2 are tested. The displacement significance of the whole subnet is tested using F-Test and the displacement significance of single station is tested using T-test. The results of significance test are listed in Table 2. The symbols "✓" and "×" indicate significant and insignificant respectively. The results of significance test show that the absolute displacements of all the subnet points are significant. The absolute displacement directions of all 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).

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 enough and reliable for high precise deformation analysis. Therefore, the relative vertical displacement of the subnet is not analysed in this paper. The results of significance test 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. According to this, it can be inferred that currently, the faults and/or landslide body near these base stations are relatively stable. Of course, the stability of the faults and landslide body still needs to be continuously analysed in the future.

5. Conclusive remarks

The solution of Victorian regional CORS network is not precise enough and stable for high precise deformation monitoring and analysis if the amount of data used to generate the solution is less than 12 hours. The precision of 3D coordinates derived from daily GPSnet solution (24-hour data) is 3~5mm 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 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 ~7cm/year and direction of current Australian continent derived independently. The relative horizontal positions of the subnet points are not notably affected from local geological features. It can be inferred that the faults and/or landslide body near these base stations are relatively stable.

Preliminary results indicate that the methodology of data processing and deformation analysis based on CORS is feasible and effective. However, further investigation is required when more GPSnet data covering a larger chronological span and more GPSnet base stations can be 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 displacement 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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