

Quality Control and Integrity Monitoring of the Victorian GPS Reference Station Network

Neil BROWN¹, Allison KEALY¹, James MILLNER², Peter RAMM², and Ian WILLIAMSON¹, AUSTRALIA

KEYWORDS: GPS, reference network, quality, integrity

ABSTRACT

Permanent GPS reference station networks are being established worldwide following the establishment of GPS as a primary means for spatial data acquisition. Often these networks are used to augment the regional geodetic framework, such as GPSnet in Victoria, Australia.

As a key component of the geodetic infrastructure, high importance is placed upon quality control and integrity monitoring of the GPSnet reference network. There are two key components to such a quality system: analysis of the raw observations and stability monitoring. This paper discusses the operational environment of GPSnet with emphasis given to quality and integrity issues. The policies, procedures and techniques and studies being used to manage and accommodate these quality concerns are examined.

CONTACTS

¹ Department of Geomatics
The University of Melbourne 3010
Australia
Ph: +61 3 8344 9696
e-mail: neb@sunrise.sli.unimelb.edu.au

² Geodetic Infrastructure Land Victoria
570 Bourke Street
Melbourne 3002
Australia
Ph: +61 3 8636 2376
e-mail: James.Millner@nre.vic.gov.au

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INTRODUCTION

Permanent GPS reference station networks are being implemented throughout the world following the establishment of the Global Positioning System (GPS) as a primary means for spatial data acquisition. Often these networks are used to augment the regional geodetic framework, such as Land Victoria's GPSnet in Victoria, Australia. GPSnet was officially launched in July 1996 and currently consists of 15 permanently operating reference stations, comprising receivers from a number of different manufacturers. The Victorian State government operates several of the GPSnet base stations in collaboration with various private and local government organisations. GPSnet is used for a very diverse range of applications including cadastral surveying, mining, precision farming and vegetation mapping.

Quality control and integrity monitoring are important for the success of a CORS network. There are requirements for consistent, continuous raw code and phase data that meet minimum quality criteria. In Victoria, purpose written software is used to monitor the quality and integrity elements of these raw data. It is also preferable that the GPS reference stations provide an accurate realisation of the datum. However, this can cause problems, especially when many users of the geodetic infrastructure are still very reliant on lower-order ground marks that were typically coordinated using traditional surveying methods. Local issues, such as earthquakes and massive earthworks that cause mass soil movements, that might effect base station stability must also be addressed.

In this paper the state of geodetic infrastructure in Australia and Victoria is explained after which the operational environment of the Victorian GPS reference network is discussed. The focus of the paper then shifts to quality and integrity issues of a CORS network and the resulting policy, processes and investigations that are being undertaken in Victoria to address them.

GPS GEODETIC INFRASTRUCTURE

With the increasing number and diversity of GPS users there is a trend towards the establishment and use of individual reference stations that are primarily focused on the generation of information for a single application. Unchecked, this spatial information will lack the consistency and homogeneity required for data warehousing. A more coordinated approach is preferable to draw on the recognised benefits of data sharing. Many of the existing continuously operating GPS reference (CORS) networks have been primarily intended to augment the existing geodetic infrastructure because of the benefits they offer in the cost sharing and the capture, integration and utilisation of spatial data. According to Davies (2000) CORS stations can be though

of as active geodetic marks. As with classical geodetic marks, the accuracy, access, maintenance and other considerations are dependent on the intended users and applications of the infrastructure.

In Australia, the Federal government through the National Mapping Division of Geoscience Australia (formerly AUSLIG) owns and operates the Australian Fiducial Network (AFN) and Australian Regional GPS Network (ARGN). Together, the AFN and ARGN consist of 15 dual frequency receivers spread across Australia and the Australian Antarctic Territories. The AFN stations contribute to the International GPS Service (IGS) worldwide reference network. The AFN also provides the zero-order (highest level) control for the recently adopted Geocentric Datum of Australia 1994 (GDA94) and provides the connection to the International Terrestrial Reference Frame (ITRF). Data from the AFN are freely downloadable for processing by GPS users. Alternatively, the AUSLIG Online GPS Processing Service (AUSPOS), which employs data from the IGS network, may be used to calculate precise ITRF and GDA94 coordinates using several hours of static dual frequency data collected anywhere on the earth (Dawson et al., 2001). In Australia this means users are able to get GPS coordinates derived directly from the GDA94 zero-order control at the level of one centimetre or better.

The density of AFN reference stations does not adequately cater for a number of more local GPS applications in the State of Victoria. For example, rapid static or kinematic survey-grade positioning across Victoria is not possible using the AfN/ARGN networks. Significantly, no AFN/ARGN stations are located within Victoria. Land Victoria, under the auspices of the Department of Natural Resources and Environment, has a mandated responsibility to establish and maintain a geodetic reference system for Victoria. Victoria's geodetic reference system was originally established using classical surveying techniques and was used primarily by federal, state, and local governments, and utility companies to maintain uniformity in land surveys. In order to provide a common platform for GPS developments in Victoria, Land Victoria has established the state-wide reference station network GPSnet. In its current configuration GPSnet comprises 15 continuously operating geodetic receivers with an average spacing of 160km over the state and approximately 50km around the greater Melbourne metropolitan region, see Figure 1.

The policy of Land Victoria is for GPSnet to provide the capability for users to get positions at the metre to centimetre-level using GPS anywhere within the state. The full network is expected to be completed in 2002 and provide a uniform positioning accuracy of approximately five centimetres across the state (Ramm et al., 2000). GPSnet has an open access, manufacturer independent platform to encourage GPS development within Victoria. GPSnet base stations use geodetic grade dual frequency receivers with choke ring antennas. Specific site details can be found at www.land.vic.gov.au/geodesy.

GPSnet is used to augment the 120,000 plus ground marks in Victoria and is a key component of the Victorian Geodetic Strategy. As such Land Victoria has a commitment to monitoring the quality of GPSnet under the Victorian Geospatial

Information Strategy (VGIS) guidelines. It is also deemed important, in light of developments in Spatial Data Infrastructures (SDI), that data produced using GPSnet is homogenous and consistent with data from other states. If this accuracy is achieved, integration of state and regional data sets will be simplified and at a high standard. Significantly, a number of the GPSnet base stations are jointly operated with local government or private industry, imposing some unique operational requirements.

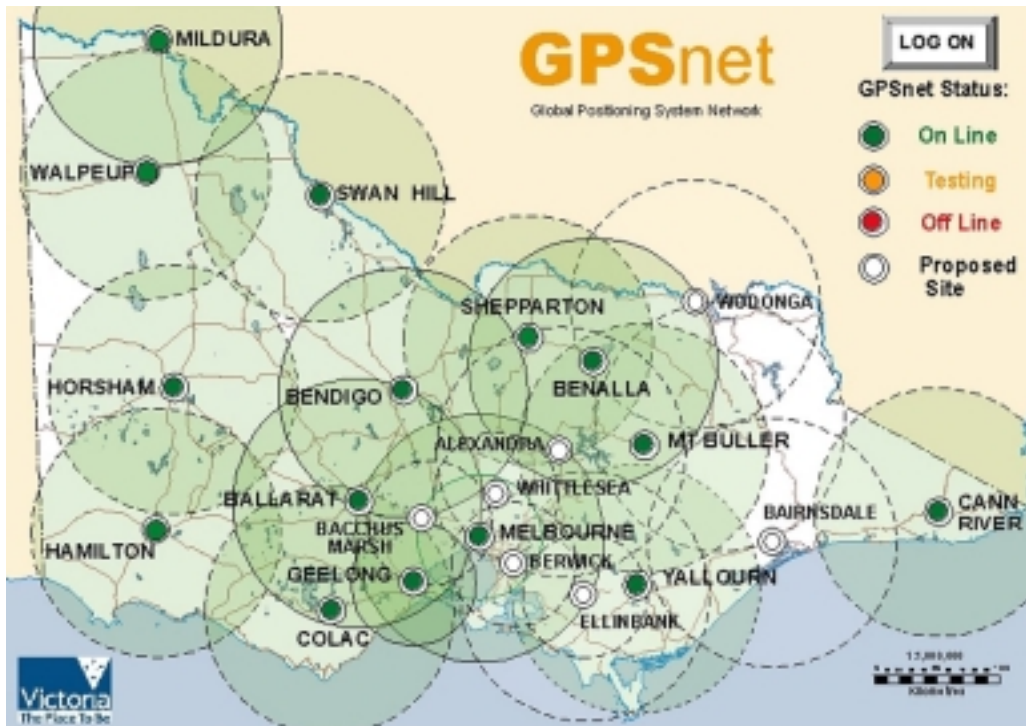


Figure 1: The Victorian GPS reference network

COLLABORATIVE GPSNET BASE STATION ESTABLISHMENT

To facilitate the establishment of the Victorian GPSnet base station network, Land Victoria seeks out potential hosts and adds to local investment to achieve a common standard of infrastructure. Collaborative base station hosts include local governments, large survey organisations, natural resource managers, and utility companies.

A common infrastructure standard is required to meet traditional positional accuracy requirements normally expected of a ground marked state geodetic network. Furthermore, the standard must address equipment security expectations that also ensure local site access and remote computer control for adequate operation, management and maintenance requirements.

GPSnet base station equipment and architecture are generally located within a Host organisation's locked IT server room. GPS antennas are usually sited on a rooftop at the most stable location free of multipath, for example above the lift core or stairwell. A typical example can be seen in Figure 2.

A number of sites are not associated with traditional ground marks; instead the antenna reference point (ARP) has been coordinated using a mixture of GPS and conventional surveying with nearby ground marks. A guiding principle being coordinates can simply be updated as required and therefore are accompanied with a time tag. Of course care must be taken that the correct antenna offsets are used during processing, especially if the antenna of the reference and rover stations are not the same make and model.

Ideally the GPSnet base station coordinates would be referenced directly to the AFN so that there is good agreement with the national framework. However, due to the sequential adjustment of GDA94 from the AFN down to the low order control there is generally a centimetre-level bias in the local ground control when compared to coordinates derived directly from the AFN. In some parts of the state this difference is 1-2cm and in others it is up to 15cm (Dawson, 2001). By referencing the GPSnet base stations to nearby ground control the local consistency of the datum is maintained. In time these biases, which are a legacy from traditional surveying methods, will be eliminated with the introduction of more satellite-based measurements into the datum realisation. In the meantime surveyors use ground control to verify base station coordinates and to fit constrain their results to the superseded reference frame AGD66. This datum is still used and will continue to be until all data sets are transformed to the new datum.



Figure 2: GPSnet Mildura

In the future, it is envisaged that GPSnet will be composed of base stations built to current OCRs Site Monumentation recommendations (National Geodetic Survey, 2001). Although concrete pillars are not especially difficult or costly to build to the CORS standard, managing the GPSnet system architecture that is required to send data files over the Internet while ensuring adequate standards for security and multipath are met, will be a considerable challenge. In the short term a small number of stations on geologically stable pillars are to be used in monitoring the stability of the network.

GPSNET DATA AND SERVICES

GPSnet stations operate 24 hours a day and collect data at a one second recording interval. Every GPSnet station is real-time capable, and several GPSnet sites transmit local real-time corrections for deformation or mining operations. Based on American and European mobile telecommunication standards it is prohibitively expensive to

construct the high density of radio transmission stations that are capable of delivering wireless data across Australia's vast reaches. This lack of appropriate communications infrastructure presently inhibits complete statewide coverage of real-time corrections in Victoria using digital mobile phone technology.

The convergence of GPS equipment and fixed line networked communication technology has made it possible to efficiently centralise GPSnet data. One-hour RINEX file with a five second observation interval are sent from GPSnet base stations via the Internet to a central server on an hourly basis. This centralisation process allows additional quality and integrity scrutiny over the data and, in time, more effective use by integrated applications and services, such as computing Virtual Reference Stations (see van der Marel, 1998) and online processing.

Access to RINEX files of five second epoch interval is available to subscribers from the GPSnet website. File downloads attract a fee in accordance with Land Victoria's Pricing Policy. Proprietary formats (eg Trimble SSF) are available from eleven of the fifteen sites to facilitate easy automatic processing of mapping data with software like Trimble's Pathfinder Office.

GPSNET USERS

The geodetic infrastructure in Victoria was originally created to aid land settlement and mapping. Today, many of the users of the geodetic infrastructure in Victoria still come from the land surveying and government mapping sectors. The majority of these users primarily connect to control via ground marks. These ground marks are generally of a lower order than the GPSnet base stations. As use of GPS becomes more common, the use of ground marks by industry will decline, thereby reducing the dependency on lower order control.

At the time of GPSnet's conception it was anticipated that Land Surveyors would, at least initially, be the primary users of the reference network. However, the generally small survey companies surveyors have proved slow to take up GPS technology because of a number of issues (Geospatial Science Initiative, 2001). Firstly, concern over legal traceability with respect to cadastral surveys resulting from ambiguous legislation. Capital outlay on GPS equipment, especially dual-frequency receivers, is prohibitive for the predominantly small (3-5 person) surveying companies in Victoria. Lastly, concerns over the practicality of GPS surveying in built or natural environment where obstructions limit the availability of satellites. Larger multi-disciplinary firms have found the GPS network to improve productivity and efficiency.

Many of the users of GPSnet come from within Land Victoria's parent organisation, the Department of Natural Resources and Environment (NRE). NRE is involved with all types of mapping and natural resource management. A wide range of applications that use GPSnet include: road access, vegetation and topographic mapping, forestry (disease, deforestation and koala mapping), precision agriculture and channel

dredging to name a few. Users from NRE are typically interested in automatic code-based differential GPS for reliable metre or sub-metre level positioning.

GPSNET DATA QUALITY

There are two main aspects of data quality for a CORS network like GPSnet. The first is the integrity and fundamental quality and utility of the raw code and phase data. The second is the utility and stability of the network. Together these factors determine the level of positioning that is achievable using the network. As outlined earlier, GPSnet is intended for users seeking centimetre level positioning. In order to ameliorate potential data quality and antenna stability concerns, the quality conditions outlined in Table 1 have been documented to ensure the accuracy and homogeneity of the GPSnet coordinates is maintained. These quality specifications form part of the Victorian Geospatial Information Strategy (VGIS).

Table 1: GPSnet network monitoring minimum quality conditions

Category	Criteria
Preliminary Analysis of Data Pre-processing of data monitor its integrity	<ul style="list-style-type: none"> All data to have minimum of C/A code, L1 and L2 phase and L1 Doppler observations. Multipath, cycle slips, data gaps, latency and noise to be monitored.
Rapid variations Relatively large movements that occur over a small period	<ul style="list-style-type: none"> Detection of any movements above system noise over the period of an hour
Gradual variations Small, cumulative movements that become significant over a long period	<ul style="list-style-type: none"> Detection of any movements above system noise over the period of a day, week, month, 3 months, 6 months and a year, or some other time period as appropriate Comparison of current versus reference epoch using 24hr of data
Fault detection Determination of the reason for the change in base station coordinates	<ul style="list-style-type: none"> Confirmation of fault using alternate methods (if appropriate) Reason for movement determined Steps taken to reduce recurrence (if appropriate)
Updates to coordinates Coordinates of the base stations are updated to ensure their accuracy	<ul style="list-style-type: none"> New station coordinates that are consistent with the national framework and other stations Generated as appropriate SMES and base station data simultaneously updated Notification to users
Data Archiving Results of network monitoring archived	<ul style="list-style-type: none"> Results archived to provide lineage Study of historical movement to detect trends and highlight problems Support of legal traceability of GPS measurements
Independent checking Non-GPSnet checking of base station coordinates	<ul style="list-style-type: none"> Performed once every two years or if problems arise
Connection to national framework Ensure consistency with national geodetic framework	<ul style="list-style-type: none"> GPSnet data processed with data from the Australian Fiducial Network GPSnet incorporated into national adjustments

DATA INTEGRITY

Prior to any detailed analysis of the reference network stability it is necessary to pre-process the data to monitor its integrity. Various software utilities are available to perform this testing (e.g. TEQC, TurboEdit, DelftQC) at different levels of

sophistication. Under the Victorian Geodetic Strategy the primary concerns for GPSnet are:

1. Data availability.
 - a) The data arrived at the central server (and hence is available for download by users).
 - b) The data is uncorrupted (intact with correct RINEX format).
2. The receivers are all functioning correctly. Specifically,
 - a) All receiver channels are operational.
 - b) Measurements to all visible satellites are being recorded.
 - c) There are no gaps in the data
 - d) All observation types specified in Table 1 are being recorded correctly.

Issues regarding the interference, multipath and obstructions should have been taken care of during the site selection process, but are still important to be aware of and monitor.

TEQC (see www.unavco.ucar.edu) provides a comprehensive tool for analysing general data quality at the zero-difference level, but does not break down the results into the various observation types and much of its output regarding data gaps and missing observations is reported graphically making it difficult to report automatically certain occurrences. DelftQC (available on request from Delft University of Technology) works at a lower level providing quality information for every satellite epoch without providing summaries. Output includes estimates of P-code and C/A code multipath, tropospheric and ionospheric delays, and CA-P1 bias for each satellite for every epoch.

In order to meet the above requirements for GPSnet software has been written by the University of Melbourne in collaboration with Land Victoria and is undergoing development and testing. The software automatically processes the zero-difference raw RINEX data as it arrives at the central server and alerts the network manager via e-mail if any of the above requirements are not met. Summaries of the performance of each base station are compiled. Additionally the software performs administrative tasks such as archiving the data. Cycle slip and outlier detection is performed using the wide-lane code and phase linear combination based algorithm developed by Blewitt (1990) and used in the TurboEdit software. Code multipath RMS on both frequencies is estimated using the TEQC algorithm (Estey and Meertens, 1999).

GPSNET BASE STATION ANTENNA STABILITY

Due to the monumentation of GPSnet base stations there are concerns that geological or other events may cause some movements of the base station antenna. Such movements may be the result of diurnal heating and expansion of the buildings, wind effects or mass soil movements and geological events. The collaborative base station at Yallourn is of the most concern. A very large open-cut coal mine is adjacent to this site and has a shearing effect on the whole area. GPSnet Yallourn is used for deformation monitoring around the mine site and is currently resurveyed on a regular

basis. Movements of about 17mm in height and 8mm in horizontally are seen over a period of 18 months. Additionally this area is one of the more geologically active parts of Victoria and experiences earthquakes from time to time. The monitoring criteria given in Table 1 have been used to address these issues and are based on the premise that antenna movement is inevitable. Emphasis is given to rigorous detection of any such movements and updating of coordinates in a timely fashion before they have consequences for users. At present specifications have not been set on the magnitude of the departure from published coordinates that will require publication of updated coordinates. Some base stations, such as Yallourn, are used for demanding applications and must be maintained to a very high accuracy (millimetre level). Before specifications can be set, it is necessary to determine the noise level of GPSnet. The question of what amount of movement can be reliably distinguished must be established. Noise is primarily a function of data quality, multipath and baseline length.

The preferred benchmark for monitoring the stability of the GPSnet base stations is the AFN because a) this is the highest level control for the GDA94 datum, b) the AFN are all monumented with geologically stable pillars, and c) the AFN sites are regularly processed with other IGS sites as part of the realisation of ITRF and therefore have very good ITRF coordinates. In order to use the AFN as control, sophisticated software must be used as most GPSnet base stations are 200 to 600 or so kilometers from the nearest AFN station. The Bernese software (Hugentobler et al., 2001) has been used in the studies conducted to date.

CALIBRATION OF GPSNET

Processing is performed in the ITRF97 reference frame and then transformed to GDA94 (which is fixed at the 1994.0 epoch of ITRF92) using a 7-parameter transformation and parameters interpolated from those given by AUSLIG (2001). Three or four AFN sites (Tidbinbilla, Mt Stromlo, Ceduna and Hobart) are held as fixed in the adjustments. So far only a small amount of the available archive data has been processed. As the time series grows it will provide a good overview of station stability. Preliminary results indicate RMS of daily solutions in the order of 2-4mm in easting and northing and 3-8mm in height using the IGS Final Orbits product.

In the event of an earthquake, such as has been experienced at Yallourn, a major concern is the proper operation of the receiver and its uninterrupted backup power supply (UPS). A momentary interruption in the power supply may cause loss of data and reset the receiver software. Due to the spacing of GPSnet base stations it is critical that any such interruptions are detected and resolved in a timely manner. Experience at Yallourn has also shown that these interruptions can cause noisy data, dramatically reducing the usability of the data for a period of time. Such problems (short of power/data loss) are not necessarily readily detected with zero-difference processing. Problems are first noticed when overly large code and/or phase RMS values are computed during network processing.

In order to determine the noise level of GPSnet and, hence, the sensitivity of any network monitoring, a precise GPS antenna mount was designed and constructed. The mount allows for precise movement of a GPS antenna in three dimensions. By inducing a precisely known change in the position of a reference receiver and comparing versus the calculated shift the noise level is to be assessed.

An experiment was conducted in which 120 hours of data were collected using a Leica SR530 receiver and a choke ring antenna mounted on the adjustable mount. The receiver was placed on the roof of the Geomatics Building at Melbourne University simulating a GPSnet base station. During the experiment a number of controlled movements of the antenna were made with at least 24 hours of clean data either side of the movement. I.e. the first epoch of data was clean, the second has a movement imposed upon the antenna, the third hour (epoch 2) was static etc. The antenna mount was aligned with grid north so that a known movement could be made in each of the east, north and height directions.

Pre-analysis of the data shows that it is generally clean of any anomalies with an average of about 7 satellites and an average GDOP of about 2 with a maximum of 5.8. No data was lost to obstructions using an elevation cut-off of 15 degrees.

As previously mentioned, GPSnet data is sent via FTP to the central server at the end of each hour. Therefore, the earliest that any deformation may be detected is at immediate processing on arrival of the one hour RINEX files. The purpose of this experiment is to assess the ability to detect movement using various amounts of data, the smallest being of one hour duration.

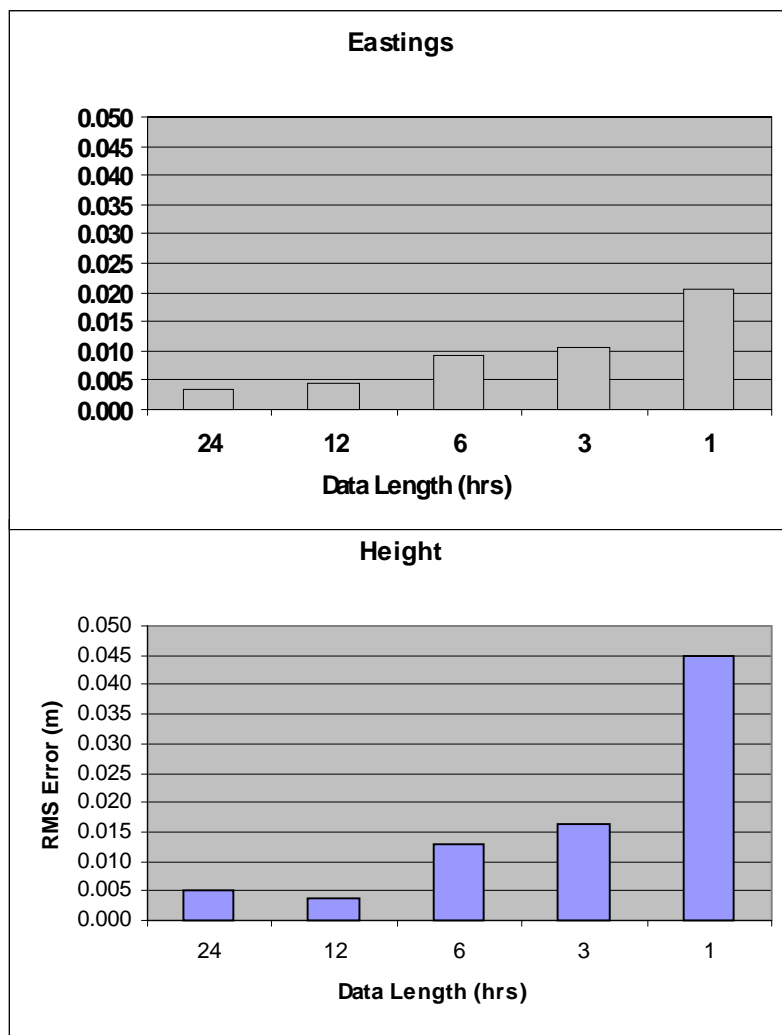
The data was processed with Bernese using both the IGS Rapid and the IGS Final orbits and three AFN stations held fixed. The Rapid and Final orbits produced similar results and so only the results using the Final orbits have been shown. Figures 3 and 4 show the RMS error of the mechanical minus measured movement in the easting and height components respectively. The reliability of the solution shows a strong relationship with the amount of data used to generate the solution. As the amount of data decreases estimation of the tropospheric error becomes problematic which is shown clearly in the results.

The corresponding formal error estimates from the processing were very conservative, which is typical of GPS (Barnes et al., 1998, Wang, 1999). For the shorter sessions the RMS errors were about 1mm in easting and northing and 5mm in height. However, in relative terms the estimated precisions of the results generally reflected the difference in quality between the various epochs.

CONCLUSION

Due to developments in GPS processing, very high accuracy coordinates related closely to the national zero-order control are possible. However, many users of the geodetic infrastructure in Victoria continue to rely on traditional ground marks. The

Victorian GPS reference network, GPSnet, accommodates the needs of the positioning community within Victoria and GPSnet derived coordinates are consistent with nearby ground marks. As the industry's dependence on ground control diminishes over time, GPSnet will develop to have closer linkages to the national infrastructure (especially the AFN) and thereby improve the accuracy and consistency of spatial data sets across the country. Quality control and integrity monitoring are important for the success of a CORS network. There are requirements for consistent, continuous raw code and phase data that meet minimum quality criteria. It is also important that coordinates derived from the reference network match the local control. In Victoria, purpose written software is used to monitor the basis quality and integrity of the raw data. Bernese is being used in preliminary study to ensure that the GPSnet sites, many of which are located on masts on the tops of buildings, are stable and provide accurate coordinates.



Figures 3 and 4: RMS Errors of mechanical vs measured movement for different data spans

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ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge the support of Land Victoria and the Centre for Spatial Data Infrastructures and Land Administration, The University of Melbourne in preparing this paper.

BIOGRAPHICAL DETAILS

Neil Brown

Neil graduated from the University of Melbourne in 1999 with a Bachelor of Arts and a Bachelor of Geomatics (Honours). He is currently undertaking a Doctor of Philosophy degree in the Department of Geomatics, University of Melbourne on stochastic modelling of the GPS observables.

Allison Kealy

Allison Kealy is currently a lecturer in the Department of Geomatics at the University of Melbourne, specialising in the research areas of GPS, GLONASS and integrated systems. Allison received her PhD in Geodesy from the University of Newcastle upon Tyne, UK in 1996, after which she spent 2 years in industry providing technical support for GPS/GLONASS manufacturers Ashtech Ltd.

James Millner

Before joining Land Victoria as the GPSnet Development Manager, James worked with the Product Planning Group Nikon Corporation in Tokyo Japan. With extensive experience developing GPS applications, James received the Sir Thomas Mitchell Excellence in Surveying Award 1997 for innovations in technology transfer and international promotion of the surveying profession.

Peter Ramm

Peter Ramm is the Chair of the Australian Intergovernmental Committee on Survey and Mapping (ICSM). ICSM's role is to provide leadership in surveying, mapping and charting through coordination, cooperation and standards development. Peter is also the Director, Geodetic Infrastructure, Land Victoria where he is leading a fundamental change in delivering geodetic services. His previous responsibilities have included policy development, management a large utility survey and hydrographic operation and management of government businesses.

In 1997, Peter's achievements were recognised with the awarding the inaugural Thornton Smith Prize for outstanding contribution to the surveying and geomatics industry by Melbourne University. Peter has a Bachelor of Surveying from Melbourne University, and a Graduate Diploma in management. He is a Licensed Surveyor and a Fellow of the Institution of Surveyors Australia.

Professor Ian Williamson

PhD (NSW), DrHC (Olsztyn), FTSE, FISAust, FIEAust, HonMFIG, HonFMSIAust, LS, CPEng

Ian Williamson is Professor of Surveying and Land Information, Head, Department of Geomatics and Director, Centre for Spatial Data Infrastructures and Land Administration at the University of Melbourne. His teaching and research is concerned with designing, building and managing land administration, cadastral, and land and geographic information systems in both developed and developing countries. He is a Licensed Land Surveyor and Chartered Professional Engineer.

He has undertaken research and consultancies worldwide including for Australian governments, AusAID, many individual country governments, the United Nations and the World Bank. He was Chairperson of Commission 7 (Cadastral and Land Management) of the International Federation of Surveyors 1994-98, and is currently Director, FIG/UN Liaison 1998-2002. He is an Honorary Member of the FIG. At the University of Melbourne he has been President of the Academic Board and Pro-Vice-Chancellor. He is currently Chairperson of the Victorian Government's Geospatial Information Reference Group and Chairperson of Working Group 3 (Cadastral) of the United Nations sponsored Permanent Committee for GIS Infrastructure for Asia and the Pacific (2001-2004).



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Author/s:

BROWN, NE; KEALY, A; MILLNER, JM; RAMM, PR; WILLIAMSON, IP

Title:

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Date:

2002

Citation:

BROWN, N. E., KEALY, A., MILLNER, J. M., RAMM, P. R. & WILLIAMSON, I. P. (2002).
Quality Control and Integrity Monitoring of the Victorian GPS Reference Station Network.
XXII Fig International Conference, CD-ROM, pp.1-13. International Federation of Surveyors.

Publication Status:

Published

Persistent Link:

<http://hdl.handle.net/11343/33882>

File Description:

Quality Control and Integrity Monitoring of the Victorian GPS Reference Station Network