CORSnet-NSW: A Success Story

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ABSTRACT

The introduction and expansion of Global Navigation Satellite System (GNSS) Continuously Operating Reference Station (CORS) networks across Australia and internationally has greatly improved access to positioning infrastructure for a wide range of GNSS applications and related research. Within only five years, CORSnet-NSW has matured into a world-class, state-wide, multi-function GNSS CORS network that balances public-good and commercial mandates. Now comprising 180 CORS, the network has revolutionised internal and external GNSS operations, not only supporting the surveying and spatial information profession but also making important contributions to national and regional geodesy. This paper outlines the success story of CORSnet-NSW, including its current status and the impact it has on providing first-class state infrastructure for GNSS users in New South Wales. The present difference between datum realisation via SCIMS and via CORSnet-NSW is explained, and efforts undertaken at LPI to rectify this situation by contributing to the modernisation of Australia's national datum are discussed. Finally, it is outlined how LPI supports the surveying profession and the wider spatial community in regards to GNSS. The State's CORS infrastructure has become crucial in catering for an increasing demand for accurate, reliable and easily accessible GNSS positioning information in today's society. In Australia, state jurisdictions provide the essential link between national initiatives and academia on the one hand and the profession on the other, e.g. via maintaining positioning infrastructure and conducting applied research that informs legislation and best practice guidelines.

KEYWORDS: *CORSnet-NSW, GNSS, CORS, positioning infrastructure, applied research.*

1 INTRODUCTION

Global Navigation Satellite System (GNSS) Continuously Operating Reference Station (CORS) networks have been introduced and recently expanded significantly across Australia and internationally to provide improved access to positioning infrastructure for a wide range of GNSS applications in areas such as surveying, mapping, asset management, precision agriculture, engineering and construction, airborne imaging and sensors, and utilities management. Real Time Kinematic (RTK) or Network RTK (NRTK) GNSS positioning

methods in particular, once initialised, provide high-precision coordinates and allow 'real-world digitising' with the ability to significantly enhance productivity. For example, CORS networks are well-suited to support improving cadastral infrastructure with RTK GNSS techniques (Janssen et al., 2011a), and NRTK produces superior coordinate results in regards to both precision and accuracy (e.g. Janssen, 2009c; Janssen and Haasdyk, 2011).

GNSS positioning technology is used around the globe, with 3.6 billion GNSS devices in use in 2014 – the surveying sector only accounts for a small portion of this number. By 2019, the number of GNSS devices is expected to increase to over 7 billion, i.e. an average of one device per person on the planet. The global core GNSS market is predicted to increase by 8.3% annually between 2013 and 2019 before slowing down to 4.6% towards 2023, i.e. the GNSS downstream market is expected to grow, on average, faster (7%) than the forecasted global Gross Domestic Product (GDP) during this period (6.6%) (GSA, 2015). The Location-Based Services (LBS) and road sectors dominate predicted cumulative GNSS revenues (with a combined total of more than 91%), driven by booming sales of smartphones, in-vehicle devices, location-aware applications and data services (Figure 1). This clearly illustrates the importance of GNSS positioning infrastructure, particularly in regards to rapidly growing mass-market applications.

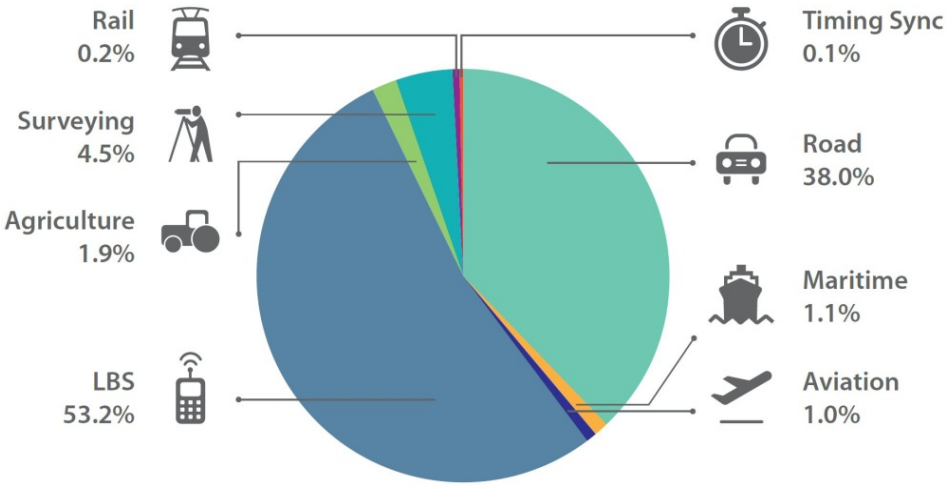

Figure 1: Predicted cumulative core GNSS revenue distribution by application 2013-2023 (GSA, 2015).

While the surveying sector is a very small and specialised GNSS market, it is a crucial one that underpins all others by providing the fundamental reference for GNSS positioning services. On behalf of the Surveyor General of New South Wales (NSW), Land and Property Information (LPI) has a legislative, regulative responsibility to maintain the geodetic control network in NSW. As such, LPI is the custodian of more than 250,000 marks in the NSW Survey Control Information Management System (SCIMS – see Kinlyside, 2013), which includes about 6,000 traditional 'passive' trigonometrical stations as well as at least 180 'active' GNSS CORS.

The Trigonometrical Survey of New South Wales, as the State's geodetic control network was then known, commenced in 1867 and continued with little interruption for almost 50 years until it was suspended for reasons of economy and war in 1916. By then, about one third of the State (mainly in the south-east) had been covered by a series of well-conditioned triangles of first and lower orders, observed as distances and angles between trigonometrical stations. The survey was resumed intermittently between the two World Wars with much of its progress attributable to the Royal Australian Survey Corps, particularly the connections to the

Victorian and Queensland networks, and along the NSW North Coast. In the 1950s and 1960s, the Division of National Mapping (now Geoscience Australia) extended the first-order networks into the western part of the State, and other networks were established by the NSW Department of Lands (now LPI). Together with the first-order traverses performed by the Royal Australian Survey Corps, the geodetic network had extended to approximately half of the State prior to the national adjustment of 1966 – this had taken 100 years (Rassaby, 1980).

In contrast, it took only five years to cover more than two thirds of NSW with 150 active GNSS CORS via CORSnet-NSW by July 2014 (Janssen, 2014), with more being added to the network today. While active survey control marks are more accurate and easier to maintain than passive control marks, both are required by the profession. Consequently, LPI continues to preserve, upgrade and maintain passive control marks using GNSS (Gowans et al., 2015) and other terrestrial methods.

This paper outlines the current status of CORSnet-NSW and the impact it has on providing first-class state infrastructure for GNSS users in NSW. The present difference between datum realisation via SCIMS and via CORSnet-NSW is explained, and efforts undertaken at LPI to rectify this situation through the upcoming national adjustment as part of the national Modernising Australia's Datum initiative (ICSM, 2015) are discussed. Finally, it is outlined how LPI supports the surveying profession and the wider spatial community in regards to GNSS infrastructure and applications.

2 CORSnet-NSW

CORSnet-NSW is Australia's largest state-owned and operated GNSS CORS network. It is built, owned and operated by LPI, a division of the NSW Department of Finance, Services and Innovation. Day-to-day operation is performed by the Survey Infrastructure and Geodesy (SI&G) section. LPI's first CORS was installed in 1992 in Bathurst, using in-house developed programming to support internal survey and aerial photography operations (Kinlyside and Yan, 2005). In 2004, a pilot-project network of seven CORS was installed in the Sydney metropolitan area and made available to the public one year later under the name SydNET (Roberts et al., 2007).

A renewed effort of expansion to extend the coverage of CORS throughout NSW commenced in 2009 as part of a 5-year, multimillion-dollar Survey Infrastructure Improvement Project (SIIP), which corresponded with the rebranding of the network as CORSnet-NSW (Janssen et al., 2010). In only five years, the network increased from 27 stations in November 2009 to 160 CORS in December 2014 (Figure 2) – an extraordinary achievement, considering the technical and resourcing challenges faced and time taken to get approval to build some sites (Janssen et al., 2011c, 2013). Today, the network continues to expand (Janssen et al., 2015). LPI aims to release its 200th CORS in conjunction with the modernised Australian datum and associated products (e.g. a new AUSGeoid) in early 2017 and be a major stakeholder in the evolving National Positioning Infrastructure (NPI) plan.

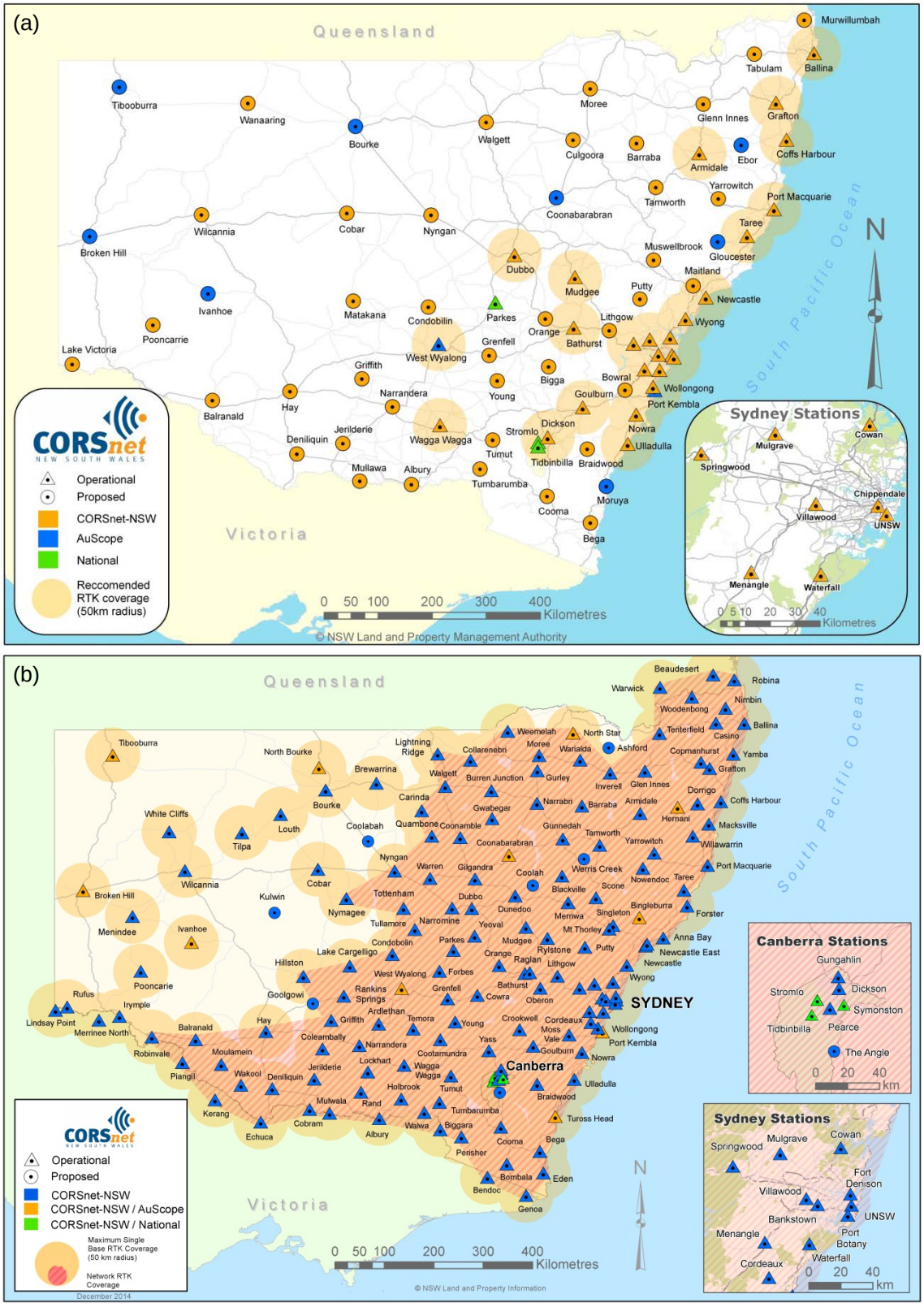

Figure 2: CORSnet-NSW network map as of (a) November 2009 and (b) December 2014.

2.1 Current Status

CORSnet-NSW is now a state-wide network of GNSS CORS providing fundamental positioning infrastructure for New South Wales (and the Australian Capital Territory) that is

accurate, reliable and easy to use (Janssen et al., 2011b, 2015; LPI, 2016). It supports the spatial community and provides stimulus for innovative spatial applications and research using satellite positioning technologies. As of March 2016, CORSnet-NSW consists of 180 active reference stations across the State.

The current coverage of CORSnet-NSW is illustrated in Figure 3, showing stations that are operational (indicated by small triangles) as well as planned stations (indicated by small circles) to be built in the coming months. A 50 km radius around active stations is shown to illustrate the maximum recommended coverage area for single-base RTK operation, while NRTK coverage at the 2-cm level (95% confidence level, horizontally) is shown as a striped, pink polygon in areas that have sufficient station density to support this technique.

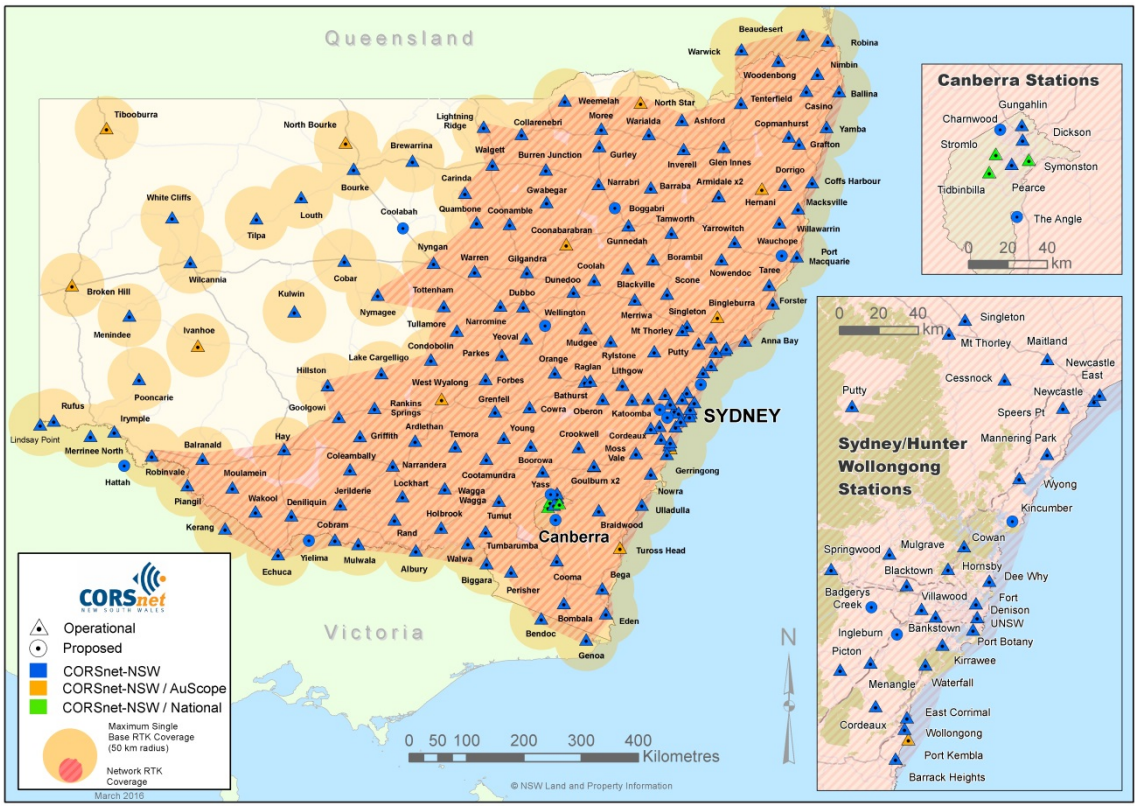

Figure 3: CORSnet-NSW network map as of March 2016 (LPI, 2016).

Currently, 75% of the area of NSW (and 99.8% of the population) is covered by the single-base RTK service, while NRTK is available to 56% of the area of NSW (and 98.6% of the population). More than 62% of the state's population is within 10 km of their nearest CORS. A sub-metre Differential GNSS (DGNSS) service is provided across the entire State. Other services include the provision of RINEX and Virtual RINEX data for post-processing applications (Janssen, 2013).

Figure 4 illustrates CORSnet-NSW station redundancy, i.e. the area concurrently covered by two or more CORS. In practice, this means that if the primary CORS should not be available for any reason, an alternative nearby CORS should ensure nearly the same user experience in regards to accuracy, time-to-fix, reliability of ambiguities, etc. Currently, such backup coverage is available to 39% of the State's area for RTK and 95% for DGNSS. Improving such redundancy to ensure the more effective and efficient delivery of services to our customers is of significant importance to LPI.

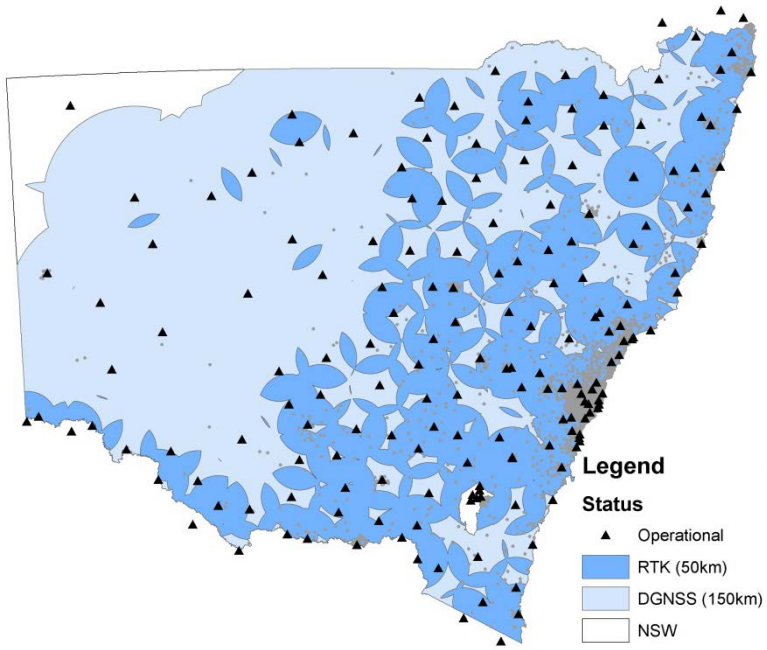

Figure 4: CORSnet-NSW backup redundancy map as of March 2016 (each dot indicates 2,000 residents per statistical local area).

All CORSnet-NSW stations are built to stringent LPI Tier 3 quality requirements in regards to technical design, installation, operation and maintenance (LPI, 2012a). Eleven CORSnet-NSW stations were built to (inter)national geodetic specifications with joint state/federal funding as part of the scientific, national (Tier 2) AuScope CORS network (Janssen, 2009a). Five CORS (Fort Denison, Port Botany, Newcastle East, Port Kembla and Eden) were built specifically to augment long-term tide gauges located along the NSW coast in order to support sea-level monitoring (Janssen et al., 2013). It should be noted that the tide gauge records available from Fort Denison, Sydney Harbour (since 1886) and the Pilot Station, Newcastle (since 1925) are two of the longest continuous records in the southern hemisphere.

Leveraging cross-border data-sharing arrangements, CORSnet-NSW also incorporates a number of interstate CORS in order to adequately cover areas in the Australian Capital Territory, along the Queensland and Victorian borders, and the external territory of Norfolk Island, in which the NSW Surveyor General executes certain responsibilities. Most stations in NSW are hosted by local councils (the equipment being owned by LPI), and two by private industry. In total, 90% of CORSnet-NSW stations are hosted by LPI's partners (currently 100+). Examples of typical CORSnet-NSW installations are given in Figure 5.

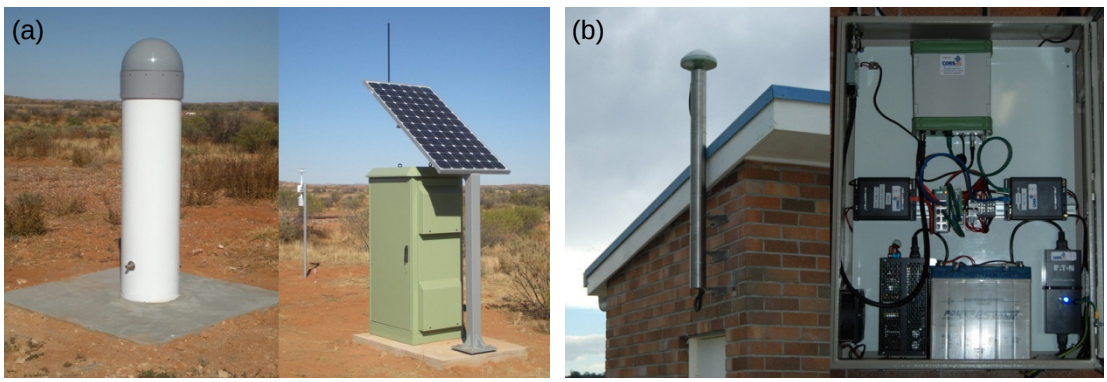

Figure 5: Typical CORSnet-NSW monumentation and auxiliaries at (a) Tier 2 and (b) Tier 3 sites.

In order to provide a legally traceable survey monument that allows the GNSS antenna to be oriented to True North without the need to introduce an antenna height, the CORSnet-NSW Adjustable Antenna Mount (CAAM, see Figure 6) was developed and patented by LPI specifically for use within CORSnet-NSW (Commins and Janssen, 2012). All Tier 3 CORSnet-NSW CORS installations since March 2011 use the CAAM, which has proven to be very effective and particularly invaluable when replacing or upgrading GNSS antennas because a zero antenna height is always maintained. This design is freely available to other CORS operators (LPI, 2012a).

Figure 6: Internal workings of the CAAM (Commins and Janssen, 2012).

CORSnet-NSW uses a mix of modern Leica and Trimble GNSS receivers, tracking both GPS and GLONASS satellites. LPI has specifically avoided the exclusive use of only one type of receiver to minimise risks and increase business/service continuity. Diversification has been limited to two brands in order to simplify fleet management. The network uses a mix of high-precision survey antennas (70%) and Dorne Margolin choke ring antennas (30%), generally with radomes installed. LPI intends to have future antennas individually calibrated by Geoscience Australia at its new test facility in Canberra (Riddell et al., 2015).

The NSW Foundation Spatial Data Framework (FSDF) 2020 Strategy (internal document) directs CORSnet-NSW to support new GNSS constellations and signals. More than half of all CORS are hardware-ready for (or at least capable of) tracking additional GNSS constellations such as Galileo and BeiDou in the future. This functionality will be activated by CORSnet-NSW only when each system officially reaches its Initial Operational Capability (IOC), system reliability has been proven and there is sufficient user demand. In the meantime, BeiDou satellites are currently tracked at six Tier 2 CORS (i.e. Bingleburra, Broken Hill, Coonabarabran, Hernani, North Bourke and North Star) and 67 Tier 3 CORS for research and evaluation purposes. This is particularly important given Australia's strategic geographic position on the globe, resulting in a multitude of satellite constellations being available in this region (Rizos, 2008). In this context, Figure 7 illustrates the number and distribution of GNSS satellites expected to be available by 2020, as well as the number of visible satellites for users anywhere on Earth. It is clearly evident that Australia is located in a GNSS positioning 'hotspot'.

The majority of all CORS feature dual communications (main and backup, e.g. ADSL and Next G) to ensure the highest possible standard in regards to data availability and data completeness. Installs are equipped with a variety of auxiliary devices such as industrial-strength modems, remote reboot relays, digital cameras with selective motion detection, door alarms, automatic cooling fans, solar power (on selected sites) and Uninterruptible Power Supply (UPS) units that last up to 30 days.

This is complemented by two mirror-image Network Control Centres (NCCs), located in Sydney and Bathurst, that utilise Commercial-Off-The-Shelf (COTS) CORS management software with full redundancy (Yan and Jap, 2011). ICT architecture allows for immediate failover between the two NCCs to ensure continuous data supply to users. The data centres employ server virtualisation technology to maximise hardware utilisation, flexibility and scalability while at the same time minimising power consumption, space requirements and carbon footprint. Network connectivity and availability is constantly monitored using external service providers. A third, ad-hoc development system is used for internal system testing. Services, system status, network information and applied research results are provided on the CORSnet-NSW website (LPI, 2016), which includes live information and other information.

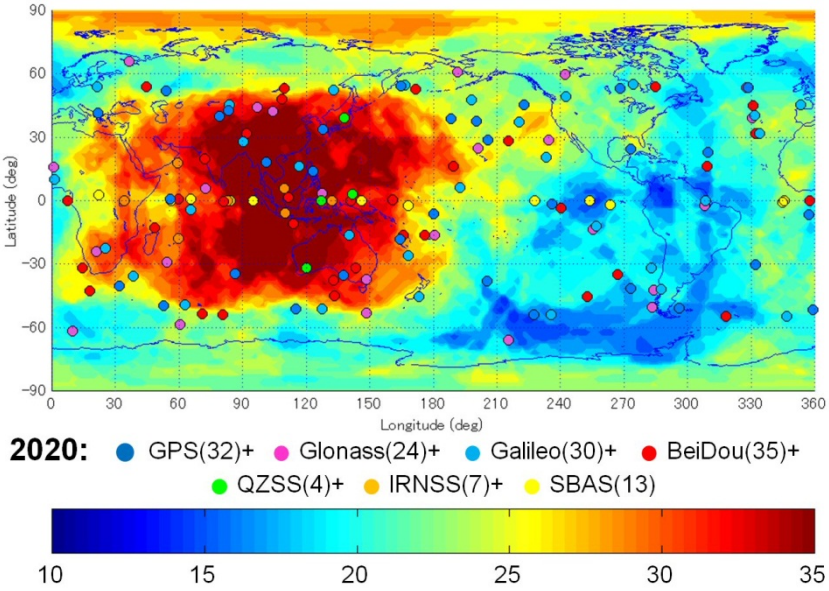

Figure 7: Number of visible GNSS satellites above 30º elevation expected in 2020 (courtesy Prof Chris Rizos).

The coordinates of each CORS are determined via the national Regulation 13 process (GA, 2016c), providing consistent positioning infrastructure that is compatible with other (public and private) CORS operators across the country and provides legal traceability. It should be noted that these 'Reg 13' coordinates are currently not compatible with SCIMS – therefore LPI also provides 'local' coordinates compatible with surrounding ground control marks in SCIMS (see section 3).

All CORSnet-NSW activities (builds, surveys, operations, maintenance and upgrades) are conducted in-house using SI&G staff. Contractors are only used for minor works (e.g. electrical or excavation work) during the build phase of some CORS. ICT support is provided internally through LPI. CORSnet-NSW operates 24/7, 365 days a year with front-line customer support services available during business hours (0830-1630 hrs). The CORSnet-NSW NCC is operated by three Full Time Equivalent (FTE) staff with strong ICT backgrounds that are embedded in SI&G (i.e. NCC Team Leader, NCC Operator, and NCC Support Officer). Site builds, maintenance and upgrades are conducted by one FTE staff (Senior Infrastructure Officer), while a variety of other SI&G staff (1.5 FTE) provide survey, research and management support (e.g. Bernese processing, local tie surveys, Regulation 13 certification, webpage updates).

Raw data is wholesaled to three premium resellers (SmartNetAus, AllDayRTK and Trimble VRS Now Australia), while CORSnet-NSW subscriptions are currently available through 16

authorised resellers servicing a wide range of applications. In addition, raw data from all LPI-owned CORSnet-NSW stations support national and local positioning applications via inclusion in the Asia-Pacific Reference Frame (APREF – see GA, 2016a) and Geoscience Australia's free online GPS processing service (AUSPOS – see GA, 2016b), resulting in better performance for users in and around NSW.

CORSnet-NSW infrastructure has recently been used in proven trials of Precise Point Positioning (PPP) solutions delivered by the Japanese Quasi-Zenith Satellite System (QZSS) via the LEX (L-band experiment) signal for precision agriculture applications in rural NSW (Harima et al., 2015). This was a small but significant first milestone in NSW's desire to introduce satellite-based delivery (through either premium resellers, NPI, international coordination or other mechanisms) to service new and emerging market sectors (NSW FSDF 2020 Strategy) and realise LPI's aspiration to improve service delivery through new technologies.

2.2 Quality Control

Quality control and integrity monitoring of CORS infrastructure is becoming increasingly important for legal traceability of data and measurements as well as for long-term stability studies of station coordinates. CORSnet-NSW operation and performance is monitored by LPI staff in real-time using Trimble's Pivot CORS network management software, which also has the ability to detect abrupt station movement in real-time. Long-term, multi-year station stability monitoring is performed in-house by determining high-precision daily coordinate solutions using the Bernese software (Dach et al., 2015) in an automated process (Haasdyk et al., 2010). Station coordinates are obtained in the International Terrestrial Reference Frame (ITRF – see Altamimi et al., 2011) and transformed into the Geocentric Datum of Australia 1994 (GDA94 – see ICSM, 2014) using the parameters given by Dawson and Woods (2010). For more information about coordinate systems, datums and associated transformations in the Australian context the reader is referred to, e.g., Janssen (2009b), Dawson and Woods (2010) and Haasdyk and Janssen (2011).

The ongoing analysis of the incoming data and computed coordinates can immediately reveal issues related to local ground deformation (or unauthorised interference with the CORS), thus contributing to the development of the National Distortion Model (ICSM, 2015). Site specific velocities of the network can be determined at higher densities than those provided by the global International GNSS Service (IGS) network, allowing comparisons with existing tectonic plate models and the development of a continuously updating National Plate-Motion Model (ICSM, 2015).

For each CORSnet-NSW site, the resulting coordinate time series showing the difference of the observed station coordinates from the official coordinates is made available on the CORSnet-NSW website (Figure 8). Results show that LPI station coordinates are calculated with millimetre-level precision and agree well with their Regulation 13 values, while velocities are obtained with 2-4 mm/yr precision and agree with the expected tectonic motion across NSW. System performance and station stability are also independently monitored by third parties, including premium resellers and the APREF analysis centres.

The stability of all Tier 2 CORSnet-NSW pillars is monitored by LPI at suitable intervals through high-precision Reference Mark (RM) surveys. These terrestrial surveys determine the horizontal position of the pillar relative to three surrounding reference marks with an accuracy

of better than 1 mm (95% confidence interval) and the vertical position of the pillar plate to within class L2A specifications (maximum misclose 2√d mm) (Janssen, 2009a).

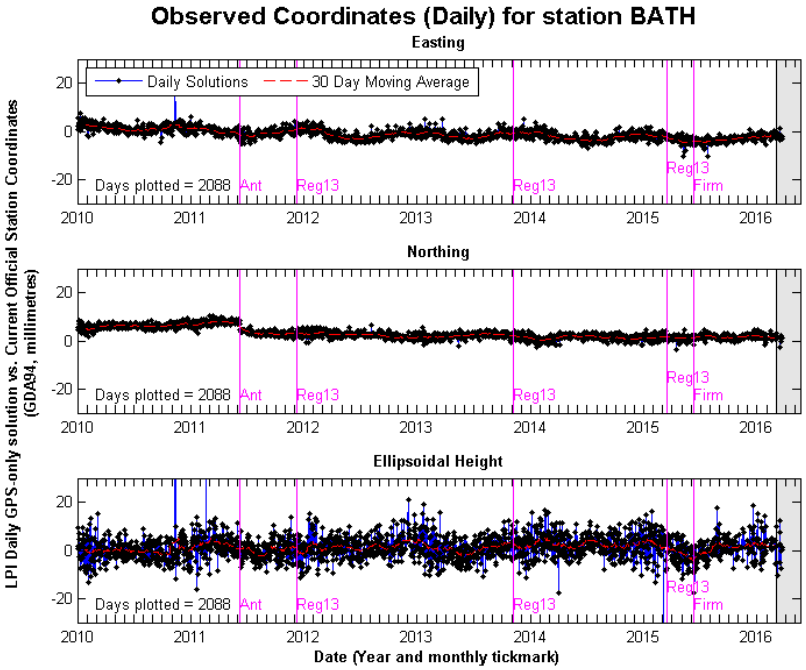

Figure 8: Observed position vs. official position of Bathurst CORS (LPI, 2016).

2.3 Future Plans

As indicated in Figure 3, CORSnet-NSW will continue to expand, with additional stations being built on a needs and opportunity basis. The LPI Statement of Business Intent clearly documents the authority's intention to expand the network to at least 200 CORS by the end of the 2016/17 financial year. Additional internal funding submissions aim to boost CORSnet-NSW to 220 stations by the end of the 2017/18 financial year. The network may grow even further subject to the outcomes of Geoscience Australia's AuScope II federal funding bid (AuScope, 2011). When CORSnet-NSW achieves its next major milestone, its 200th CORS, the majority of the State's users (i.e. urban users) will be within 10 km of their nearest CORS, thereby unlocking the potential of GNSS heighting. The network's continued expansion and ICT upgrades aim to provide users with even higher quality services, levels of reliability and backup, and to fully support the market's transition from experimentation to acceptance, to full or even sole reliance on CORS-based positioning.

CORSnet-NSW is providing the backbone of the ongoing efforts for Australian datum modernisation across NSW, which will result in significant improvements for the surveying and spatial information community in particular and the general GNSS user market in general (e.g. Haasdyk et al., 2014b; ICSM, 2015).

3 SCIMS VS. CORS COORDINATES

We are currently in a challenging transition period between traditional, passive ground control infrastructure and modern, active GNSS CORS infrastructure. Similarly, Australia is transiting to a modernised datum (ICSM, 2015). As such, CORS coordinates are currently provided in a variety of 'flavours' to suit different users. It is well known that systematic

distortions of up to 0.2 m horizontally and 0.3 m vertically exist in NSW between the legal coordinate datum as realised by SCIMS, known in NSW as GDA94(1997), and observations in the more homogenous realisation of the national datum as provided by CORSnet-NSW and Geoscience Australia's AUSPOS service, known in NSW as GDA94(2010) (e.g. Haasdyk et al., 2010; Janssen and McElroy, 2010; Gowans and Grinter, 2013). As an example, Figure 9 illustrates the regional nature of these distortions across the Central West, Sydney and Hunter regions of NSW.

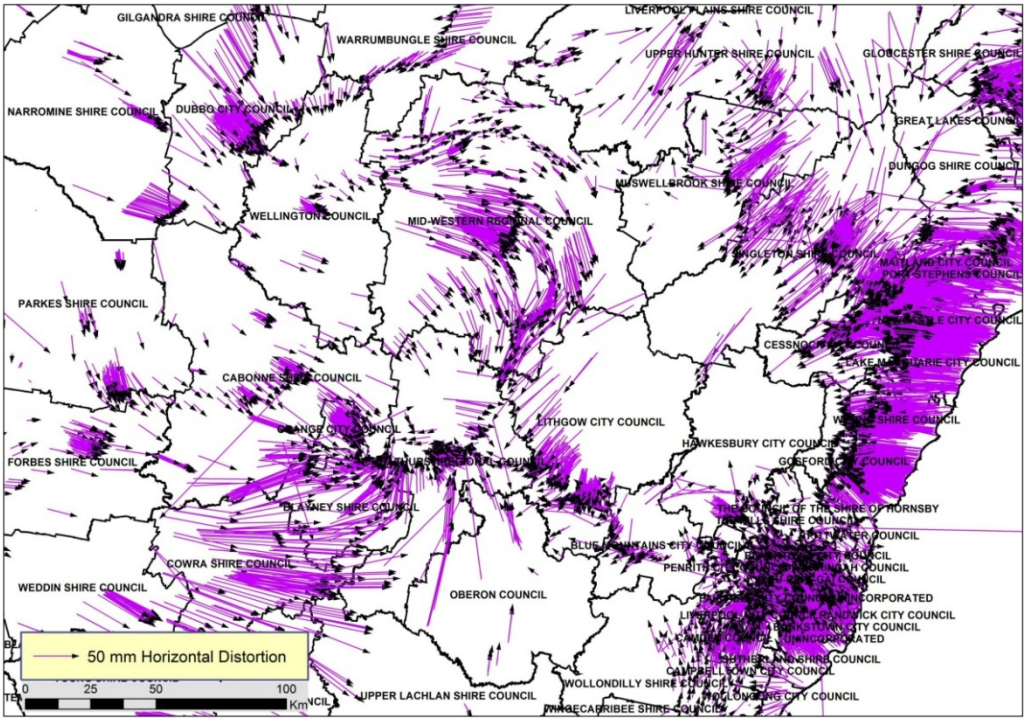

Figure 9: GDA94(1997) to GDA94(2010) horizontal distortion vectors at marks observed by GNSS, across the Central West, Sydney and Hunter regions of NSW.

Removing these distortions across NSW requires a re-adjustment of the entire NSW geodetic control network, without a hierarchy of fixed control. This will occur as part of the national adjustment to produce a modernised datum for Australia (Haasdyk et al., 2014a). In the interim, a site transformation is required to relate CORS-derived positions to the local (and legally accepted) ground control available in NSW via SCIMS (Haasdyk and Janssen, 2012). It should be noted that a site transformation is not required for (non-specialist) users interested only in relative accuracy and repeatability. Currently, efforts are underway to measure the existing distortions at a large number of trigonometrical stations and other strategic marks across the State and to obtain additional GNSS datasets for datum improvement (Gowans et al., 2015).

LPI carries out local tie surveys to connect each CORSnet-NSW station to the surrounding ground survey control, thereby bridging the gap between GDA94(1997) and GDA94(2010) (Gowans and Grinter, 2013). The immediate goal of each tie survey is to provide a best 'local-fit' position of the CORS that is consistent with surrounding ground control by intentionally propagating the local distortions in GDA94(1997) and the Australian Height Datum (AHD) to the CORSnet-NSW station. However, the ultimate goal is the opposite, i.e. propagating the Regulation 13 (or APREF-derived) CORSnet-NSW station coordinates outward to the ground survey network, via passive trigonometrical stations, as part of the national adjustment for the modernised Australian datum.

The growing use of CORS networks for GNSS-based height transfer has substantially increased the importance of accurate, absolute N values (or geoid undulations). Fortunately, the current AUSGeoid09 model has been shown to provide N values with unprecedented absolute accuracy across NSW and Australia (e.g. Janssen and Watson, 2010, 2011; Brown et al., 2011; Sussanna et al., 2014; Allerton et al., 2015; Sussanna et al., 2016). LPI continues to collect long-duration GNSS datasets on levelled benchmarks in order to improve future AUSGeoid products across the State.

4 BENEFITS OF USING GNSS CORS INFRASTRUCTURE

GNSS CORS infrastructure provides unparalleled access to positioning infrastructure that is accurate, reliable and easy to use for a wide range of GNSS applications and has become a critical foundation of today's society. This was formally recognised on 26 February 2015 with the United Nations adopting resolution 69/266 entitled "A Global Geodetic Reference Frame for Sustainable Development" (UN, 2015). This resolution outlines the importance of a globally coordinated approach to geodesy and recognises the need to invest proactively in the global geodetic reference frame (essentially the ITRF) and, by extension, our national connections into this frame. The resolution recognises the significant and ubiquitous role of geospatial information and calls for increased cooperation and investment into geodesy, including the open sharing of geospatial data, further capacity-building in developing countries and the creation of international standards and conventions. This is a mandate, from the highest source, to improve our geodetic framework and spatial information systems, and assist developing nations to do the same.

In Australia, for CORS operators and custodians of the national datum, benefits of modern GNSS CORS infrastructure include the ability for datum definition at unprecedented precision, rationalisation of infrastructure, establishment of multi-user systems, and the provision of positioning services that are similar and compatible across and between networks.

The many benefits for users of GNSS CORS networks include easy access to infrastructure that is maintained externally, facilitates a direct and consistent connection to datum, and provides some degree of legal traceability for satellite-based positioning. RTK and NRTK in particular allow instant 'real-world digitising' with the ability to significantly enhance productivity through increased precision, reliability, speed and ease of operation. The demand for high-quality spatial data is ever increasing, and the economic benefits offered by state-of-the-art GNSS-based positioning are immense. Improved productivity in the Australian surveying and land management sector alone was estimated to be 20-40% in 2012 and a further 20% by 2020, with billions of dollars in savings and productivity gains (ACIL Allen Consulting, 2008, 2013).

5 BENEFITS OF CORSnet-NSW

CORSnet-NSW has been designed, built and is operated on a 'build once, use many times' principle that serves the widest range of users (operational and scientific) and balances LPI's public-good and commercial responsibilities.

5.1 Supporting LPI

CORSnet-NSW was principally built with two main aims in mind, i.e. to support LPI's legislative and regulative responsibility to maintain the geodetic control network in NSW, and to support (and improve) internal LPI operations. Any commercial gain was seen as a welcome bonus that would help offset operational, maintenance and upgrade costs.

Internal LPI applications mainly revolve around the maintenance and improvement of the State's survey control network (SCIMS contains more than 250,000 survey marks across NSW). While the active GNSS CORS infrastructure is more accurate and easier to maintain than passive ground control marks, both are required by the profession. Consequently, LPI continues to preserve, upgrade and maintain passive control marks (Gowans et al., 2015). CORS-supported GNSS observations are crucial for this work, as well as for the ongoing efforts to update and upgrade the State's Digital Cadastral Database (DCDB). CORSnet-NSW has provided significant quality and productivity gains for airborne LiDAR and aerial imagery surveys (in regards to determining aircraft trajectories as well as providing ground control and test points for such surveys) and supported related research (e.g. Colombo et al., 2010a, 2010b, 2016).

5.2 Supporting National Positioning Infrastructure and the National Datum

LPI supports and sees itself as a major stakeholder in the National Positioning Infrastructure (NPI) policy and plans, which aim to provide reliable, compatible, homogeneous and sustainable positioning infrastructure across Australia to deliver access to fit-for-purpose position, navigation and timing (PNT) information in a multi-GNSS enabled information economy (Hausler and Collier, 2013).

Across NSW, the CORSnet-NSW infrastructure provides the backbone for the ongoing national efforts to produce a modern, next-generation datum for Australia (e.g. Donnelly et al., 2014; Haasdyk et al., 2014b; ICSM, 2015) by constraining the Regulation 13 certified (or APREF-coordinated) CORSnet-NSW stations. The GNSS baselines observed as part of the CORSnet-NSW local tie surveys (Gowans and Grinter, 2013) are crucial to propagate these coordinates outward into and through the existing survey ground control networks. This will provide a homogeneous national datum realisation across NSW and Australia, thereby significantly improving the State's geodetic infrastructure for years to come. In support of these efforts, LPI has performed extensive data-mining and cleaning of archived GNSS and terrestrial observations (e.g. Haasdyk and Watson, 2013; Haasdyk et al., 2014a), collected a large amount of new GNSS data across the State (Gowans et al., 2015) and made progress towards updating its SCIMS database in order to facilitate the modernised datum (e.g. Donnelly et al., 2013; Kinlyside, 2013).

In this context, it is important to remember that geodetic control underpins *all* spatial data, including water, boundaries, addresses, utilities, transport, elevation and imagery, but also that most revenue and GNSS data consumption will come in the near future from applications such as Location-Based Services and transport (GSA, 2015).

5.3 Supporting Governance and Best Practice

As a state jurisdiction, LPI is responsible for regulations, directions and guidelines, e.g. the Surveying and Spatial Information Regulation (NSW Legislation, 2015) and Surveyor

General's Directions. Of particular relevance to GNSS users in NSW are Surveyor General's Direction No. 9 (GNSS for Cadastral Surveys – LPI, 2014) and No. 12 (Control Surveys and SCIMS – LPI, 2012b). The former provides guidance in the use of GNSS technology for cadastral surveys, while the latter facilitates the continuing improvement of available survey control in collaboration with industry. Furthermore, LPI provides comprehensive guidelines for the establishment of GNSS CORS to ensure that all stations contributing to CORSnet-NSW, APREF and NPI are of the highest possible and consistent quality (LPI, 2012a).

GNSS validation networks, which include CORSnet-NSW sites, offer users in NSW the opportunity to test their equipment, processing, procedures and competency against a reliable external source in order to meet legal requirements (LPI, 2014).

5.4 Supporting Applied Research

LPI continues to be active in conducting applied research that contributes to national initiatives, educates the profession, informs legislation and best practice guidelines, and enhances internal operations and decision making. SI&G, in particular, is mandated through the NSW FSDF 2020 Strategy to "adapt to new positioning services through applied research and innovation" (internal document). These efforts have produced 80 papers over the last 7 years (2009-15), communicating research findings to both the scientific community and the profession (i.e. technical vs. more general), and feedback has been very positive. Some specific GNSS-related examples of contributing to best practice guidelines via conducting applied research include:

- Demonstrating that CORSnet-NSW users achieve the biggest benefit from NRTK by using 1-2 minute observation windows separated by at least 10-30 minutes and being aware of overly optimistic coordinate quality indicators provided by the GNSS rover equipment (e.g. Janssen and Haasdyk, 2011).
- Showing that a site transformation consisting of a block shift is sufficient to relate CORSnet-NSW-derived RTK/NRTK observations to SCIMS ground control for surveys requiring centimetre-level accuracy, provided AUSGeoid09 is applied (e.g. Haasdyk and Janssen, 2012).
- Quantifying AUSGeoid09 performance across NSW and showing that resulting GNSS-derived heights generally agree with AHD at the ±0.05 m level (1 sigma) (e.g. Janssen and Watson, 2010; Sussanna et al., 2014; Allerton et al., 2015; Sussanna et al., 2016).
- Showing that positioning results using Virtual RINEX data are comparable (at the few-mm to few-cm level) to those based on observed data, thus allowing GNSS users to benefit from network-based corrections for post-processing applications (e.g. Janssen, 2013).
- Educating GNSS users about the effect of the ionosphere on positioning quality (e.g. Janssen, 2012; Colombo et al., 2016).
- Informing GNSS users about the capabilities of Precise Point Positioning (e.g. Grinter and Janssen, 2012; Rizos et al., 2012; Grinter and Roberts, 2013; Harima et al., 2014).
- Explaining the intricacies of control surveys and the impact of utilising satellite positioning technology for such surveys (e.g. Dickson, 2012).
- Providing guidance for CORS network operators and designing the patented CORSnet-NSW Adjustable Antenna Mount (CAAM) to ensure that CORSnet-NSW installations are of the highest quality (e.g. Janssen et al., 2011c; Commins and Janssen, 2012).

This shows that the CORSnet-NSW network is utilised (directly and indirectly) in many ways, some of which may not be obvious at first glance.

6 CONCLUDING REMARKS

On behalf of the NSW Surveyor General, LPI has a legislative, regulative responsibility to maintain the geodetic control network in NSW. GNSS CORS infrastructure has become crucial to cater for the increased demand for accurate, reliable and easily accessible positioning in today's society. State jurisdictions provide the essential link between national initiatives and academia on the one hand and the profession on the other, e.g. via maintaining geodetic infrastructure and conducting applied research that informs legislation and best practice guidelines.

This paper has outlined the current status of CORSnet-NSW and the efforts undertaken at LPI to further improve the State's geodetic control network on the basis of the GNSS CORS infrastructure through the upcoming national adjustment as part of the modernised Australian datum. It has also discussed how LPI supports the surveying profession and the wider spatial community in regards to GNSS infrastructure, demonstrating the enormous contribution that CORSnet-NSW makes to the geodetic fabric across NSW and Australia.

By reaching its 150 CORS milestone in July 2014, CORSnet-NSW has matured within only five years into a world-class, state-wide, multi-function GNSS CORS network that balances public-good and commercial mandates. Currently comprising 180 CORS, the network is expected to grow to 220 CORS by 2018. CORSnet-NSW has revolutionised internal and external GNSS operations, not only supporting the surveying and spatial information profession but also making important contributions to national and regional geodesy.

CORSnet-NSW's evolution, operation and continued development is testimony of LPI's vision to be a world leader in spatial information and its mission to develop and maintain products and services to empower commercial and government organisations, tertiary organisations, the public and the community of NSW. SI&G's applied research achievements demonstrate its commitment to promoting LPI as the NSW Government's centre of excellence in spatial information.

REFERENCES

ACIL Allen Consulting (2008) Economic benefits of high resolution positioning services, Report prepared for Victorian Department of Sustainability and Environment and the Cooperative Research Centre for Spatial Information, 62pp.

ACIL Allan Consulting (2013) Precise positioning services in the surveying and land management sector, Report prepared for the Department of Industry, Innovation, Climate Change, Research and Tertiary Education, 34pp.

Allerton J., Janssen V. and Kearsley A.H.W. (2015) AUSGeoid09 performance in mountainous terrain: A case study in the Blue Mountains, *Proceedings of Research@Locate15*, Brisbane, Australia, 10-12 March, 58-68.

Altamimi Z., Collilieux X. and Metivier L. (2011) ITRF2008: An improved solution of the International Terrestrial Reference Frame, *Journal of Geodesy*, 85(8), 457-473.

AuScope (2011) The Australian Earth Observatory – infrastructure roadmap, http://www.auscope.org.au/wp-content/uploads/2015/11/AEO_AuScope_Nov_2011.pdf (accessed Mar 2016).

Brown N.J., Featherstone W.E., Hu G. and Johnston G.M. (2011) AUSGeoid09: A more direct and more accurate model for converting ellipsoidal heights to AHD heights, *Journal of Spatial Science*, 56(1), 27-37.

Colombo O.L., Brunker S., Jones G., Janssen V. and Rizos C. (2010a) Wide-area, sub-decimetre positioning for airborne LiDAR surveys using CORSnet-NSW, *Proceedings of XXIV FIG International Congress 2010*, Sydney, Australia, 11-16 April, 20pp.

Colombo O.L., Brunker S., Jones G., Janssen V. and Rizos C. (2010b) Testing sub-decimeter, kinematic wide-area positioning for airborne LiDAR surveys using the CORSnet-NSW network, *Proceedings of ION GNSS 2010*, Portland, Oregon, 21-24 September, 1004-1018.

Colombo O.L., Hernández-Pajares M., Janssen V. and García-Rigo A. (2016) Comprehensive ionospheric delay modelling for single-frequency GNSS precise positioning: First steps, Poster presented at *IGS Workshop 2016*, Sydney, Australia, 8-12 February.

Commins R. and Janssen V. (2012) Improving GNSS CORS design: The CORSnet-NSW Adjustable Antenna Mount (CAAM), *Journal of Global Positioning Systems*, 11(2), 109-115.

Dach R., Lutz S., Walser P. and Fridez P. (2015) Bernese GNSS software version 5.2 user manual, Astronomical Institute, University of Bern, Switzerland, 852pp.

Dawson J. and Woods A. (2010) ITRF to GDA94 coordinate transformations, *Journal of Applied Geodesy*, 4(4), 189-199.

Dickson G. (2012) Control Surveys: Why things are the way they are and not the way you think they should be!, *Proceedings of Association of Public Authority Surveyors Conference (APAS2012)*, Wollongong, Australia, 19-21 March, 12-28.

Donnelly N., Crook C., Haasdyk J., Harrison C., Rizos C., Roberts C. and Stanaway R. (2014) Dynamic datum transformations in Australia and New Zealand, *Proceedings of Research at Locate'14*, Canberra, Australia, 7-9 April, 48-59.

Donnelly N., Fraser R., Haasdyk J. and Tarbit S. (2013) GeodesyML – A GML application schema for geodetic data transfer in Australia and New Zealand, *Proceedings of Surveying and Spatial Sciences Conference (SSSC2013)*, Canberra, Australia, 15-19 April, 15pp.

GA (2016a) Asia-Pacific Reference Frame (APREF), http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/asia-pacific-reference-frame (accessed Mar 2016).

GA (2016b) AUSPOS – Online GPS processing service, http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/auspos (accessed Mar 2016).

GA (2016c) Regulation 13 certificates, http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/regulation-13-certificates (accessed Mar 2016).

Gowans N. and Grinter T. (2013) Tying it all together: CORSnet-NSW local tie surveys, *Proceedings of Association of Public Authority Surveyors Conference (APAS2013)*, Canberra, Australia, 12-14 March, 104-119.

Gowans N., McElroy S. and Janssen V. (2015) Survey infrastructure preservation and upgrade: Trigonometrical stations in NSW, *Proceedings of Association of Public Authority Surveyors Conference (APAS2015)*, Coffs Harbour, Australia, 16-18 March, 67-84.

Grinter T. and Janssen V. (2012) Post-processed Precise Point Positioning: A viable alternative?, *Proceedings of Association of Public Authority Surveyors Conference (APAS2012)*, Wollongong, Australia, 19-21 March, 83-92.

Grinter T. and Roberts C. (2013) Real time Precise Point Positioning: Are we there yet?, *Proceedings of IGNSS Symposium 2013 (IGNSS2013)*, Gold Coast, Australia, 16-18 July, 16pp.

GSA (2015) GNSS Market Report Issue 4, http://www.gsa.europa.eu/market/market-report (accessed Mar 2016).

Haasdyk J., Davies L. and Watson T. (2014a) Progress towards a new geodetic datum for Australia, *Proceedings of Association of Public Authority Surveyors Conference (APAS2014)*, Pokolbin, Australia, 31 March – 2 April, 28-41.

Haasdyk J., Donnelly N., Harrison C., Rizos C., Roberts C. and Stanaway R. (2014b) Options for modernising the Geocentric Datum of Australia, *Proceedings of Research at Locate'14*, Canberra, Australia, 7-9 April, 72-85.

Haasdyk J. and Janssen V. (2011) The many paths to a common ground: A comparison of transformations between GDA94 and ITRF, *Proceedings of IGNSS Symposium 2011 (IGNSS2011)*, Sydney, Australia, 15-17 November, 16pp.

Haasdyk J. and Janssen V. (2012) Site transformations: A block shift in thinking, *Proceedings of Association of Public Authority Surveyors Conference (APAS2012)*, Wollongong, Australia, 19-21 March, 29-47.

Haasdyk J., Roberts C. and Janssen V. (2010) Automated monitoring of CORSnet-NSW using the Bernese software, *Proceedings of XXIV FIG International Congress 2010*, Sydney, Australia, 11-16 April, 19pp.

Haasdyk J. and Watson T. (2013) Data-mining in NSW: Towards a new and improved Australian datum, *Proceedings of Association of Public Authority Surveyors Conference (APAS2013)*, Canberra, Australia, 12-14 March, 85-102.

Harima K., Choy S., Kakimoto H., Kogure S. and Collier P. (2015) Utilisation of the Japanese Quasi-Zenith Satellite System (QZSS) augmentation system for precision farming in Australia, *Proceedings of IGNSS Symposium 2015 (IGNSS2015)*, Gold Coast, Australia, 14-16 July, 14pp.

Harima K., Choy S., Li Y., Grinter T., Choudhury M., Rizos C., Wakabayashi Y. and Satoshi K. (2014) Performance of real-time Precise Point Positioning using MADOCA-LEX augmentation messages, *Proceedings of XXV FIG International Congress (FIG2014)*, Kuala Lumpur, Malaysia, 16-21 June, 18pp.

Hausler G. and Collier P. (2013) National Positioning Infrastructure: Where are we now?, *Proceedings of IGNSS Symposium 2013 (IGNSS2013)*, Gold Coast, Australia, 16-18 July, 16pp.

ICSM (2014) Geocentric Datum of Australia technical manual, version 2.4, http://www.icsm.gov.au/gda/gda-v_2.4.pdf (accessed Mar 2016).

ICSM (2015) Australian datum modernisation: Statement on datum modernisation – 25 March 2015, http://www.icsm.gov.au/geodesy/modern.html (accessed Mar 2016).

Janssen V. (2009a) Precision rules! How to establish an AusCORS site, *Position*, 44, 64-66.

Janssen V. (2009b) Understanding coordinate systems, datums and transformations in Australia, *Proceedings of SSSI Biennial International Conference (SSC2009)*, Adelaide, Australia, 28 September – 2 October, 697-715.

Janssen V. (2009c) A comparison of the VRS and MAC principles for Network RTK, *Proceedings of IGNSS Symposium 2009 (IGNSS2009)*, Surfers Paradise, Australia, 1-3 December, 13pp.

Janssen V. (2012) Likely impact of the approaching solar maximum on GNSS surveys: Be alert but not alarmed, *Proceedings of Association of Public Authority Surveyors Conference (APAS2012)*, Wollongong, Australia, 19-21 March, 66-82.

Janssen V. (2013) Investigation of Virtual RINEX data quality, *Proceedings of IGNSS Symposium 2013 (IGNSS2013)*, Gold Coast, Australia, 16-18 July, 11pp.

Janssen V. (2014) CORSnet-NSW reaches 150 CORS milestone, *Azimuth*, 53(8), 26-27 & 31.

Janssen V., Commins R., Watson P. and McElroy S. (2013) Using GNSS CORS to augment long-term tide gauge observations in NSW, *Proceedings of Surveying and Spatial Sciences Conference (SSSC2013)*, Canberra, Australia, 15-19 April, 12pp.

Janssen V., Grinter T. and Roberts C. (2011a) Can RTK GPS be used to improve cadastral infrastructure?, *Engineering Journal*, 15(1), 43-54.

Janssen V. and Haasdyk J. (2011) Assessment of Network RTK performance using CORSnet-NSW, *Proceedings of IGNSS Symposium 2011 (IGNSS2011)*, Sydney, Australia, 15-17 November, 18pp.

Janssen V., Haasdyk J. and McElroy S. (2015) CORSnet-NSW: State infrastructure for GNSS applications and applied research, *Proceedings of IGNSS Symposium 2015 (IGNSS2015)*, Gold Coast, Australia, 14-16 July, 17pp.

Janssen V., Haasdyk J., McElroy S. and Kinlyside D. (2011b) CORSnet-NSW: Improving positioning infrastructure for New South Wales, *Proceedings of SSSI Biennial Conference (SSSC2011)*, Wellington, New Zealand, 21-25 November, 395-409.

Janssen V., Haasdyk J., McElroy S. and Kinlyside D. (2011c) Technical challenges faced by CORS network operators: Experiences from New South Wales, Australia, *International Journal of Geoinformatics*, 7(3), 23-33.

Janssen V. and McElroy S. (2010) Coordinates and CORSnet-NSW: Dealing with distortions in GDA94, *Position*, 50, 24-27.

Janssen V. and Watson T. (2010) Improved AHD71 height determination from GNSS using AUSGeoid09 in New South Wales, Australia, *Journal of Global Positioning Systems*, 9(2), 112-121.

Janssen V. and Watson T. (2011) Performance of AUSGeoid09 in NSW, *Proceedings of Association of Public Authority Surveyors Conference (APAS2011)*, Bathurst, Australia, 6-7 April, 27-36.

Janssen V., White A. and Yan T. (2010) CORSnet-NSW: Towards state-wide CORS infrastructure for New South Wales, Australia, *Proceedings of XXIV FIG International Congress 2010*, Sydney, Australia, 11-16 April, 14pp.

Kinlyside D. (2013) SCIMS3: The next generation Survey Control Information Management System, *Proceedings of Association of Public Authority Surveyors Conference (APAS2013)*, Canberra, Australia, 12-14 March, 174-186.

Kinlyside D. and Yan T. (2005) SydNET – First results, *Proceedings of Association of Public Authority Surveyors Conference (APAS2005)*, Batemans Bay, Australia, 16-17 March, 10pp.

LPI (2012a) Guidelines for CORSnet-NSW Continuously Operating Reference Stations (CORS), version 1.1, http://www.lpi.nsw.gov.au/surveying/corsnet-nsw/user_guides (accessed Mar 2016).

LPI (2012b) Surveyor General's Direction No. 12: Control Surveys and SCIMS, http://www.lpi.nsw.gov.au/surveying/publications/surveyor_generals_directions (accessed Mar 2016).

LPI (2014) Surveyor General's Direction No. 9: GNSS for Cadastral Surveys, http://www.lpi.nsw.gov.au/surveying/publications/surveyor_generals_directions (accessed Mar 2016).

LPI (2016) CORSnet-NSW, http://www.corsnet.com.au/ (accessed Mar 2016).

NSW Legislation (2015) Surveying and Spatial Information Regulation 2012, http://www.legislation.nsw.gov.au/viewtop/inforce/subordleg+436+2012+cd+0+N (accessed Mar 2016).

Rassaby H.S. (1980) Foreword, in Register of geodetic stations of New South Wales: Region 1 Newcastle – Sydney – Wollongong, Central Mapping Authority of NSW, Bathurst, 27pp.

Riddell A., Moore M. and Hu G. (2015) Geoscience Australia's GNSS antenna calibration facility: Initial results, *Proceedings of IGNSS Symposium 2015 (IGNSS2015)*, Gold Coast, Australia, 14-16 July, 12pp.

Rizos C. (2008) Multi-constellation GNSS/RNSS from the perspective of high accuracy users in Australia, *Journal of Spatial Science*, 53(2), 29-63.

Rizos C., Janssen V., Roberts C. and Grinter T. (2012) Precise Point Positioning: Is the era of differential GNSS positioning drawing to an end?, *Proceedings of FIG Working Week 2012*, Rome, Italy, 6-10 May, 17pp.

Roberts C., McElroy S., Kinlyside D., Yan T., Jones G., Allison S., Hendro F. and Hoffman S. (2007) Centimetres across Sydney: First results from the SydNET CORS network, *Proceedings of the Spatial Sciences Institute Biennial International Conference (SSC2007)*, Hobart, Australia, 14-18 May, 152-161.

Sussanna V., Janssen V. and Gibbings P. (2014) Absolute performance of AUSGeoid09 in mountainous regions, *Journal of Applied Geodesy*, 8(3), 195-203.

Sussanna V., Janssen V. and Gibbings P. (2016) Relative performance of AUSGeoid09 in mountainous terrain, *Journal of Geodetic Science*, in press.

UN (2015) Resolution 69/266 of 26 February 2015: A global geodetic reference frame for sustainable development, http://www.un.org/en/ga/69/resolutions.shtml (accessed Mar 2016).

Yan T.S. and Jap C.K. (2011) CORSnet-NSW: Deploying a CORS network in a corporate IT environment, *Proceedings of IGNSS Symposium 2011 (IGNSS2011)*, Sydney, Australia, 15-17 November, 8pp.