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Implementing network-RTK: the SydNET CORS infrastructure

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ABSTRACT

As is well known, the limitation of single-base real-time kinematic (RTK) GPS carrier phase-based techniques is the constrained distance between base receiver and the rover receiver due to distance-dependent measurement biases. For high productivity GPS surveying techniques, requiring very fast on-the-fly ambiguity resolution, the baseline length is generally restricted to less than 10km. However, techniques have been developed to overcome this distance dependence using a network of GPS reference stations. Because the measurement biases can be modelled and corrected for using multi-reference receiver data, the positioning accuracy will be almost independent of the inter-receiver distance. This class of techniques is now variously referred to as Network-RTK, Multi-Reference Station Positioning, Wide Area Positioning, and the Virtual Reference Station Technique. The authors will describe the basis of Network-RTK techniques, and discuss the challenges in implementing the infrastructure necessary to support Network-RTK users in Sydney. This paper will also describe the components of a continuously operating reference station (CORS) network currently being established in the Sydney basin area, suitable for supporting Network-RTK techniques.

KEYWORDS: RTK, Network-RTK, GPS networks, CORS infrastructure

1. INTRODUCTION

1.1 Background

The standard mode of precise *differential* GPS positioning is for one reference receiver to be located at a base station whose 3D coordinates are known in a geocentric reference frame, so that the second receiver's coordinates are determined relative to this reference receiver. This is the principle underlying pseudorange-based differential GPS (or DGPS for short) techniques. To achieve high accuracy applications, carrier-phase data must be used, but this comes at a cost of system complexity because the measurements are *ambiguous*. Therefore, ambiguity resolution (AR) algorithms must be incorporated as an integral part of the data processing software. Such high-accuracy techniques are the result of progressive R&D innovations, which have been subsequently implemented by the GPS manufacturers in their top-of-the-line "GPS surveying" products (e.g., Rizos, 2002a).

Over the last decade, several significant developments have resulted in this high-accuracy performance also being available in real-time. That is, immediately following the making of measurements, and after the data from the reference receiver has been transmitted to the field receiver for processing via some data communication links (e.g., VHF or UHF radio, cellular telephone, FM radio sub-carrier or satellite com link), accurate positions are produced in the field. Real-time precise positioning is, of course, possible when the GPS receiver is in *motion*. These systems are commonly referred to as real-time-kinematic or RTK systems and make feasible the use of GPS-RTK for many time-critical applications such as engineering surveying, GPS-guided earthworks/excavations, machine control and other high-precision navigation applications (e.g., Lachapelle *et al*., 2002).

The limitation of single-base RTK is the distance between reference receiver and the user receiver due to distance-dependent biases occurring such as orbit error, and ionospheric and tropospheric signal refraction. This has restricted the inter-receiver distance to 10km or less if very rapid AR is desired (i.e., less than a few seconds).

Wide Area Differential GPS (WADGPS) and the Wide Area Augmentation System (WAAS) on the other hand, use a network of base stations separated by hundreds of kilometres over a wide geographic area. The measurement biases can be modelled and corrected at the user's receiver, and therefore, the positioning accuracy will be almost independent of the inter-receiver distance. However, these are predominately pseudorange-based systems intended to deliver accuracies at the metre to sub-metre level.

Continuously operating reference stations (CORS) have been deployed to support very high accuracy geodetic applications since the 1980s (Evans *et al*., 2002). Geodetic techniques are by their very nature 'multi-station', taking advantage of the geometric strength, reference datum stability (and redundancy) afforded by network-based positioning. Such CORS networks have been deployed globally, as well as in geodynamic 'hot spots' like Japan and Southern California where there is significant tectonic motion (*ibid*., 2002).

In Europe, as in many other countries, countrywide 'active control stations' have been established, consisting of CORS that collect data specifically for survey and mapping applications. In Australia, the State-wide CORS network in Victoria, *GPSNet,* serves the same purpose. Until recently however, such CORS networks have contributed to improving surveying productivity by obviating the need for GPS surveyors to operate two receivers: the reference receiver and the user receiver. They have not been used in an optimal manner to address the distance constraint of single-base positioning (real-time or post-mission) in the same way that the WADGPS/WAAS techniques have done so for pseudorange-based positioning, or "GPS geodesy" has for ultra high accuracy geoscientific applications.

1.2 Network-based Positioning

How can carrier-phase-based GPS surveying take advantage of developments in geodesy and global navigation to overcome the distance constraint? If 'high productivity' rapid-static and kinematic GPS surveying techniques are to continue to be used, then the answer is to take advantage of CORS networks in such network-based implementations as *Network-RTK*, or more generally *Network-Based Positioning* (Lachapelle *et al*., 2002).

For many years, CORS networks have supported geodetic (e.g., multi-station) processing of data from reference receivers simultaneously with the user receiver data. This is typically done by a web-based service such as *AUSPOS* (http://www.auslig.gov.au/geodesy/sgc/wwwgps/), which requires the user to upload their data to the web-engine, subsequently sending the coordinate results to the user. *AUSPOS* (and similar services) is not a real-time service and currently only supports static positioning for occupations of several hours or more using dual-frequency user receivers. GPS surveyors use these on-line processing services to establish high-order geodetic control, but the services are unsuitable for high-productivity engineering-type surveys. AUSPOS and similar services rely on data collected and archived by the International GPS Service (http://igscb.jpl.nasa.gov), hence inter-receiver distances are many hundreds (even thousands) of kilometres. The Australian Regional GPS Network (http://www.auslig.gov.au/geodesy/argn) is an example of a sparse network that *augments* the IGS global network, and provides data to web-engines such as *AUSPOS*.

To address applications other than geodesy/geodynamics, many countries (and even states within countries) have established CORS networks that collect data for users to subsequently access and process themselves. This is an important distinction; as such networks only provide 'passive' services such as data downloads of RINEX-formatted measurement files. As with 'geodetic' CORS networks, the user needs to operate only one GPS receiver. However, because the survey user must process data using software typically provided by the GPS manufacturer, and rapid GPS survey techniques are used (e.g., kinematic, rapid static, 'stop-and-go', etc. – Rizos, 2002a), the distance between the user receiver and the closest reference receiver must be less than the maximum recommended for GPS surveying applications. This is less than 10km for very rapid AR and typically 20-30km for rapid-static techniques.

The Hong Kong GPS Network (Kwok, 2002) is an example of a CORS network with a density of base stations that a user is always within 10km of a reference receiver (and usually two, to permit checking). On the other hand, the State-wide GPSNet (http://www.land.vic.gov.au/GPSnet/) established in Victoria, is a typical example of a 'passive' CORS network, with base station spacing of between 50 and 100km. In order to upgrade such a CORS network to real-time operations would require the implementation of a Network-RTK system if no user were to be disadvantaged by being more than 10km from a base station.

Several European countries have upgraded their CORS networks to implement RTK. In some cases, such as in Denmark where the density of base stations is high, of the order of 10-20km station spacing, it is possible to use standard single-base RTK techniques (Leica, 2003, *personal communication*). In Germany, the Satellite Positioning Network (SAPOS) (Elsner, 1996) has been upgraded in recent years to offer a Network-RTK service across all German states. This is a model that is likely to be followed by other 'passive' CORS networks as they upgrade to real-time operations.

2. NETWORK-RTK

Network-RTK is the logical outcome of the continuous search for a GPS positioning technique that challenges the current constraints of single-base RTK, namely the need to be within 10km of the base station if the highest performance is to be achieved.

2.1 Network- RTK Concept

Network-RTK is a centimetre-accuracy, real-time, carrier-phase-based positioning technique capable of operating over inter-receiver distances up to many tens of kilometres with equivalent performance to current single-base RTK systems. The most crucial characteristic of contemporary RTK techniques that must be preserved is very rapid time to AR, *measured in seconds*. Hence, the base stations must be deployed in a dense enough pattern to model distance-dependent errors to such an accuracy that residual double-differenced carrier phase observable errors can be ignored in the context of such rapid AR (Rizos, 2002b).

Network-RTK requires a data processing 'engine' with the capability to resolve the integer ambiguities between the static reference receivers that make up the CORS network. The 'engine' must be capable of handling double-differenced data from receivers 50-100km apart, operate in real-time, instantaneously for all satellites at elevation cut-off angles down to a couple of degrees (even with high noise data that is vulnerable to a higher multipath disturbance). The Network-RTK correction messages can then be generated.

The utility of the Network-RTK messages (as opposed to standard RTK messages) are:

- Elimination of orbit bias and ionosphere delay.
- Reduction of troposphere delay, multipath disturbance and observation noise.
- RTK can be extended to what might be considered 'medium-range' baselines (up to 100km).
- Low-cost single-frequency receivers can be used for RTK and rapid static positioning.
- Very high accuracy applications using low-cost GPS receivers (e.g. deformation monitoring, geodetic control network, etc.) are possible.
- Improve the accuracy, reliability, integrity, productivity and capacity of GPS positioning.

In addition to the *data processing engine*, the Network-RTK system needs to have a *data management system* and a *data communication system*. It needs to manage corrections generated in real-time, the raw measurement data, multipath template for each reference stations (for multipath mitigation), ultra-rapid IGS orbits, etc. There are two aspects to the data communication system: (a) between the master control station (MCS - where the *data* *processing engine* and data archive are located) and the various reference stations, and (b) communication between the MCS and users. From the Network-RTK implementation point of view, there are three possible architectures (Rizos, 2002b): (1) generation of the Virtual Reference Station and its corrections, (2) generation and broadcast of an Area Correction Model, or (3) broadcast the raw data from all of the reference stations. These are briefly described below.

2.1.1 Virtual Reference Station (VRS):

- At the MCS server, the VRS can be generated and the RTCM 20/21 message created and transmitted once the server knows the position of the roving user.
- There is no further request from the roving user if the rover supports RTCM 20/21 format, except that the user needs to send their location to the server.
- Two-way communicationis required, with the user informing the server where they are, and the server continuously sending data to the user for RTK applications.
- There are some limitations on the number of simultaneous users accessing the VRS service due to server capacity.
- This configuration has been used by Trimble/Terrasat in their commercial product, *The Trimble Virtual Reference Station* (Vollath *et al.*, 2000).

2.1.2 Area correction model broadcasting:

- At the MCS server, the corrections, e.g. dispersive and non-dispersive atmospheric correction terms or carrier phase measurement residuals for each satellite at each reference stations, will be generated using data from the CORS network.
- The corrections can be used to generate an interpolation model or the VRS at the user end. The correction generation algorithms can be different.
- One-way communication is sufficient.
- There is no limit on the number of users.
- This requires a new data format, and the volume of transmitted data is more than in the case of a single reference station.
- This configuration has been proposed as a Network-RTK RTCM format by Leica and Geo++, and will be implemented in RTCM version 3 (Han, 2003, *personal communication*).

2.1.3 Raw data broadcasting:

- Broadcast raw measurements (CMR or RTCM 18/19 message format) from either the MCS server or from the multiple reference stations individually.
- Generate the VRS, or corrections, at the user site. The computation load is therefore shifted to the user.
- This requires a new data format.
- One-way communication is sufficient.
- There is no limit on the number of users.

A discussion of the pros and cons of each type of implementation is beyond the scope of this paper. Tests will need to be conducted to determine which of these is best suited for the type of applications that will be addressed by the network service.

2.2 The Singapore Integrated Multiple Reference Station Network (SIMRSN)

Due to the complexity and cost (typically between $30-$50,000 per station) involved in establishing CORS networks, the data links and the data processing/management servers at the MCS, there have been comparatively few university-based Network-RTK systems established to support research. During the last few years, to the best of the authors' knowledge, only the Singapore Integrated Multiple Reference Station Network (SIMRSN) has been operating *both* as a research facility and an operational Network-RTK service for the benefit of GPS surveyors. The SIMRSN is a joint R&D initiative among the Surveying and Mapping Laboratory, Nanyang Technological University (NTU), Singapore; the Satellite Navigation and Positioning group at the University of New South Wales (UNSW); and the Singapore Land Authority (currently the main user) (Chen *et al*., 2000).

The SIMRSN consists of five continuously operating reference receivers (tracking satellites on a '24/7' basis), connected by dedicated ISDN data lines to the MCS at NTU. It is a high-quality and multi-functional network designed to serve the various needs of real-time precise positioning, such as surveying, civil engineering, precise navigation, road pricing, etc. (Chen *et al*., 2000). The SIMRSN also services off-line users, who can access archived RINEX data files via the Internet. The inter-receiver distances are of the order of several tens of kilometres at most. However, tests conducted in 2001 have shown that even a network with such comparatively short baselines had difficulty in modelling the disturbed ionosphere in equatorial regions during the last solar maximum period of the 11-year sunspot cycle (Hu *et al*., 2002). Unique facilities such as SIMRSN can therefore act as a test bed for network-based positioning techniques. The SIMRSN model of a network that is *both* a research facility and an operational network service for users is being adopted for a proposed Network of GPS Reference Stations in the Sydney metropolitan area of NSW.

3. THE SYDNET CORS NETWORK

The authors believe that over the next few years many 'passive' CORS networks around the world will be upgraded to Network-RTK capability. The SydNet CORS network will be established with network-based positioning capability from the very start, including Network-RTK.

The SydNet project is being sponsored by the NSW Department of Lands (DoL) as an initiative of State Government infrastructure. The NSW Department of Lands has been active in using GPS for a variety of surveying and mapping applications for over a decade (Kinlyside, 1999, 1995, 1993). The development of a Network-RTK system for the State's largest capital city is a natural and logical extension of the organisation's previous and current involvement in GPS applications for surveying and geodesy. The commitment to SydNet by the NSW DoL is a medium-term one and it is expected that receiver hardware will be upgraded towards the end of the decade to track new GPS signals as well as signals from the yet-to-be-launched Galileo GNSS.

- UNSW will be the main supplier and development contractor.
- Initially SydNet will only service the Sydney basin region (an area of approximately 100x100km), but it is planned for expansion over time to cover other areas in NSW.
- In Phase 1 of the project, SydNet will implement the SIMRSN Network-RTK algorithms to support VRS-type Network-RTK and provide an offline service for RINEX data download.
- User testing of the system is planned for early 2004.
- SydNet will be an important research facility for the Cooperative Research Centre for Spatial Information (http://www.spatialinfocrc.org/programs.html).
- SydNet will be available for testing various network-based positioning techniques, both commercial products and those developed by research organisations.
- SydNet will be able to participate in experiments on non-positioning applications such as 'GPS meteorology'.

3.1 SydNet Reference Stations

Each reference station consists of a dual-frequency geodetic grade GPS receiver with suitable antenna and a device converting serial data stream into TCP/IP packets over Ethernet. SydNet will use existing GPS receivers belonging to DoL and UNSW, with the intention of reducing the amount of initial capital investment required. Currently, there are four Trimble 4000SSE receivers and four Leica CRS1000 receivers committed to SydNET. Two new receivers are being procured to increase the number of reference stations to ten. The receivers will be upgraded in due course to track the new GPS signals and the Galileo GNSS signals as they become available to users.

At time of writing, seven locations in the Sydney have been proposed as reference station sites. These locations were chosen based on 15-20km spacing and for convenient connection to the NSW Rail Infrastructure Corporation (RIC) fibre optic data network.

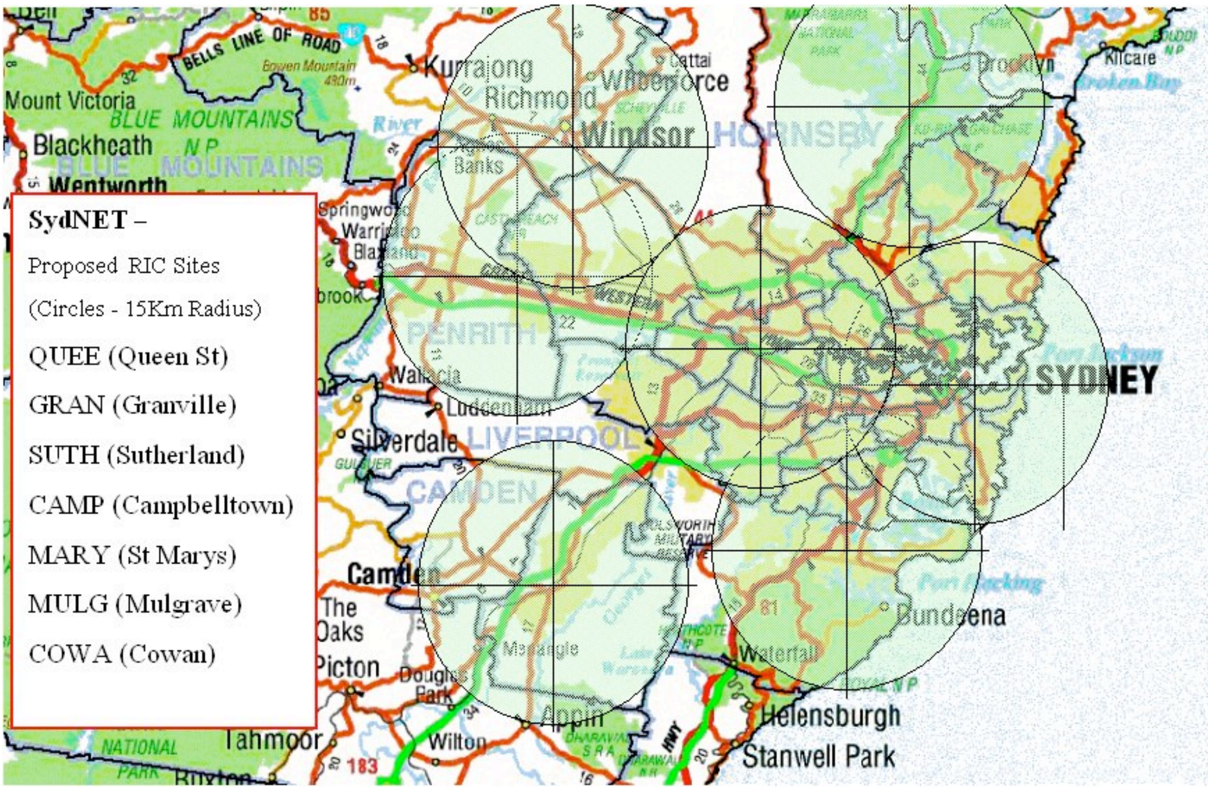

Figure 1. Initial SydNet station sites (15km radius circles)

3.2 The SydNet Communication Link

Early in 2003, DoL approached NSW Rail Infrastructure Corporation to use the Argus Telecommunications network in order to providing the communication links between the reference station receivers and the servers at the MCS. Argus is a commercial subsidiary of Railway Infrastructure Corporation providing telecommunications service to the railway system in NSW and has fibre-optic network installed extensively throughout the Sydney railway network.

Data from the reference stations is sent via the Argus' network back to the MCS. As previously mentioned, the data are transmitted in TCP/IP packets over Ethernet. Tests have not yet been conducted, but it is expected that the Argus network is more than adequate for the relatively small data volume from each SydNet station to the MCS (raw GPS measurements at a rate of 1 Hz). The SydNet communication links can be seen as a Wide Area Network (WAN).

3.3 The SydNet Master Control Station

At this stage, it is planned that SydNet Master Control Station will be hosted by the Australian Centre for Advanced Computing and Communications (ac3) located at the Australian Technology Park, Redfern, NSW. Ac3 provides a professionally managed, premium facility that was purpose built for high availability, is highly secure and highly connected to the Internet backbones, including a connection to Argus.

The SydNet database system is designed to store satellite pseudorange and carrier-phase measurements at one-second epochs from up to 100 base stations and retain the data on line for one month. Offline users will be able to download this data through the FTP server for free. After that period, the data will be archived indefinitely in RINEX format.

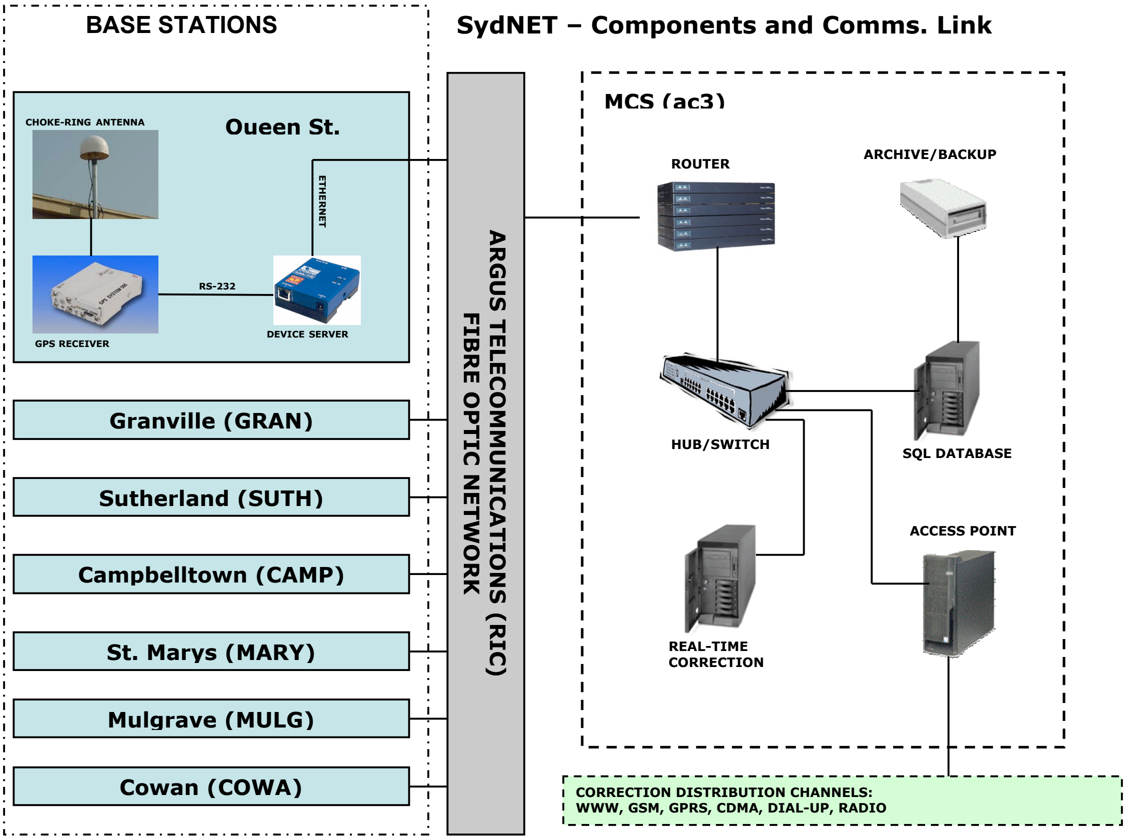

Figure 2. MCS servers and connections to SydNet sites

For real-time users, correction data will be accessed over the Internet on a particular internet protocol (IP) address. This method allows user to access the data using the General Packet Radio Service (GPRS) or Code Division Multiple Access (CDMA) network. A modem will also be made available for testing of direct dial-up connection and comparison with Internet connections. Radio broadcast is planned for the next phase of the project.

3.4 The SydNet: Management Issues

The SydNet Phase 1 Project is being managed using the PRINCE2 project management methodology (as with most other current and on-going projects within the Land and Property information division of DoL). Major authorisations for the project are made through a project board, which currently comprises two executives from DoL and two external members. An important component of PRINCE2, and for ongoing DoL and Government support, is a comprehensive business case.

Some of the business benefits of SydNet are that it will enable DoL to exploit high-precision positioning in real time, to improve service delivery and outcomes for customers. In particular, it will enable DoL to:

- Provide an efficient means to establish control for improving the spatial accuracy of the Digital Cadastral Data Base and the Digital Topographic Data Base.
- Make a significant contribution towards DoL's commitment to provide financial and other support to the Cooperative Research Centre for Spatial Information (CRC-SI).
- Improve DoL's approach and reduce the cost of managing and maintaining permanent survey marks across the state of NSW.
- Facilitate and enhance the delivery of LPI strategic development programs including promotion and development of value added services.
- Provide a mechanism for establishing the legal traceability of position.

Figure 3. The SydNET logo

4. CONCLUDING REMARKS

Currently there is only one commercially available Network-RTK product, the Trimble VRS (Vollath *et al.*, 2000). This system is in operation in several parts of the world, including in the Brisbane area, Queensland (Higgins, 2003, *personal communication*). Leica has recently announced that it too will be offering a Network-RTK product (Leica, 2003, *personal communication*). The trend to 'passive' CORS networks being upgraded to offer services to users in *real-time* clearly is an opportunity for companies that offer Network-RTK products, because standard single-base RTK would require a density of base stations that is unrealisable (i.e. too costly) for many CORS network operators.

The proliferation of CORS networks at all scales, global, national, state and local, will be a challenge to organisations that seek the implementation of common standards of service, and those that wish to see a seamless network-based positioning capability across all networks.

The integration of networks with different operators, and different functionalities, is an added challenge. In Australia, there is the opportunity to address these challenges at the national and state level through such initiatives as the 'network research' to be undertaken by the CRC-SI (http://www.spatialinfocrc.org).

The SydNet network may be considered a 'second generation' CORS network, as it will be established with network-based positioning capability from the very start. Furthermore, what makes SydNet unique is an architecture that is designed from the core database outwards. The physical infrastructure, the communication links and the database are all controlled by the one agency, the NSW Department of Lands. By providing such a framework, new reference receivers will be able to be connected to this 'backbone' on an *ad hoc* basis. The SydNet CORS network is the first step in ultimately replacing NSW's primary geodetic network of trig stations with an extensive network of 'active control stations'.

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