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Development of SydNET Permanent Real-time GPS Network

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Abstract. Over the past few years, there has been substantial growth in multiple-reference-station networks used to overcome the limitations of standard real-time kinematic (RTK) systems. SydNET is a project to establish a permanent real-time GPS network in the Sydney basin area providing Network-RTK support to users in the area. SydNET is being developed by NSW Department of Lands in partnership with the School of Surveying & SIS at the University of New South Wales. This paper presents recent developments of the SydNET network. Preliminary test results will be presented which will show the network's performance, achievable accuracy. It will outline the SydNET system, its operation, current status and vision of future development as a high precision positioning service infrastructure.

Key words: 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, 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, mobile phone, FM radio sub-carrier or satellite link), accurate positions are produced in the field. Real-time precise positioning is then 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 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 Ambiguity Resolution (AR) is desired (ie 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 users' 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 Victorian CORS network, *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 a reference 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 far for pseudorange-based positioning.

1.2 Network-based positioning

Rapid static and kinematic GPS surveying techniques can become more productive by taking advantage of CORS networks in such network-based implementations as *Network-RTK* or more generally *Network-based Positioning* (Lachapelle *et al*., 2002).

CORS networks support multi-station (e.g. geodetic) processing of data from reference receivers simultaneously with the user receiver data. These days, this is typically achieved 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 returning the results of the processing to the user. AUSPOS 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 online processing services to establish high-order geodetic control but the services are obviously 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 states 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, user only needs to operate 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.

1.3 Network-RTK concept

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. It 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 ambiguity resolution (AR), measured in seconds. Hence the base stations must be deployed in a pattern dense enough to model distance-dependent errors to such 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 multi-path disturbance). The Network-RTK correction messages can then be generated.

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

- Elimination of orbit bias and ionosphere delay.
- Reduction of troposphere delay, multi-path disturbance and observation noise.
- RTK can be extended to what might be considered 'medium-range' baselines (up 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, multi-path template for each reference stations (for multi-path 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 communication is 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 and 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.

1.4 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 control centre, 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 research and development initiative between the Surveying and Mapping Laboratory, Nanyang Technological University (NTU), Singapore; the School of Surveying & Spatial Information Systems 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 CORS, connected by dedicated ISDN data lines to the control centre 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-station 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 the SydNET network being established in the Sydney metropolitan area.

2 SydNET CORS Network

2.1 Introduction

The SydNET real-time CORS network is being established with network-based positioning capability from the very start, including Network-RTK. The project is funded by the NSW Department of Lands (Lands) as an initiative of State Government infrastructure. 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.

SydNET is also an important research facility for the Cooperative Research Centre for Spatial Information (http://www.spatialinfocrc.org/programs.html). It will be available for testing various network-based positioning techniques, both commercial products and those developed by research organisations. Additionally, SydNET can also be utilised for experiments on non-positioning applications such as 'GPS meteorology'.

2.2 Project Management and Structure

As with most other current projects within Lands, SydNET Project is managed using the PRINCE2 project management methodology. Major authorisations for the project are made through a project board which currently comprises two executives from Lands, one external member from UNSW and one external member from the Roads & Traffic Authority (RTA).

The School of Surveying & SIS at the University of New South Wales is the main IP supplier and development contractor. The first phase of SydNET is only servicing the Sydney basin region - an area of approximately 100x100km - but it is planned for expansion over time to cover other areas in NSW. In this initial phase, SydNET is implemented using the SIMRSN Network-RTK algorithms which support VRS-style Network-RTK and provide an online service for RINEX data download.

2.3 Locations and Coverage

In 2003, Lands approached RailCorp with the idea of utilising their fibre-optic network in order to provide the communication links between receivers at the reference stations and servers at the Network Control Centre (NCC). RailCorp is a state-owned corporation which provides passenger rail network throughout NSW. RailCorp has fibre-optic network installed extensively throughout their electrified railway network.

As many as eighteen sites on RailCorp's network were inspected for feasibility of installing a GPS reference station with the intention of providing coverage over Sydney basin area based on 15 to 20km spacing. Seven sites are subsequently chosen because they provide the best possible sky view, least radio interference, safety and suitable infrastructure for installing a permanent GPS antenna and receiver. These sites are located in Chippendale, Villawood, Waterfall, Mulgrave, Springwood, Cowan and Menangle. At the time of writing, six stations have been installed at these locations. Menangle is still to be constructed.

Figure 1 Location of SydNET sites and their coverage

2.4 Reference station hardware

Each reference station consists of a dual-frequency geodetic grade GPS receiver with choke-rings antenna and a device converting serial data streams into TCP/IP packets over Ethernet. SydNET is using existing GPS receivers belonging to Lands and UNSW, with the intention of reducing the amount of initial capital investment required. Currently, three Trimble 4000SSe receivers from Lands are being deployed in SydNET stations with a number of Leica System 500 receivers from UNSW available for testing and ad-hoc stations. Four new Ashtech µZ-CGRS receivers have also been procured and deployed to augment the network. The receivers will be upgraded as new GPS signals and the Galileo GNSS signals become available to users.

2.5 SydNET communication link

Data from the reference stations is transmitted via RailCorp's network back to the NCC in TCP/IP packets over Ethernet. There is a 10 Mbps physical link to RailCorp's network at each station. This is more than sufficient for the current data stream which is in the range of 20 to 30 kbps. Currently there is one main data stream of raw GPS measurements at a rate of 1Hz. With significant remaining bandwidth available, it is possible to add more data streams or equipments for testing and research purposes. In some of the stations, multi-ports serial converters are being installed to enable different streams of data for operational, research and signalling purposes.

2.6. SydNET Network Control Centre

The Network Control Centre (NCC) for SydNET is 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 RailCorp's fibre-optic network.

Data streams from SydNET reference stations are aggregated at ac3. A media converter was installed by RailCorp in Lands equipments cabinet which connects RailCorp's fibre-optic network to Lands' network. Measurements data from all SydNET stations are processed by SydNET servers to provide real-time correction and also post-processing data.

Traditionally, correction data is transmitted to users via radio on a specifically allocated frequency. This requires specialised hardware both on the service provider's side and on the users' side and also specific radio spectrum license. A more advanced technique is to use GSM mobile network but this still requires service provider to invest in expensive modem banks and routers. A dial-in system such as GSM has limited number of lines and hence users at the same time. Another disadvantage is the cost associated with using mobile network.

2.7 Real-time data distribution

Real-time correction data from SydNET is distributed via the Internet. The choice is then given to users to arrange access to the data on the Internet. A suggested method is by using General Packet Radio System (GPRS) service which is available in most part of Sydney. With a suitable GPRS-enabled device, users can access the data and connect it to their GPS receiver. For testing and internal use, Lands and UNSW use either a Compaq iPAQ PDA with a GPRS jacket or an O2 XDA with built-in GPRS phone. Both devices run Pocket PC operating system. Client software has been developed to access SydNET server and retrieve correction data. This data is then transmitted on the device's serial port which is connected to the GPS receiver in the field.

Other alternatives to GPRS network are CDMA1x and 3G which are both available in Sydney as well. Similar to GPRS, users can get either an add-on CDMA 1X card or a PDA with built-in CDMA 1X capability such as the i-mate PDA2K.

3 Conclusions

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. The physical infrastructure, the communication links and the database are all controlled by 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'.

References

Chen X.; Han S.; Rizos C.; Goh P.C. (2000): ***Improving real-time positioning efficiency using the Singapore Integrated Multiple Reference Station Network (SIMRSN)***, 13th Int. Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation, Salt Lake City, Utah, 19-22 September, 9-18.

Elsner C. (1996): ***Real-time differential GPS: The German approach***, GIM Int. Journal for Geomatics, 10(5), 76-79.

Evans A.G.; Swift E.R.; Cunningham J.P.; Hill R.W.; Blewitt G.; Yunck T.P.; Lichten SM, Hatch RR, Malys S, Bossler J (2002): ***The Global Positioning System Geodesy Odyssey***, Navigation, 49(1), 7-34.

Hu G.; Khoo H.S.; Goh P.C.; Law C.L. (2002): ***Performance of Singapore Integrated Multiple Reference Station Network (SIMRSN) for RTK positioning***, GPS Solutions, 6(1-2), 65-71.

Kwok S. (2002): ***The Hong Kong GPS network and reference stations***, Journal of Geopsatial Engineering, 2(2), 57-65.

Kinlyside D.; Jones G. (1999): ***DGPS Applications in the Land Information Centre***, Procs 4th Int. Symp. on Satellite Navigation Technology & Applications, Brisbane, QLD, 20-23 July 1999.

Kinlyside D.; Bannister M.; (1995): ***Using OmniSTAR and GPS in Outback NSW***, Procs Satellite Navigation Technology Conference, UNSW, Brisbane, QLD, 26-28 June 1995.

Kinlyside D.; Dickson G.; (1993): ***DGPS Activities of the Land Information Centre***, Procs Satellite Navigation Technology Conference, UNSW, Kensington, NSW, 19-21 July 1993.

Lachapelle G.; Ryan S.; Rizos C. (2002): ***Servicing the GPS user***, Chapter 14 in Manual of Geospatial Science and Technology, J. Bossler, J. Jenson, R. McMaster & C. Rizos (eds.), Taylor & Francis Inc., 201-215.

Rizos C. (2002a): ***Making sense of the GPS techniques***, Chapter 11 in Manual of Geospatial Science and Technology, J. Bossler, J. Jenson, R. McMaster & C. Rizos (eds.), Taylor & Francis Inc., 146-161.

Rizos C. (2002b): ***Network RTK research and implementation: A geodetic perspective***, Journal of Global Positioning Systems, 1(2), 144-150.

Vollath U.; Buecherl A.; Landau H.; Pagels C.; Wagner B. (2000): ***Multi-base RTK positioning using Virtual Reference Stations***, 13th Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation, Salt Lake City, Utah, 19-22 September 2000, 123-131.