

Network RTK Research and Implementation – A Geodetic Perspective

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BIOGRAPHY

Chris Rizos is a Professor at the School of Surveying & SIS, UNSW, Australia, and leader of the Satellite Navigation and Positioning (SNAP) Group (<http://www.gmat.unsw.edu.au/snap/>). He has been engaged in GPS research since the mid-1980s, which was at first focused on geodetic applications. More recently Chris has broadened the SNAP group's research across a wide range of positioning applications that can be addressed by GNSS and various ground-based wireless location technologies. He is currently secretary of Section 1 "Positioning" of the International Association of Geodesy (IAG).

BACKGROUND: WHY COMPLICATE MATTERS?

The standard mode of precise *differential* positioning is for one reference receiver to be located at a base station whose coordinates are known, while the second receiver's coordinates are determined relative to this reference receiver. This is the principle underlying pseudo-range-based differential GPS (or DGPS for short) techniques. However, for high precision applications, the use of carrier phase data must be used, but comes at a cost in terms of overall system complexity because the measurements are *ambiguous*, requiring that ambiguity resolution algorithms 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. Over the last decade or so several significant developments have resulted in this high accuracy performance also being available in real-time -- that is, in the field, immediately following the making of measurements, and after the data from the reference receiver has been transmitted to the (second) field receiver for processing via some sort of data communication links (e.g., VHF or UHF radio, cellular telephone, FM radio sub-carrier or satellite com link). Real-time precise positioning is even possible when the GPS receiver is in *motion*. These systems are commonly referred to as RTK systems ("real-time-kinematic"), 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.

The limitation of single base RTK is the distance between reference receiver and the rover receiver due to distance-dependent biases such as orbit error, and ionospheric and tropospheric signal refraction. This has restricted the inter-receiver distance to 10km or less. On the other hand, Wide Area Differential GPS (WADGPS) and the Wide Area Augmentation System (WAAS) use a network of master and monitor stations spread over a wide geographic area, and because the measurement biases can be modelled and corrected for, the positioning accuracy will be almost independent of the inter-receiver distance (or baseline length). However, these are pseudo-range based systems intended to deliver accuracies at a metre level. Continuously operating reference stations have been deployed globally to support very high accuracy geodetic applications for well over a decade. How can GPS surveying take advantage of such developments in geodesy and global navigation? The answer is to take advantage of multiple reference station networks, in such implementations as *Network RTK*.

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 (the distance between a rover and the closest reference station receiver) with equivalent performance to current single base RTK systems (operating over much shorter baselines). The reference 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 rapid ambiguity resolution. Network RTK is therefore the logical outcome of the continuous search for a GPS positioning technique that challenges the current constraints of cm-accuracy, high productivity, carrier phase-based positioning.

NETWORK-BASED POSITIONING: THE GEODETIC PERSPECTIVE

All GPS-based positioning techniques operate under a set of *constraints* (Rizos, 2002). These constraints may be baseline length, attainable accuracy, assured reliability, geometrical strength, signal availability, time-to-solution, instrumentation, operational modes, and so on. GPS product designers must develop systems (comprising hardware, software and field procedures) that are optimised for a certain target user market, by addressing only those constraints that are crucial to the most common user scenarios. For example, current single base RTK systems are capable of high performance when measured in terms of such parameters as accuracy, time-to-solution (i.e. speed of ambiguity resolution after signal interruption), utility (due to the generation of real-time solutions), flexibility (being able to be used in static and kinematic applications), ease-of-use, and cost-effectiveness. As a result the sale of RTK systems is booming. However, the authors believe that the 10km baseline constraint will increasingly become an issue.

RTK GPS users will demand an infrastructure of base stations to support them, in much the same way that DGPS users have for many years been able to take advantage of free-to-air or fee-based differential services. However, it is generally unrealistic to deploy reference receivers across a country, or even just within a city, at such a density that all users are within 10km of a reference receiver transmitting RTK messages. Network RTK techniques use base station separations of several tens of kilometres, hence requiring fewer reference receivers. This significantly reduces the infrastructure investment required. The development of Network RTK can be viewed from three distinct perspectives:

- (1) The evolution of the high productivity *GPS Surveying* technique in order to preserve single base RTK performance, but to permit much greater GPS inter-receiver distances. The change from single base to multi-base allows for the empirical modelling of the distance-dependent measurement biases. It is this modelling (and the transmission of ‘corrections’ for the normally unaccounted for biases) that overcomes the distance constraint, with no requirement for an upgrade to the user equipment software. The same GPS surveying user functionality is preserved.
- (2) The use of sparse networks of base stations is the basis of WADGPS and WAAS positioning techniques (Lachapelle et al., 2002). Data from the base station network are sent to a central computing facility, and empirical models of the distance-dependent biases are generated in the form of ‘corrections’ (which may be in the form of proprietary messages, or an industry standard RTCM or WAAS message type). These corrections are transmitted to user across a wide geographic area (most commonly via satellite communication links). However, because such *Augmented GPS Navigation* techniques use pseudo-range data, and the separation of the base stations is typically many hundreds to several thousands of kilometres, sub-decimetre level positioning accuracy is unattainable. The evolution to Network RTK would require a significant improvement in accuracy, through the use of carrier phase data and a much denser deployment of reference receivers.
- (3) *GPS Geodesy* has evolved since the early 1980s into a powerful, ultra precise positioning technique that is used for a range of applications, including the definition of the fundamental geodetic framework and the measurement for tectonic motion. GPS Geodesy uses a multi-receiver data processing methodology in which all measurement biases, no matter how small, are carefully accounted for in the functional and stochastic models of the double-differenced carrier phase observables. Continuously operating reference station (CORS) networks have been established around the world to support a range of geodetic applications.

Positioning accuracy at the few parts-per-billion (ppb) are now routinely obtained, using sophisticated data processing algorithms in packages such as the Bernese software (Rothacher & Mervart, 1996). (One ppb is equivalent to 1mm relative accuracy over a baseline one thousand km in length.) Clearly GPS Geodesy could evolve into the Network RTK technique, if receivers were permitted to be in motion and data processing could be undertaken in real-time. Both of these are significant challenges. Furthermore, the Network RTK strategy could be used to densify high precision CORS networks for certain geodetic applications.

The author describes below several developments in GPS Geodesy that could be viewed as being predecessors to the development of the Network RTK concept. In fact, network-based positioning techniques have been an interest of geodesists for some time. During the past decade the International Association of Geodesy (IAG) has established several Special Study Groups (SSG) to research several topics concerned with permanent GPS networks. In 1999 the IAG established SSG1.179 “Wide Area Modelling for Precise Satellite Positioning”. The Chair, SSG1.179, Dr. Shaowei Han, will report to the IAG at the next General Assembly in 2003, in Sapporo (Japan).

KINEMATIC GEODESY: AN EVOLUTIONARY ‘DEADEND’?

Colombo et al. (1995) describes an experiment in which a moving vessel in Sydney Harbour (Australia) was positioned to sub-decimetre accuracy relative to several GPS reference receivers deployed at distances up to 1000km from the mobile receiver. This was a dramatic new GPS Geodesy technique that challenged the requirement that geodetic accuracy over long inter-receiver distances was only possible for a *static* receiver that was collecting carrier phase data over many hours. It was indeed a geodetic technique because: (a) all measurement biases were accounted for in the functional model, (b) sub-part-per-million relative accuracy was obtained, and (c) a simultaneous multi-receiver solution was performed. The first author coined the expression “kinematic geodesy” to describe this technique. In 1995 an Australian Research Council grant was obtained to support graduate studies into high precision, long- and medium-range, kinematic GPS positioning, as reported in Han (1997).

The data processing algorithm used by Colombo et al. (1995) was particularly innovative, consisting of a partitioned Kalman filter that estimated the slow-changing biases such as due to satellite orbit error and atmospheric effects, at the same time generating epoch-by-epoch kinematic coordinate solutions for the mobile receiver, using carrier phase data from several reference receivers (as well as the mobile receiver). The observation biases were carefully modelled, as in the ‘standard’ geodetic methodology used by GAMIT and the Bernese software, and 3-D accuracy is of the order of 3-5cm, for any length of baseline. During the last ten years, this technique has been used in Australia, Denmark, Japan, Spain, The Netherlands and the U.S. for applications as diverse as sea buoys, boats, aircraft, trucks, and altimetric satellites. Recent publications reporting on “kinematic geodesy” projects include Colombo et al. (2000, 2001, 2002).

However, the promise shown by this technique has not led to its widespread adoption by geodesists. Nevertheless this technique can lay claim to having demonstrated, for the first time, the feasibility of carrier phase-based positioning of a moving platform over very long baselines. Amongst its shortcomings are the simultaneous analysis of all GPS data (from reference receivers and the mobile receiver), and the difficulty in implementing this technique in real-time.

LOW-COST DEFORMATION MONITORING: THE UTILITY OF MIXED NETWORKS

Deformation monitoring of structures (such as bridges, buildings, etc.) and ground monumentation (in volcanic, ground subsidence and geological faulting zones) are ideal geodetic applications of GPS (Rizos et al., 1997). To keep the cost of such monitoring systems low, single-frequency GPS receivers are often used (see, e.g., the theses by Chen, 2001; Roberts, 2002). However, data from single-frequency GPS receivers cannot be corrected for ionospheric delay, as is the case with dual-frequency data. Therefore a *combination* of single- and dual-frequency instrumentation in a mixed-mode network is a feasible methodology for ensuring high accuracy coordinate results using a large number of static receivers must be deployed permanently across a region experiencing deformation, while keeping hardware costs as low as possible. This is possible by augmenting the single-frequency receivers with a small number of dual-frequency receivers surrounding the zone of deformation. The primary function of this *fiducial* network is to generate empirical ‘correction’ terms to the double-differenced phase observables within the

deformation monitoring network. This research was funded by the Australian Research Council (1999-2001), in address the need for a low-cost Indonesian volcano monitoring system.

This methodology has been tested in many networks, and results reported in a large number of papers, including Rizos et al. (2000a, 2000b), Chen et al. (2001). Dai et al. (2001) extended this methodology to include integrated GPS/GLONASS reference receiver networks. This methodology can address geodetic applications where a CORS network of geodetic quality GPS receivers exists. Furthermore, this data processing strategy is identical to what we now know as the Network RTK, or multiple reference station, class of techniques. That is, there are three distinct processes: reference station network data processing to generate ‘corrections’, correction of double-differenced phase data involving user receiver(s), and (static or kinematic) baseline processing using the corrected GPS phase observables. It is this separation of processes that sets this class of techniques apart from the conventional multi-station geodetic technique, and the “kinematic geodesy” approach described earlier. The extension of this methodology to operate in real-time, though an engineering challenge, is relatively straightforward.

NETWORK RTK ISSUES: THEORETICAL & PRACTICAL CHALLENGES

Many investigators have contributed to the definition of the appropriate functional and stochastic models for medium-range and long-range GPS/GLONASS survey-type positioning (as opposed to geodetic techniques) using CORS networks. Research has addressed topics such as: multipath mitigation algorithms, troposphere model refinement, regional ionosphere modelling algorithms, phase centre calibration, and orbit bias modelling. The authors would be unable to do justice to all contributions in this review paper and refer the reader review papers such as Rizos & Han (2002). Although most of these research topics are of general interest to precise GPS positioning, several are explicitly related to the processing of CORS network data in order to generate the empirical ‘correction’ data that must be transmitted to users in Network RTK type implementations. Some of these topics include: rapid ambiguity resolution for the network receivers, validation of the ambiguities so resolved, the nature of the model for the distance-dependent biases across the CORS network, the method of interpolation of the corrections for the user-base station baseline, and the format for the transmitted ‘correction’ data.

After the double-differenced ambiguities associated with the reference station receivers have been fixed to their correct values, the double-differenced GPS/GLONASS residuals can be generated. The spatially correlated errors to be interpolated could be the pseudo-range and carrier phase residuals for the L1 and/or L2 frequencies, or other linear combinations. One core issue for multi-reference receiver techniques is how to interpolate the distance-dependent biases generated from the reference station network for the user's location? Over the past few years, in order to interpolate (or model) the distance-dependent residual biases, several interpolation methods have been proposed. They include the Linear Combination Model (Han & Rizos, 1996; Han, 1997), the Distance-Based Linear Interpolation Method (Gao & Li, 1998), the Linear Interpolation Method (Wanninger, 1995), the Low-Order Surface Model (Wübbena et al., 1996; Fotopoulos & Cannon, 2001), and the Least Squares Collocation Method (Raquet, 1998; Marel, 1998). The theoretical and numerical comparison of the various interpolation algorithms has been made by Dai et al. (2003), and there is no obviously ‘superior’ technique. The essential common formula has been identified: all use $n-1$ coefficients and the $n-1$ independent ‘correction terms’ generated from a n reference station network to form a linear combination that mitigates spatially correlated biases at user stations.

While theoretical and numerical studies have contributed to the development of the Network RTK class of techniques, there are a host of ‘practical’ issues that must be addressed in order to implement a RTK service that operates ‘24/7’. For example, the Network RTK system needs 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), precise/predicted IGS orbits, etc. There are two aspects to the data communication system: (a) between the master control station (MCS - where all the calculations are undertaken) and the various reference stations, and (b) communication between the MCS and users. Furthermore, from the Network RTK implementation point of view, there are three possible architectures: (1) generation of the Virtual Reference Station (VRS) and its corrections, (2) generating and broadcasting Network RTK corrections, or (3) broadcasting raw data for all the reference stations. The debate about the ‘best’ architecture is still raging, and it is likely that combinations of some or all may be implemented, with the appropriate RTCM/RTK messages being defined. However, research into all aspects of Network RTK, theoretical and practical, is difficult to undertake in universities because of the expense of establishing and operating ‘test networks’.

SINGAPORE INTEGRATED MULTIPLE REFERENCE STATION NETWORK

Due to the complexity (and cost) involved in establishing fully functioning reference receiver networks, the data links and the data processing/management servers at the master control station (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 that can be used by surveyors. The SIMRSN is a joint research and development initiative between the Surveying and Mapping Laboratory, of the Nanyang Technological University (NTU), Singapore (<http://gis.ntu.edu.sg/generaterinex/index.htm>), the Satellite Navigation and Positioning group, of the University of New South Wales (UNSW), Australia (<http://www.gmat.unsw.edu.au/snap/work/singapore.htm>), and the Singapore Land Authority (SLA). In Singapore the project was funded by the National Science and Technology Board (1998-2001), while in Australia it was funded by the Australian Research Council (1999-2001).

The SIMRSN consists of five continuously operating reference stations (tracking satellites 24 hours a day), connected by high speed data lines to the MCS at NTU (Figure 1). 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. The SIMRSN also serves off-line non real-time users 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., 2002a; 2002b; 2002c).

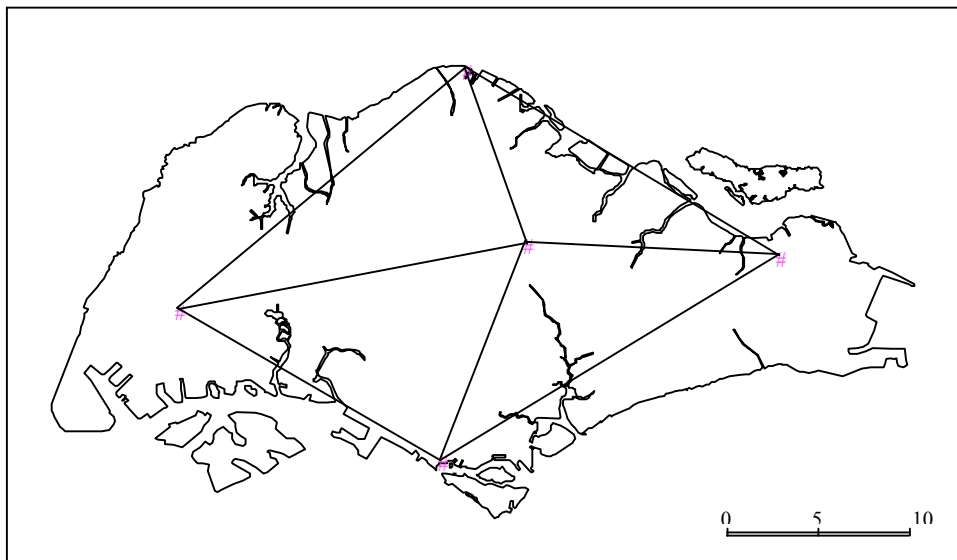


Figure 1. The Singapore Integrated Multiple Reference Station Network – supporting R&D into Network RTK and other network-based positioning concepts.

CONCLUDING REMARKS

Network RTK is best implemented by a service provider, an organisation that operates the receiver network infrastructure, the necessary data communication links and the MCS facility. This is a radically different scheme to the standard single base RTK where the GPS Surveyor owns and operates all of the equipment. At present there are very few continuously operating Network RTK systems. However, with the likely upgrade of CORS networks

around the world to offer RTK services over the next few years, the author believes that there will be a boom in Network RTK implementations.

There is currently only one commercial product, the Trimble VRS (Vollath et al., 2002), although the Leica company has also developed a Network RTK system (Euler et al., 2001). A number of test networks have been operating in Europe, the U.S., Australia, New Zealand, China and Japan. However, the world's only university-developed Network RTK system has been operating in Singapore for a number of years. Australian and Singaporean researchers have gained invaluable insight into the challenges of operating such an infrastructure on a '24/7' basis. It is intended to mirror this facility in Sydney during 2003, supporting independent research into Network RTK algorithms, products, operational issues, and business models, carried out outside North America, Europe and east Asia.

The 'roots' of Network RTK can be found in geodesy, surveying and precise navigation. Each sub-discipline can claim some credit for the development of the Network RTK concept. The author in this paper has emphasised the geodetic perspective, and shown how geodetic methodology and applications were a driver for multi-reference receiver techniques that ultimately led to the development of Network RTK. The paper has also highlighted the contributions of Australian and Singaporean researchers to the development and implementation of the data processing algorithms, and associated data management and communication systems, that underpin the first totally university-developed Network RTK service in the world.

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