Reference Station Network Based RTK Systems - Concepts and Progress

Rizos C
School of Surveying and Spatial Information Systems
The University of New South Wales, Sydney NSW 2052 AUSTRALIA
E-mail: c.rizos@unsw.edu.au

Han S
Thales Navigation
471 El Camino Real
Santa Clara, CA 95050, USA

BIOGRAPHY

Chris Rizos is a Professor at the School of Surveying & SIS, UNSW, and leader of the Satellite Navigation and Positioning (SNAP) Group, which specialises in addressing precise static and kinematic applications of GPS. He is secretary of Section 1 'Positioning' of the International Association of Geodesy (IAG).

Shaowei Han is Principal Scientist and managing a technical research group in Thales Navigation based in Santa Clara, California. Before he joined Thales Navigation, he was a Senior Lecturer in the School of Geomatic Engineering (now the School of Surveying & Spatial Information Systems), UNSW, Australia. His research interests are in GPS/GLONASS ambiguity resolution and error mitigation methods for carrier phase-based kinematic positioning over short-, medium-, and long-range, Network-RTK, GPS attitude determination and the integration of GPS, INS and Pseudolites. He is currently chair of the IAG Special Study Group 1.179 "Wide Area Modelling for Precise Satellite Positioning".

ABSTRACT

The limitation of single base "real-time kinematic" (RTK) techniques is the distance between base receiver and the rover receiver due to distance-dependent biases, namely orbit bias, ionosphere bias and troposphere bias. Techniques have been developed to overcome this distance dependence using a network of GPS reference stations spread over a wide geographic area. Because the measurement biases will be modelled and corrected for, the positioning accuracy will be almost independent of the inter-receiver distance. Since the mid-1990s investigators have been investigating the optimal means of processing reference receiver data, and then providing 'correction' information to users, in real-time. This technique is now generally referred to as Network-RTK. In 1993 the International Association of Geodesy (IAG) established a Special Study Group on "Wide Area Modelling for Precise Satellite Positioning". This paper focusses on the progress made during the last few years in designing Network-RTK architectures and the associated data processing algorithms and issues. Although many university investigators have been researching the fundamental challenges in functional and stochastic modelling, currently there is only one commercially available Network-RTK product, the Trimble VRS. However, with the use of the Internet as the primary data communication link, it is predicted that many more implementations of Network-RTK will come 'online', at various sites around the world, over the next few years.

0. INTRODUCTION

The standard mode of precise *differential* positioning is for one reference receiver to be located at a station whose coordinates are known, while the second receiver's coordinates are determined relative to this reference receiver. In addition, the second receiver may be static or moving, and carrier phase measurements must be used to assure high positioning accuracy. This is the basis for pseudo-range-based differential GPS (or DGPS for short) techniques. However, for high precision applications, the use of carrier phase data comes at a cost in terms of overall system complexity because the measurements are *ambiguous*, requiring that *ambiguity resolution* (AR) 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, through the use of "on-the-fly" (OTF) ambiguity resolution algorithms. 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 machine control, GPS-guided earthworks/excavations, automated haul truck operations, and other autonomous robotic navigation applications.

The limitation of the single base RTK is the distance between base receiver and the rover receiver due to distance-dependent biases, namely orbit bias, ionosphere bias and troposphere bias. Techniques have been developed to overcome this distance dependence whereby the resolving of the widelane integer ambiguities is attempted first, then using the ionosphere-free combination to resolve the integer ambiguity with wavelength 10.7cm (Blewitt, 1989; Dong & Bock, 1989). The performance cannot be as good as short-range-RTK, and furthermore cannot actually be used in practice, in real-time. On the other hand, Wide Area Differential GPS (WADGPS) and the Wide Area Augmentation System (WAAS) have been extensive investigated, but they are pseudo-range based systems intended to deliver accuracies at the one metre level. Both WADGPS or WAAS require a network of master and monitor-stations spread over a wide geographic area. Because the measurement biases will be modelled and corrected for, the positioning accuracy will be almost independent of the inter-receiver distance (or baseline length). Carrier phase observations in these systems will generally be used to smooth the pseudo-range data.

An OTF ambiguity resolution technique using multiple reference stations has been proposed in the mid-1990s, which reduces the distance-dependent biases for medium-range applications (see, e.g., Han & Rizos, 1996; Wübbena et al., 1996). The system mulitple reference stations setup and test results for RTK performance improvement was reported by several investigators, such as Han (1997) and Raquet (1998). A new package of hardware and software for GPS network-based reference station infrastructure known as the Virtual Reference Station (VRS) system was announced by Spectra Precision Terrasat in 2000 at the ION GPS'2000 conference in Salt Lake City (Vollath et al., 2000). Within the Subcommittee SC 104 of RTCM, a working group for the definition of multiple reference station-based RTK (referred to as simply as Network-RTK) was established with some proposals on the nature of the Network-RTK messages (Townsend et al., 2000; Euler et al., 2001; Trimble, 2002).

1. NETWORK RTK CONCEPT & CONFIGURATIONS

1.1 Network-RTK Concept

Network-RTK studies aim to develop a centimetre accuracy RTK system capable of operating over distances up to many tens of kilometres (the distance between a rover receiver and the closest reference station receiver) with equivalent performance to current single base RTK systems over distance up to 10km. The reference stations must be deployed in a dense enough pattern to model distance-dependent errors to such an accuracy so that residual errors can be ignored in the context of ambiguity resolution. The estimated distance between reference stations should be of the order of 50-100km, but is dependent on the geographic location of the network and the level of ionospheric activity (see Figure 1 for the Singapore multiple reference station network, where the inter-station distances due to the high ionospheric activity are all less than 40km!). In addition, the rover must operate within the region defined by the reference station network.

Network-RTK requires an ambiguity resolution 'engine' which will fix the integer ambiguities between the static multiple reference receivers, located at stations of known position, that make up the network. The 'engine' must be capable of handling double-differenced data from stations 50-100km apart, operate in in real-time, instantaneously for all satellites at elevation cutoff angles down to a couple degrees. The network-RTK correction messages can then be generated with sufficient accuracy, but only after ambiguities are fixed within the multiple reference station network. The utility of the Network-RTK messages are:

- Elimination of orbit bias and ionosphere delay.
- Reduction of troposphere, multipath and observation noise.

- RTK can be extended to medium-range (up 100km).
- Low-cost single-frequency receivers can be used for RTK and rapid static positioning at medium-range.
- Very high accuracy applications using low-cost GPS receivers. e.g. deformation monitor, geodetic control network, etc., is possible.
- Improve accuracy, reliability, integrity, productivity and capacity of GPS positioning.

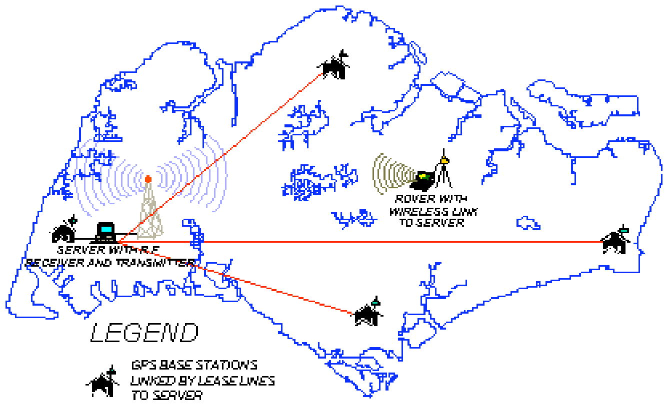

Figure 1. Concept of Network-RTK: the Singapore example (Hu et al., 2002)

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), precise/predicted International GPS Service (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.

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. These are briefly described below.

1.2 Virtual Reference Station

- At the MCS server, the VRS can be generated and the RTCM 20/21 message can be created for transmission once the server knows where the roving user is.
- There is no further request from the roving user side if the rover supports RTCM 20/21 format, except that the rover needs to send its location to the server.
- Two-way communication is required, with the rover telling the server where it is, and the server continuously sending data to the rover 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.

1.3 Correction Broadcasting

- At the MCS server, the corrections, e.g. dispersive and non-dispersive correction terms or carrier phase measurement residuals for each satellite at each reference stations, will be generated using data from the multiple reference station network.
- The corrections can be used to generate an interpolation model or the VRS at the rover 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 much 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++.

1.4 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. In other words, the server is largely redundant.
- Generate the VRS, or corrections, at the rover site. The computation load is therefore shifted to the user.
- This requires a new data format, and the transmission scheme is similar to architecture 1 (Section 1.2). Trimble has proposed this scheme for the Network-RTK RTCM format.
- One-way communication is sufficient.
- There is no limit on the number of users.
- The advantage is that the rover is completely independent of the reference station network provider.

2. NETWORK RTK OUTSTANDING ISSUES - CURRENT RESEARCH ACTIVITIES

2.1 Error Modelling Through Improvement to the Functional Models

Error modelling through the improvement of functional models for medium-range and long-range high precision satellite positioning using reference station networks includes the topics: multipath mitigation algorithms, troposphere model refinement, regional ionosphere modelling algorithms, and orbit bias modelling. These biases could be estimated individually through some special approaches, or by inserting different parameters into the functional model for the different error biases.

The absolute field calibration technique for GPS antennas has been developed, based on the controlled antenna motion with a robotic arm (Wübbena et al., 2000). This technique can be used to calibrate all antennas in a multiple reference station network. With absolutely calibrated antennas it is possible to separate phase centre variations and multipath. An approach for multipath calibration based on controlled antenna motion was proposed at Hanover University, Germany (Menge et al., 1999).

Investigating the use of semi-parametric least squares for the mitigation of systematic errors in GPS processing has been conducted at Curtin University of Technology, Australia (Jia, 2000). Current focus is on the lumping together of all systematic errors and representing them as a single smoothing function, estimated via semi-parametric least squares over the processing session. Initial results from a 'short' 30km baseline are encouraging.

An adaptive Finite-duration Impulse Response filter, based on a least-mean-squares algorithm, has been developed to derive a relatively noise-free time series from continuous GPS results at The University of New South Wales, Australia (Ge et al., 2000). This algorithm is suitable for real-time applications, and numerical simulation studies indicate that the adaptive filter is a powerful signal decomposer that can significantly mitigate multipath effects.

There have been many ionosphere studies over the last decade. Using ionospheric regional modelling to improvement on-the-fly ambiguity resolution for GPS positioning over long distances has been undertaken by the University of Laval and the University of New Brunswick, Canada, through the GEOIDE project (www.scg.ulaval.ca/gps-rs/) (Santerre et al., 2000; St-Pierre et al., 1999). The ionospheric tomography technique has also been used to help resolving GPS ambiguities on-the-fly at distances of hundreds of kilometres during increased geomagnetic activity (Colombo et al., 2000a). An approach, refer to the "grand solution", which estimates orbit, refraction, and local bias error states, along with the rover's trajectory, was proposed by Colombo et al. (2000b). The modelling and estimation of the tropospheric zenith delay both for more accurate real-time and post-processed navigation, and for rapid and precise meteorological updates have been implemented.

With regard to Real-Time Kinematic (RTK) positioning using multiple reference stations, a survey conducted by Dr. Euler, Chair of the RTCM SC104 working group "Network RTK", of the WG members found:

- The expected RTK accuracy could be between the sub-decimetre to centimetre level (one sigma).
- The reference station distances should be at spacings of the order of 50-70km for one centimetre accuracy (one sigma), or at 200km and above for one decimetre accuracy (one sigma).
- The size of the reference station area should be about 500km x 500km, however the goal could be nationwide to continentwide coverage.
- The medium for distribution of data could be uni-directional techniques (broadcast-like: UHF, VHF, TV, DARC, etc.), or bi-directional techniques (GSM, UTMS, etc.).
- The baud rates for transmission are from 2400 Baud upwards, including 1Hz observation data.

- The tolerated latency is up to 10 seconds without SA or up to 2 seconds with SA on. However, the orbit information can be delayed up to 120 seconds, ionosphere data up to 10 to 60 seconds, and troposphere data up to 30 seconds. The real-time positioning output is expected with less than 100 milliseconds delay.
- The requirement for reference station equipment is at least dual-frequency receivers, with open sky coverage.

Regarding GPS/Glonass surveying and navigation applications using multiple reference stations, a new method has been proposed by Dai et al. (2003a), in which the distance-dependent biases have been separated into the frequency-dependent errors (ionospheric bias) and frequency-independent errors (e.g. tropospheric bias and orbit bias). The separate estimates of the two types of errors, which are generated from the carrier phase measurements using the data from the reference station network, can be used to model the user distance-dependent biases for L1, L2 carrier phase and pseudo-range measurements in different ways.

2.2 Error Modelling Through Stochastic Model Refinement

High quality estimation results using least squares requires the correct selection of the functional and stochastic models. The stochastic model should represent the stochastic features of the modelling errors. It is dependent on the choice of observation functional model, hence for a different choice of functional model, a different stochastic model may be needed. For example, if the ionospheric delay is considered an unknown parameter in the functional model, the modelling errors will not include the residual (double-differenced) ionospheric bias, and hence they will more likely have random properties.

The SIGMA-□ model has been developed for stochastic modelling of GPS signal diffraction errors for high precision GPS surveys by the Technical University of Graz, Austria. The basic information used in the SIGMA-□ model is the measured carrier-to-noise power-density ratio (C/N0). Using the C/N0 data and a template technique, the proper variances are derived for all phase observations. Thus the quality of the measured phase is automatically assessed and if phase observations are suspected to be contaminated by diffraction effects they are down weighted in the least squares adjustment (Brunner et al., 1999). An extended weight model for GPS phase observation was presented by Wieser & Brunner (2000).

The mathematical and statistical modelling has also been investigated at University College London, UK. Using a multipath estimation method based on the signal-to-noise ratio and an elevation-dependent stochastic model, the height accuracy of a typical RTK session has been improved by 44% and the fidelity of quality measures has also been increased (Barnes et al., 1998).

A stochastic assessment procedure has been developed to take into account the heteroscedastic, space- and time-correlated error structure of the GPS measurements at The University of New South Wales, Australia (Wang et al., 2002). Test results indicate that by applying this stochastic assessment procedure, the reliability of the estimated positioning results is improved. In addition, the quality of ambiguity resolution can be more realistically evaluated.

Magellan's recent product Instant-RTK™ has been reported as having successfully overcome the functional and stochastic modelling challenges through empirical knowledge and real-time learning procedure, which can used to adapt the model to a changing environment (Han & Johnston, 2001).

On the other hand, stochastic modelling has been applied to the parameters in the functional model. For example, the residual ionospheric delay after applying the ionospheric delay corrections could be accounted for through processing the residual ionospheric delay correction as a stochastic observable. The stochastic model to be applied for the corrections should be generated by a reference station network. First results indeed show an enormous improvement to the success rate of ambiguity resolution (Odijk, 2000).

2.3 Ambiguity Fixing and Validation for Reference Station Networks

For medium-range multiple reference station networks, e.g. up to 100km inter-receiver distances, *instantaneous* ambiguity resolution in real-time is a challenge because of the distance-dependent errors. Instantaneous ambiguity resolution, or very short time-to-ambiguity-fix, is required because any delay to the ambiguity resolution will prevent the rover from using the corrections for RTK rover on-the-fly ambiguity resolution. Although the integer ambiguities within the multiple reference station network can be resolved at the beginning of their operation by using data collected over several hours, ambiguities have to be resolved again and again when any tracked satellite suffers from a cycle slip, or after the occurrence of a long data gap, or a new satellite rises. The main challenges for real-time reference network carrier phase data processing are:

- Repairing cycle slips in tracked satellites at the reference stations from the atmospheric delay information inferred from previous epochs. After applying this atmospheric delay estimate, the cycle slip(s) can be detected and repaired, and hence assisting in the process of resolving ambiguities in the reference receiver data.
- Prediction of ionospheric and tropospheric delays for existing satellites at the reference stations using prior measurements. In the case of a long data gap, the predicted atmospheric delay can be used to aid the resolution of the integer ambiguities.
- Prediction of the tropospheric delay for a newly-risen satellite at the reference stations using a model derived from data to other tracked satellites. The estimation of the tropospheric delay for a newly-risen satellite can aid the fixing of the integer ambiguity associated with this new satellite.

Some atmospheric bias prediction algorithms for real-time ambiguity resolution in GPS/Glonass reference stations networks were proposed by Chen et al. (2001) and Dai et al. (2003a).

2.4 VRS or Correction Generation

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 et al., 1997; 1998), the Linear Interpolation Method (Wanniger, 1995; Wübbena et al., 1996), the Low-Order Surface Model (Wübbena et al., 1996; Fotopoulos & Cannon, 2000), and the Least Squares Collocation Method (Raquet, 1997; Marel, 1998).

The Linear Combination Model is formed from the single-differenced functional equation for baselines from the user receiver to two or more reference stations(Han & Rizos, 1996; Han, 1997). The advantage of this model is the elimination of the orbit bias. The residual ionospheric delay and the tropospheric delay can also be reduced to the same degree that the epoch-by-epoch and satellite-by-satellite ionosphere and the troposphere models are able to. Multipath and measurement noises can be reduced if the user receiver is located within the network of reference stations.

A distance-based linear interpolation algorithm for ionospheric correction estimation has been suggested by Gao et al. (1997). In order to improve interpolation accuracy, two modifications were made by Gao & Li (1998). The first modification is to replace the ground distance with a distance defined on a single-layer ionospheric shell at an altitude of 350km. The second modification is to extend the model to take into account the spatial correction with respect to the elevation angle of the ionospheric delay paths on the ionospheric shell. Although this method was originally proposed by Gao et al. (1997) to interpolate residual ionospheric biases, it can also, to a certain degree, mitigate other distance-dependent biases such as tropospheric bias and orbit errors.

The Linear Interpolation Method (LIM) was first proposed by Wanninger (1995) for a regional differential ionospheric model derived from dual-frequency phase data from at least three GPS monitor stations surrounding a user station. Unambiguous double-differenced ionospheric biases can be obtained on a satellite-by-satellite and epoch-by-epoch basis after ambiguities in the reference station network have been fixed to their correct integer values. Ionospheric corrections for any station in the area can be interpolated by using the known coordinates of the reference stations and approximate coordinates of the station(s) of interest. Wübbena et al. (1996) extended this method to model the distance-dependent biases such as the residual ionospheric and tropospheric biases, and the orbit errors. Similar methods have been proposed by Wanninger (1999), Schaer (1999), Chen et al. (2000), Vollath et al. (2000), and others. The advantage of this method for real-time implementation is that the implementation is easier because only two coefficients for each satellite pair are required for transmission to the user.

The distance-dependent biases exhibit a high degree of spatial correlation across a reference station network. Low-order surfaces can be used to 'fit' the distance-dependent biases (Wübbena et al., 1996; Fotopoulos, 2000). The fitted surfaces are known as trend or regression surfaces, and they model the major trend of the distance-dependent biases. The coefficients of the low-order surfaces can be estimated via a least squares adjustment using data from the reference station network. The variables of the fitting function could be two (i.e. the horizontal coordinates), or three (horizontal coordinates and height). The fitting orders could be one, two or higher. For this method, the required number of reference stations depends on the fitting variable and the fitting order. In general, the minimum number of reference stations is four if the plane-fitting function is used. It is obvious that the Linear Interpolation Method is a special case of the plane-fitting function.

Least Squares Collocation has been used for many years to interpolate gravity at any given location using only measurements at some discrete locations. It was proposed for interpolating the distance-dependent biases in a network by Raquet (1997). This method explicitly attempts to minimise the differenced phase-code biases between any reference station receiver and the user receiver. Note that the accuracy of the Least Squares Collocation Method is dependent upon the accuracy of the covariance matrix (Raquet, 1998). In practice it is very difficult to calculate precise covariance matrices.

The theoretical and numerical comparison of the various interpolation algorithms has been made by Dai et al. (2003b). 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.

2.5 Data Communications

In general, the data communication options appropriate for Network-RTK are:

- The Internet connection is currently the primary option for Network-RTK product development.
- GSM data link, with the possibility of updating to a GPRS data link, is another option.
- Dial-up data link using modem.
- VSAT data link option (Jackson et al., 2002).

Communication between reference stations involves a variety of communication mediums and issues which are beyond the scope of this paper. Typical requirements and issues include:

- Leased modem lines
- Multiplexed modem lines
- Dealing with large modem-pools
- Frame relays
- ISDN lines
- VSAT (Point-to-Point satellite data link, one-way or two-ways)
- UHF/VHF
- any combination of the above

Data communication between users and the master control station (or server) must deal with the following issues (not an exhaustive list!):

- Must support both real-time and post-processing
- Data link requirements:
  - Modem pool
  - GPRS
  - Long-range UHF/VHF radio
  - Internet
  - Satellite broadcast (e.g. Genesis)
  - a combination of the above
- Web-interface for FTP, data download, system maintenance and billing

2.6 On-The-Fly RTK Techniques

GPS ambiguity resolution techniques have been intensively investigated since the 1980s. The integer ambiguity searching techniques has been improved dramatically over the last decade, especially through the now almost universal use of the LAMBDA method (Teunissen et al., 1995). However, it has to be recognised that the different search algorithms are generating identical integer ambiguity candidates under comparable setups, such as search windows/volumes and similar parameters (Euler & Ziegler, 2000). Research is now focussed on the role and techniques of ambiguity resolution in integrated systems of GPS, Glonass, pseudolite or GNSS signals, and the more efficient validation criteria to make sure the integer ambiguities correctly identified.

Magellan's new product Instant-RTK™ claims that it has successfully overcome the functional and stochastic modelling issues through an empirical knowledge and real-time learning procedure which can adapt to a changing environment (Han & Johnston, 2001). A series of validation criteria have been implemented, in addition to the commonly used ratio test, which are adaptative in that they are sensitive to the reliability, number of satellites, observation time and baseline length. The Instant-RTK validation criteria have successfully traded off the requirement of very short observation span and the requirement for RTK solution reliability. Moreover, the algorithm to detect, identify and adapt the outliers to guard against wrong integer ambiguity determination has been implemented, and the success rate of ambiguity resolution has been increased significantly.

Leica Geosystems' System 500 implemented a repeated search processing technique to shorten ambiguity initialisation time and to improve ambiguity resolution reliability, especially in difficult environments. This method repeats its internal determination of the integer ambiguity in real-time systems using significant shorter observation sessions. Once the two solutions are identical, the system can output its coordinates to the user. It is claimed that the system reveals in a much shorter time when it has accepted a wrong set of integers, and because two independent searches deliver identical integer ambiguity sets, boosts the reliability of the real-time system (Euler & Ziegler, 2000).

On the theoretical side, a method was proposed to evaluate the probabilities of correct integer estimation based on the variance matrix of the (real-valued) least squares ambiguities (Teunissen et al., 1999). These success rates are given for the ambiguity estimator that follows from integer 'bootstrapping'. Although less optimal than integer least squares, integer bootstrapping provides useful and easy-to-compute approximations to the integer least squares solution. In a similar manner, the bootstrapped success rates provide bounds for the probability of correct integer least squares estimation.

3. CONCLUDING REMARKS

The second author (SH) is chair of the International Assocation of Geodesy's Special Study Group 1.179 "Wide Area Modelling for Precise Satellite Positioning", and has been monitoring progress in this area. This paper has focussed on the progress made in designing Network-RTK architectures and the associated data processing algorithms and issues. Reports on the results obtained by specific multi-receiver networks have not been included, but can be found in the scientific literature.

Currently there is only one commercially available Network-RTK product, the Trimble VRS. This has been undergoing testing in several parts of the world, and commercial Network-RTK services are currently on offer to users. However, since the mid-1990s many university investigators have been researching the fundamental challenges in functional and stochastic modelling. This research has been coupled to that undertaken in ambiguity resolution in general (whose aim has been to reduce the time taken to resolve ambiguities on-the-fly, without sacrificing reliability), leading to many test implementations of high precision multiple reference station techniques. However, due to the complexity (and cost) involved in establishing fully functioning reference receiver networks, the data links and the data processing/management server at the master control station, comparatively few university-based Network-RTK systems have been established. With the use of the Internet as the primary data communication link, it is expected that many more real-time implementations of Network-RTK will come 'online', at various sites around the world, over the next few years.

References

Barnes J.B., N. Ackroyd & P.A. Cross (1998). Stochastic modelling for very high precision real-time kinematic GPS in an engineering environment, in vol. XXI Congress of the International Federation of Surveyors, 6 (ISBN 0-85406-902-X), 61-76.

Blewitt G. (1989). Carrier phase ambiguity resolution for the Global Positioning System applied to geodetic baselines up to 2000km, *Journal of Geophysical Research*, 94(B8), 10187-10203.

Brunner F. K., H. Hartinger & L. Troyer (1999). GPS signal diffraction modelling: The stochastic SIGMA-Δ model, *Journal of Geodesy*, 73, 259-267.

Chen H.Y., C. Rizos & S. Han (2001). From simulation to implementation: Low-cost densification of permanent GPS networks in support of geodetic applications, *Journal of Geodesy*, 75(9-10), 515-526.

Chen X., S. Han, C. Rizos & P.C. Goh (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.

Colombo O.L., M. Hernandez-Pajares, J.M. Juan & J. Sanz (2000a). Ionospheric tomography helps resolve GPS ambiguities on the fly at distances of hundreds of kilometers during increased geomagnetic activity, proceedings of the IEEE PLANS 2000, San Diego, California, March 2000.

Colombo O.L., A.G. Evans, M. I. Vigo, J.J. Benjamin & J.M. Ferrandiz (2000b). Long-baseline (> 1000 km), sub-decimeter kinematic positioning of buoys at sea, with potential application to deep-sea studies, 13th Int. Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation, Salt Lake City, Utah, 19-22 September, 1476-1484.

Dong D.N. & Y. Bock (1989). Global Positioning System network analysis with phase ambiguity resolution applied to crustal deformation studies in California, *Journal of Geophysical Research*, 94(B4), 3949-3966.

Dai L., J. Wang, C. Rizos & S. Han (2003a). Predicting atmospheric biases for real-time ambiguity resolution in GPS/Glonass reference stations networks, accepted by *Journal of Geodesy*.

Dai L., S. Han, J. Wang & C. Rizos (2003b). Comparison of interpolation algorithms in network-based GPS techniques, submitted to *Journal of Navigation*.

Euler H.-J., C.R. Keenan, B.E. Zebhauser & G. Wübbena (2001). Study of a simplified approach in utilizing information from permanent reference station arrays, 14th Int. Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation, Salt Lake City, Utah, 11-14 September, 379-391.

Euler H.-J. & C. Ziegler (2000). Advances in ambiguity resolution for surveying type applications, 13th Int. Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation, Salt Lake City, Utah, 19-22 September, 95-103.

Fotopoulos G. (2000). Parameterization of carrier phase corrections based on a regional network of reference stations, 13th Int. Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation, Salt Lake City, Utah, 19-22 September, 1091-1102.

Fotopoulos G. & M.E. Cannon (2001). An overview of multi-reference station methods for cm-level positioning, *GPS Solutions*, 4(3), 1-10.

Gao Y., Z. Li & J.F. McLellan (1997). Carrier phase based regional area differential GPS for decimeter-level positioning and navigation, 10th Int. Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation, Kansas City, Missouri, 16-19 September, 1305-1313.

Gao Y. & Z. Li. (1998). Ionosphere effect and modelling for regional area differential GPS network, 11th Int. Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation, Nashville, Tennessee, 15-18 September, 91-97.

Ge L., S. Han & C. Rizos (2000). Multipath mitigation using an adaptive filter. *GPS Solutions*, 4(2), 19-30.

Han S. (1997). *Carrier Phase-Based Long-Range GPS Kinematic Positioning*, UNISURV S-49, School of Geomatic Engineering, The University of New South Wales, Sydney, Australia, 185pp, ISBN 0 85839 074 4.

Han S. & C. Rizos (1996). GPS network design and error mitigation for real-time continuous array monitoring systems, 9th Int. Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation, Kansas City, Missouri, 17-20 September, 1827-1836.

Han S. & R. Johnson (2001). Survey quality real-time GPS: Solving the time to fix vs. reliability paradox, 14th Int. Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation, Salt Lake City, Utah, 11-14 September, 1550-1557.

Hu G., H.S. Khoo, P.C. Goh & C.L. Law (2002). Testing of Singapore Integrated Multiple Reference Station Network (SIMRSN) for precise fast static positioning, European GNSS Conf. GNSS2002, Copenhagen, Denmark, 27-30 May, CD-ROM proc.

Jackson M. E., C. Meertens, O. Ruud, S. Reeder & W. Gallaher (2002). Real-time GPS data transmission using VSAT technology, *GPS Solutions*, 5(4), 10-19.

Jia M. (2000). Mitigation of systematic errors of GPS positioning using vector semiparametric models, 13th Int. Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation, Salt Lake City, Utah, 19-22 September, 1938-1947.

Marel H. van der (1998), Virtual GPS reference stations in The Netherlands, 11th Int. Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation, Nashville, Tennessee, 15-18 September, 49-58.

Menge F., V. Böder, G. Seeber, G. Wübbena & M. Schmitz (1999). Variability of GPS errors on-site - Investigations of antenna PCV and multipath towards a station calibration, International Union of Geodesy and Geophysics, IUGG99, July 19-30, Birmingham, UK, 1999.

Odijk D. (2000). Weighting ionospheric corrections to improve fast GPS positioning over medium distances, 13th Int. Tech. Meeting of the Satellite Div. of the Institute of Navigation, Salt Lake City, Utah, 19-22 September, 1113-1123.

Raquet J.F. (1998). *Development Of A Method For Kinematic GPS Carrier-Phase Ambiguity Resolution Using Multiple Reference Receivers*, PhD Thesis, Dept. of Geomatics Engineering, University of Calgary, Canada.

Raquet J.F., G. Lachapelle & L. Fortes (1998). Use of a covariance analysis technique for predicting performance of regional area differential code and carrier-phase networks, 11th Int. Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation, Nashville, Tennessee, 15-18 September, 1345-1354.

Santerre R., R.B. Langley, M. Ueno, A. Biron, K. Donghyun, D. Parrot, C. St-Pierre, P. Tétreault, G. Marceau & D. Langelier (2000). Improvement of kinematic OTF-GPS positioning over long distances: Applications to bathymetric surveys, Canadian Hydrographic Conference 2000, Montréal, Canada, 15-19 May (CD-Rom Proceedings).

Schaer S., G. Beutler, M. Rothacher, E. Brockmann, A. Wiget & U. Wild (1999). The impact of the atmosphere and other systematic errors on permanent GPS networks, Presented at the IAG Symposium on Positioning, Birmingham, UK, 21 July.

St-Pierre C., R. Santerre & D. Parrot (1999). "mprovement of OTF-kinematic GPS positioning over long distances using ionospheric regional modelling, *Geomatica,* Journal of the Canadian Institute of Geomatics, 53(4), 395-403.

Teunissen P.J.G., P.J. de Jonge & C.C.J.M. Tiberius (1995). A new way to fix carrier-phase ambiguities, *GPS World*, April 1995 issue, 58-61.

Teunissen P.J.G., P. Joosten & D. Odijk (1999). The reliability of GPS ambiguity resolution, *GPS Solutions*, 2(3), 63-69.

Townsend B., A.J. VanDierendonck, J Neumann, I. Petrovski, S. Kawaguchi & H. Torimoto (2000). A proposal for standardized network RTK messages, 13th Int. Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation, Salt Lake City, Utah, 19-22 September, 1871-1878.

Trimble (2002). Network RTK Format Proposal for RTCM-SC104 Version 3.0, RTCM paper 066-2002-SC104-281.

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

Wanninger L. (1995). Improved ambiguity resolution by regional differential modelling of the ionosphere, 8th Int. Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation, San Diego, California, 12-15 September, 55-62.

Wanninger L. (1999). The performance of virtual reference stations in active geodetic GPS-networks under solar maximum conditions, 12th Int. Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation, Nashville, Tennessee, 14-17 September, 1419-1427.

Wang J., C. Satirapod & C. Rizos (2002). Stochastic assessment of GPS carrier phase measurements for precise static relative positioning, *Journal of Geodesy*, 76(2), 95-104.

Wieser A & F.K. Brunner (2000). An extended weight model for GPS phase observations, *Earth, Planets & Space*, 52, 777-782.

Wübbena G., A. Bagge, G. Seeber, V. Böder & P. Hankemeier (1996). Reducing distance dependent errors for real-time precise DGPS applications by establishing reference station networks, 9th Int. Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation, Kansas City, Missouri, 17-20 September, 1845-1852.

Wübbena G., M. Schmitz, F. Menge, V. Böder & G. Seeber (2000). Automated absolute field calibration of GPS antennas in real-time, 13th Int. Tech. Meeting of the Satellite Div. of the Institute of Navigation, Salt Lake City, Utah, 19-22 September, 2512-2522.