Development of Satellite Based Positioning and Navigation Facilities for Precise ITS Applications

X. Meng, L. Yang, J. Aponte, C. Hill, T. Moore and A. H. Dodson

Abstract—**Recent advance in network reference based real-time kinematic GPS (NRTK GPS) positioning makes it possible to track moving objects up to centimeter accuracy. This capacity will undoubtedly help implement many new applications for future ITS services, for instance, precise navigation, autonomous driving, lane based traffic or fleet management, lane based road use charging, and law enforcement. To support these activities, a testbed network of GPS reference stations has been established jointly by the authors institute and Leica Geosystems (UK) in the past three years. This testbed NRTK facility covers an area of about 20,000 km^2 in the central region of the United Kingdom. Real-time raw GPS measurements are streamed to a data server situated in the University of Nottingham via broadband connections. Real-time corrections that are used to compensate spatially correlated errors and biases between the reference station network and user terminals are generated by the data server and sent to those authorized user terminal receivers wirelessly for delivering real-time position solutions of centimeter accuracy. Trials have been carried out recently on a variety of different classes of UK roads to test the delay and completeness of the NRTK corrections, wireless connection and coverage, positioning accuracy, etc, aiming at the evaluation of the feasibility of NRTK GPS positioning for rapid roadway geometry data acquisition and the exploitation of this latest technology for ITS related applications and services. This paper presents the recent work and findings of the authors and the preliminary conclusions are drawn from field trials. It also addresses the issues that hamper the development of NRTK GPS positioning, especially its wider adoption for ITS community.**

I. Introduction

In recent years, facilities for supporting network based real-time kinematic GPS positioning and navigation have been established around the world and some of the networks cover very broad areas, even at a continent level [1-3]. Most of these facilities are originated from the Continuously Operating Reference Systems (CORS) that are used for geo-hazard monitoring, surveying and mapping purposes and gradually upgraded to be able to compute and deliver high accuracy and rate RTK corrections [3, 4]. These facilities have many incomparable advantages over traditional single GPS reference station based real-time kinematic GPS positioning. Since positioning and navigation, especially satellite based positioning, is regarded as one of the key enabling technologies, along with telecommunications, network computing and geospatial databases, in the development of ITS applications, these facilities are particularly useful for land transport applications due to its much improved positioning accuracy, flexibility, mobility, reliability and significantly reduced positioning cost. These facilities will provide an opportunity to explore many new land transport applications, for instance precise navigation for free parking space guidance in large car parks, traffic management for road user charging purpose, and most importantly, these facilities will support fast and accurate establishment of detailed road network and road surface condition databases down to lane level which is a current bottleneck for these applications due to inadequate accuracy and coverage of national or continental level geo-spatial databases (digital maps). This will pave the way for the research and practice of fully autonomous driving [5]. Future Global Navigation Satellite Systems (GNSS, a generic name for GPS, GLONASS, Galileo, COMPASS and other regional navigational augmentation satellite systems) will be dramatically enhanced with space- or terrestrial-borne augmentation systems and make ubiquitous positioning possible [6, 7].

This paper starts with a brief introduction to the fundamentals of network RTK GNSS positioning and available NRTK GNSS services in the UK which include Ordnance Survey's OSNet™ and a testbed facility that was jointly developed by the University of Nottingham and Leica Geosystems (UK). Road data acquisition trials were carried out with the correction data provided by both facilities. Results are analyzed; the statistical parameters are extracted from the sample data sets in terms of NRTK GNSS positioning accuracy, correction availability and delay; and wireless connection are investigated to quantify the overall performance of NRTK GNSS positioning for ITS applications. Existing issues with NRTK GNSS positioning

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for ITS applications, for example degraded positioning accuracy and discontinuity caused by NRTK facilities, wireless communications and satellite blockage, are discussed in the paper and relevant solutions are presented. Preliminary conclusions from these trials are drawn that are included in the end of this paper.

II. Network Real-time Kinematic GNSS Positioning and NRTK GNSS Facilities in the UK

A. *Fundamentals of NRTK GNSS Positioning*

For obtaining three dimensional (3D) positioning accuracy of a few centimeters using GNSS technology, more precise carrier phase measurements have to be collected with geodetic GNSS receivers (rovers) and at least one reference GNSS receiver that is closely (less than 20km) set up to the rovers on a precise surveyed benchmark is required to collect phase measurements simultaneously. The reference station is used to estimate those common errors and biases between the reference and rover stations. Usually the data sets are post-processed to obtain 3D coordinate time series that are ultimately referred to a local reference datum. When a data communication link is established, these estimated error and bias elements and raw measurements are transferred from the reference station to the rover receivers in real time. Centimetric real-time positioning is then achievable for a constrained area, for instance, in an area where the separation of the reference receiver and a rover is less then 20 km. This configuration has posed a particular limitation for ITS applications, where positioning continuity, mobility, flexibility and accuracy have to be maintained. More details about RTK GNSS positioning can be found from [7].

NRTK GPS was introduced in the late 1990s, aiming at overcoming the shortcomings of traditional RTK GPS positioning as above mentioned [6, 8]. Through the use of regionally covered reference network stations, spatially correlated errors due to troposphere, ionosphere, and satellite orbit biases are significantly removed from integrated data processing.

A network RTK facility usually consists of three basic elements as shown in Fig. 1, i.e. a network of reference stations with a reasonable separation between 80~100 km (left part in Fig. 1), a Central Processing Facility (CPF, boxed part), and the end user groups (right part). The reference stations that cover a region are connected to the CPF via broadband connections and once having received the raw measurements, a dedicated network processing software suite in the CPF can start integrated processing of these raw measurements to obtain network corrections or error elements in real time. The authorized users are then able to access these real-time corrections through wireless communications for conducting real time positioning [9].

B. *The UK and Nottingham/Leica NRTK GNSS Facilities*

Ordnance Survey (OS) is Great Britain's national mapping agency and providing the most accurate and up-to-date geographical data is one of its major tasks. For supporting

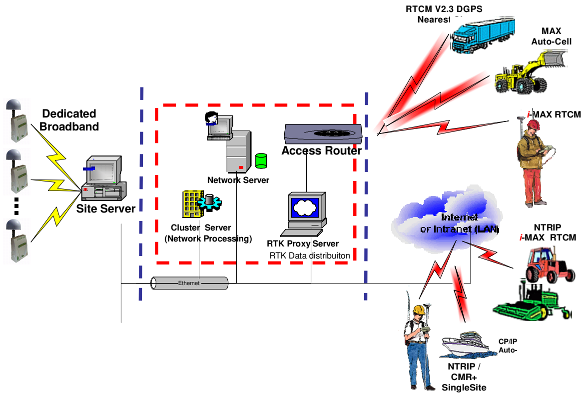

Fig. 1. Schematic of the Fundamentals of Network RTK GNSS (modified from Leica training material [14]).

these activities, OS has established the OSNet™ which consists of more than 140 permanent reference stations that cover the whole country as shown in Fig. 2. OS has two commercial partners at the moment: Leica Geosystems (UK) (with its service branded as SmartNet) and Trimble (with its service as VRS Now). OSNet™ has been fully operational since 2006 and can provide real-time and post-processing correction services to their customers.

Fig. 2. UK network reference stations (cited from: smartnet.leica-geosystems.co.uk).

Jointly with Leica Geosystems (UK), a world leading GPS manufacturer, the Institute of Engineering Surveying and Space Geodesy (IESSG) in the University of Nottingham had started to establish its own independent testing network in 2005, mainly for research purposes. The final network will consist of 16 high grade geodetic GNSS receivers and cover an area of ~20,000 km^2 in the Midlands region in the UK as boxed in Fig. 2. Up to the writing of this paper, there are 14 operational stations in this network and other two stations will be installed by the end of 2008. This network is widely used for testing new positioning and navigation algorithms and devices, and providing a support to several awarded Galileo projects [10, 11]. Leica network processing software suite SpiderNet is adopted as the core of the CPF. The current users include staff and students of the IESSG. For the road tests carried out by the authors both abovementioned facilities were utilized and the authors do not intend to distinguish them since there is virtually no difference for this usage.

III. Road Tests with NRTK GNSS Positioning

A. *Instrumentation*

A simple probe car was used in the road geometry acquisition. This car was equipped with one GNSS antenna that was installed on the car roof using a magnetic mount and two GNSS receivers shared the antenna with a signal splitter as shown in Fig. 3. Each of the receivers has a built-in mobile modem which is used to access real-time network RTK GNSS corrections wirelessly. Both the raw GNSS measurements and real-time positioning information, such as 3D coordinate time series, number of satellites tracked, types of positioning solutions, etc. were logged into the receivers' internal memory cards which has a capacity of at least 1 Gb. Data collections were carried out when the probe car was driven at a normal speed on different road types close to Nottingham and when it was on the motorway only the outside lane was occupied to avoid the signal obstruction by the passing lorries. The other benefit for this one lane driving arrangement is the possibility to draw out the precise boundaries of motorway and when the images from CCD camera array are available from a future probe car it is also possible to obtain both the exact locations of each lane and relevant information about the surface

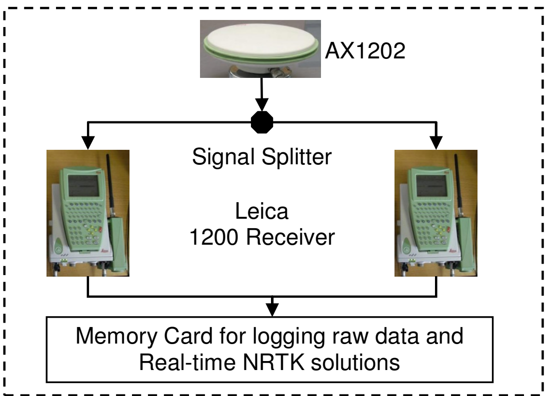

Fig. 3. A configuration for roadway data acquisition.

conditions and roadside inventories.

With a similar instrumentation as illustrated in Fig. 3 road geometry data for the major trunk roads in the Midlands area have been collected as shown in Fig. 4 and the total mileage have reached about 853 km through only a couple of hours driving, demonstrating high efficiency of this approach for precise highway geometry acquisition. However, we do need to analyze how good the data quality is and how to maintain the quality for ITS applications

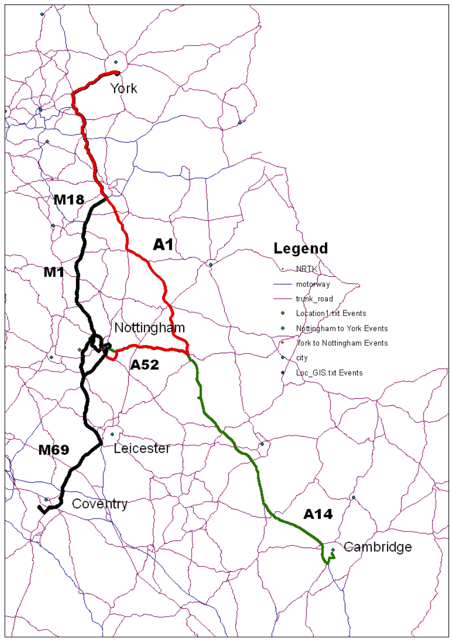

Fig. 4. Roads chosen for the data acquisition trials in the Midlands region in the UK.

B. *Data Processing and Analysis*

The raw measurements that were logged with the internal memory cards of the rover receivers were post-processed using data sets that were simultaneously collected by the reference stations in the vicinity of these testing road sections and the 3D coordinate time series in WGS84, a global reference system for displaying the locations that are determined with GNSS positioning, are converted to the 3D coordinate time series referred to a local coordinate system such as OSGB36, the UK national datum. The real-time coordinate streams generated by the rover receivers during the data collection were also converted into the local coordination system. Using the instrument configuration as discussed in the above section, total four coordinate time series can be obtained: two real-time coordinate time series and two post-processed ones. Through the comparison of these four coordinate time series, the quality parameters for NRTK GNSS positioning such as correction transmission delay and loss, wireless connectivity, positioning accuracy, GNSS signal blockage, overall system reliability, flexibility etc. can be extracted. The usages of these coordinate data sets are enormous. For instance, the horizontal coordinate time series can be used to compute the discrete locations of the lane occupied, lateral and longitudinal accelerations/decelerations and instant travel velocity of the probe car, which is a good representative for the road congestion and for estimation of CO_2 emission. The vertical coordinate component can be used to estimate the roughness of road surface condition through the computation of instant vertical velocity, acceleration and spectrum. Comparing with other sensing technologies, a great advantage of this computation is that through differencing the consecutive coordinates the contaminating noise elements, for example multipath due to the signal reflection by the pass vehicles and roadside inventories, can be virtually removed [12]. All the horizontal and vertical velocities and accelerations are the basic parameters for the evaluation of the degree of road section congestion, pollutant emission, driver's behavior, pavement condition, etc, very useful by-products along provision of precise road geometries and road profile maps.

C. A Case Study

A recent trial was carried out on 20th May 2008 with the instrumentation as described in Fig. 3. The trial started from the IESSG building and covered a section of M1, a major motorway in the UK, from Junction 23 to Junction 25 and trunk road A52. On M1, two runs of driving on the same outside lanes in both directions were made. Fig. 5 shows a trajectory of the probe car when it passed Junction 25. It can be easily seen that the trajectory was broken when the car entered the road sections underneath a flyover bridge. In the data acquisition, the GPS satellite cutoff angle was set as 10 degrees and the sampling rate was 1 Hz. The total test duration is 1:20:12 (hh:mm:ss) for one receiver and 1:20:17 for another one. Statistics were made to count the total numbers of the positioning solutions in each category, for example, the numbers of missing positions due to a complete GNSS signal blockage, standalone solution caused by the lack of NRTK corrections due to breakage in mobile link, DGPS solutions due to unfixed integer ambiguities, and NRTK GNSS solutions with 3D accuracy of a few centimeters. These statistical parameters are summarized in Table I. GPS signal blockage by the flyover bridges on M1 posed position continuity problem. To solve this problem, research by the authors is currently underway through integrating NRTK GNSS positioning with other sensor systems such as inertial navigation system (INS) or dead reckoning (DR).

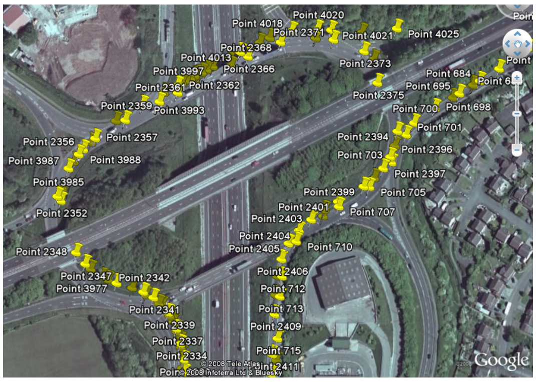

Fig. 5. Trajectories of the probe car on the Junction 25 of M1.

With a sampling rate of 1 Hz, instant speed was estimated. Since the sampling rate of this GPS positioning can be set up to 20 Hz, more detailed and accurate speed and road geometry information are able to be recovered. Fig. 6 shows instant travel speed estimates on the testing route using the horizontal coordinates.

TABLE I
POSITIONING SOLUTION STATISTICS

	Receiver I		Receiver II	
Positioning Category	No. of Samples	% of Total Samples	No. of Samples	% of Total Samples
Missing GPS measurements	736	15.3	1844	38.3
Standalone	154	3.2	390	8.1
DGPS	1693	35.2	1161	24.1
NRTK	2227	46.3	1422	29.5

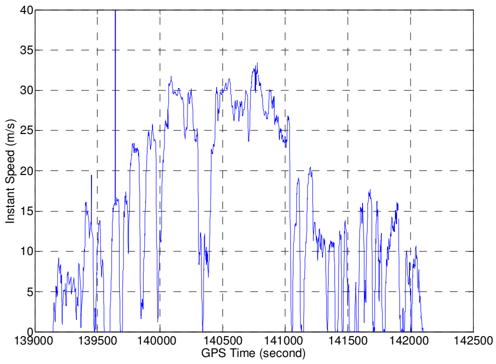

Fig. 6. Instant horizontal road section speed.

IV. ISSUES RELATED TO NRTK GNSS POSITIONING

There are many issues for NRTK GNSS positioning that need to be further addressed. Quality assurance perhaps is one of the major research topics within the NRTK GNSS positioning. Since NRTK corrections are transmitted via wireless link, emphasis has also been made to study the signal transmission delay and loss and their impact on the positioning accuracy [13].

A. NRTK GNSS correction transmission methods, delay and loss

A wireless transmission channel forms a crucial component of a NRTK application. In an NRTK GNSS facility, the data server collects the raw observations from a number of reference stations and sends corrections wirelessly to a rover positioning terminal after carrying out an integrated processing. The rover combines its local carrier phase observations with the real-time corrections from the reference stations to output position solutions at the centimeter-level. There are several available transmission methods which can be utilized for NRTK GNSS positioning. Table II includes the comparison of the major features of the different RTK data dissemination methods and it can be concluded that only mobile network and satellite communication can be used in the ITS applications. Comparing these two methods, the mobile network solution is more economic and practical at the current stage. Among the various mobile networks in today's market, the GPRS (EDGE) or 3G mobile network are the best options and the latter has a further advantage in the bandwidth and service reliability.

Due to the rapid change of the atmospheric conditions and also the GNSS satellite geometry, these correction messages from the data server have a time-limited validity. The delay and loss of corrections during the transmission procedure are two of the major affecting factors to the quality of NRTK GPS solutions. To study their impacts, parallel tests were conducted using the setting as shown in Fig. 7 in a research lab within the IESSG. The tests were carried out in a static NRTK mode with a GNSS antenna fixed on a precisely measured point to minimize the influence from irrelevant factors.

TABLE II
COMPARISON OF DIFFERENT CORRECTION DISSEMINATION APPROACHES

Type of Comm.	Radio	Mobile	Satellite	Wireless
Range	short	large	large	very short
Coverage	line of sight	nearly full	full	limited
Bandwidth	enough	enough/ limited	limited	enough
Supporting Internet	no	yes	yes	yes
Service charge	no	medium	high	cheap
Licensing	required	no	no	no
reliability	dedicated	not guaranteed	guaranteed	depend on hot-spots quality

An NRTK solution through using the correction messages that were acquired from the data server via a local Ethernet connection was adopted as a benchmark solution, whilst the rover receiver was placed close to the data server to simulate an ideal signal transmission scenario. Three parallel solutions were compared with this benchmark solution during the same time period. They had the same configurations as the benchmark one except for adopting different correction transmission methods which were, a) via a GPRS wireless link, b) via a long distance public Internet link and c) via a combination of both. The last one represents a typical commercial NRTK correction transmission scenario.

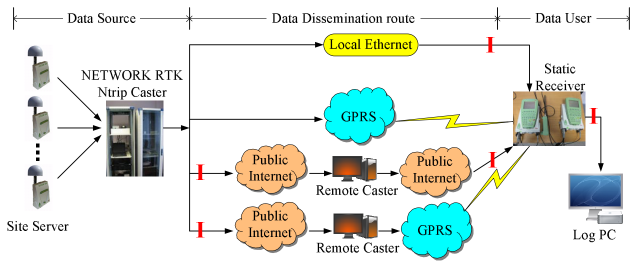

Fig. 7. Experimental plan for evaluating correction delay and loss (Ntrip: a dedicated protocol for transmitting geodetic data over the Internet).

Tables III, IV and V give a brief summary of the testing results. It is shown that, on average the correction messages may be delayed up to 0.85 seconds and 20% of the corrections may be lost during the transmission. It can be found from these tables that with the above instrument and connection settings and under a static surveying mode the 3D positioning accuracy with NRTK GNSS positioning is better than 2 cm at a confidence level of 99%. This demonstrates that correction delay and loss did not cause major positioning quality degradation.

TABLE III
STATISTICS OF MESSAGE DELAY AND MISSING

	Message Delay		Message Loss
	Average (s)	Std (s)	
Benchmark	0	0.03	0%
GPRS	0.44	0.24	1.1%
Long Distance	0.43	0.34	12.4%
GPRS +Long Distance	0.85	0.45	20.6%

TABLE IV
STATISTICS OF HORIZONTAL ERRORS

	<0.5cm	0.5~1 cm	>1 cm	Std (cm)
Benchmark	89.4%	10.6%	0.0%	0.15
GPRS	80.9%	18.6%	0.5%	0.18
Long Distance	70.5%	27.1%	2.4%	0.24
GPRS + Long Distance	68.2%	29.3%	2.6%	0.25

TABLE V
STATISTICS OF VERTICAL ERRORS

	<1 cm	1~2 cm	>2 cm	Std (cm)
Benchmark	97.0%	2.3%	0.0%	0.45
GPRS	87.7%	11.9%	0.4%	0.64
Long Distance	83.8%	15.5%	0.7%	0.69
GPRS + Long Distance	82.1%	16.8%	1.1%	0.73

B. Continuity problems of NRTK GNSS positioning for ITS applications and solutions

Past tests reveal that it is very difficult to maintain continuous positioning accuracy of a centimetric level when NRTK GNSS positioning is utilized for kinematic applications. There are several reasons responsible for this positioning quality degradation. For instance, there are usually no adequate mobile base stations along the road side or the signals are attenuated due to the local terrain. Large number of overflying bridges that are spanning highways, high-rising roadside embankments and even a passing lorry can also cause GPS signal blockage and a complete positioning failure when only GPS system alone is utilized. High level of multipath also poses difficulty in integer resolution on the fly (OTF).

Many approaches can be employed to improve or augment GNSS positioning to resolve positioning continuity problem but at different instrumentation costs and system complexity [6]. For instance, in the tests high sensitivity GPS (HSGPS) receivers were also utilized to investigate their performance for ITS applications. These receivers are very cheap and also can acquire extra range measurements from the European Geostationary Navigation Overlay Service (EGNOS), a space-borne augmentation system that consists of three geostationary satellites and a network of ground stations, for achieving accuracy better than 2 meters (www.eas.int). Fig. 8 gives a comparison between the position trajectories obtained with NRTK GNSS positioning and a cheap HSGPS receiver. It is apparent that whilst it could provide a nearly similar trajectory, HSGPS receiver of around £20 had much better capacity in delivering uninterrupted positioning solutions than a very expensive geodetic receiver of about £20,000 could.

Integration of GNSS with inertial navigation system (INS) or dead reckoning (DR) sensors are the traditional approaches for maintaining both positioning accuracy and continuity. However to achieve tightly coupled sensor integration for delivering real-time positioning is a very complicated process. INS sensors and software suites for this purpose are usually very expensive, which are limiting many highly demanding ITS applications.

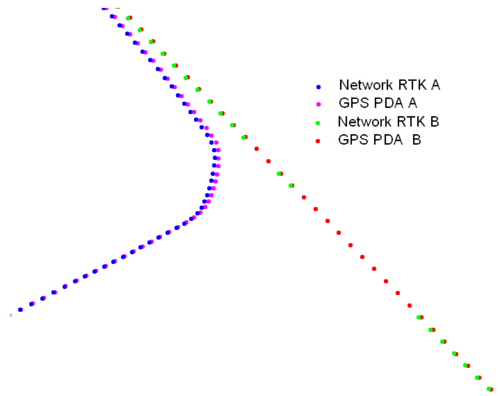

Fig. 8. Comparison of the trajectories generated by a geodetic GNSS receiver and cheap HSGPS receiver

Integrating NRTK based HSGNSS positioning with a cheap INS sensor is a very promising research which will not only provide a high level of positioning continuity and accuracy but also improve reliability of overall positioning system. Other approaches have also been investigated, for instance using algorithms based or map matching methods to bridge the position gaps as shown in Fig. 9, instead of hardware integration as previously discussed [15].

Fig. 9. Position gaps caused by an overfly bridge on M1

V. Conclusions

This paper presents the latest development of network reference stations based GNSS positioning technology and its relevance for ITS applications through highway geometry data collection trials and analysis. Issues such as correction transmission delay and loss due to wireless communications, and GNSS signal blockage are addressed and the statistics to quantify their impacts to the performance of NRTK GNSS positioning are estimated. Solutions for delivering more reliable, continuous and accurate positions are recommended. Research into all these abovementioned aspects is currently undertaken by the authors.

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