Quality assessment of a network-based RTK GPS service in the UK

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Abstract. Network-based Real Time Kinematic (NRTK) GPS positioning is considered to be a superior solution compared to the conventional single reference station based Real Time Kinematic (RTK) GPS positioning technique whose accuracy is highly affected by the distance dependent errors such as satellite orbital and atmospheric biases. NRTK GPS positioning uses raw measurements gathered from a network of Continuously Operating Reference Stations (CORS) in order to generate more reliable error models that can mitigate the distance dependent errors within the area covered by the CORS. This technique has been developed and tested considerably during recent years and the overall performance in terms of achievable accuracies, reliability and mobility is as good as or even better than can be achieved using the conventional RTK GPS positioning technique.

Currently, there are several commercial NRTK services around the world. In the United Kingdom (UK), for instance, Leica Geosystems in partnership with Ordnance Survey has been offering a NRTK GPS service since 2006. This service is called *SmartNet* and it can provide continuous centimetric level of accuracy to its subscribers.

However, NRTK GPS positioning is particularly constrained by wireless data link coverage, correction transmission delay and completeness, GPS signal availability, etc., which could downgrade the positioning quality of the NRTK results.

The paper presents some preliminary testing results of an investigation of the SmartNet service from the end users' point of view. A snapshot of the service's performance was carried out as part of a recent PhD studentship jointly awarded by the UK's Engineering and Physical Sciences Research Council (EPSRC) and Leica Geosystems (UK) to conduct comprehensive research into NRTK GPS quality control measures at the Institute of Engineering Surveying and Space Geodesy (IESSG), the University of Nottingham. In order to evaluate the service's quality several static and kinematic tests were performed using the same type of equipment and in the same way that the SmartNet subscribers would have used it.

Centimetric accuracy was generally attained during both static and kinematic tests. This high accuracy was only affected by some level of unavailability mainly caused by GPS signal blockage. Additionally, the influence of the number of satellites in view, dilution of precision (DOP) and age of corrections (AoC) over the accuracy and stability of the NRTK GPS solution was also investigated during this research and presented in the paper.

Keywords. Network RTK GPS, RTCM, GPRS, performance, accuracy, quality assessment criteria.

1. Introduction

Conventional RTK GPS positioning is a technique that allows centimetre level accuracy positioning in real time through effectively differencing away similar errors and biases that are caused by atmospheric effects and GNSS satellite orbit errors (distance dependent errors) and clock bias in carrier phase observations of the receivers at both ends of a baseline (a reference station and a rover). However, this differential positioning technique is valid only for short baseline lengths (<20km). As the baseline length increases, the errors from both receivers become less common and therefore cannot be cancelled out (Wanninger 2004). This phenomenon is called Spatial Decorrelation of Errors and is the main limitation of conventional RTK GPS positioning. Additionally, the recommended maximum baseline length for conventional RTK is about 10km due to the constraint of a radio modem that transmits the data from the reference station to the rover (Wegener and Wanninger 2005). These limitations have constrained the application scope of RTK GPS positioning, for instance, in precise vehicle tracking where mobility is a priority.

NRTK GPS positioning overcomes the drawbacks of RTK GPS and increases the GPS positioning accuracy by accurately modelling the distance dependent errors at the rover position using the raw measurements of an array of CORS surrounding the rover site (Wanninger 2004).

In addition to improving the positioning accuracy, NRTK GPS brings many other advantages to the service providers and users community; as it attempts to achieve a good balance between accuracy, productivity and cost effectiveness. NRTK GPS substantially reduces the costs of the network operators and its users. Without it the network operators would need a much denser network which is costly to set-up and maintain. The overall positioning costs will be much higher and productivity much lower (users will need to set up project based reference stations, and therefore use at least two dual-frequency receivers). Currently NRTK allows for the transmission of coordinate transformation parameters from the operators, which allows users to continuously acquire the current site grid transformation information without any manual loading or localisation on the rover, and thus better consistency in the quality of coordinates can be maintained.

Taking advantage of NRTK's benefits, many NRTK commercial services have been established in different countries in the past few years. One example is the case of SmartNet, which has operated in the UK by Leica Geosystems (UK) in partnership with Ordnance Survey Great Britain (OSGB) since January 2006.

Several recent static and kinematic trials by the authors have demonstrated the high centimetric accuracy that can be achieved by SmartNet (Meng et al. 2007a). In general the final positional quality of a NRTK GPS system as discussed by Meng et al. (2007b) is directly affected by many factors such as the hardware and software package employed, deployment of reference stations, GPRS wireless data link, correction message transmission delay and satellite signals availability.

This paper describes the preliminary results of the research jointly funded by the EPSRC and Leica Geosystems (UK), the purpose of which was to investigate NRTK GNSS quality control measures. The studies covered in this paper include the analysis of the actual positional quality of the SmartNet service from an end user's point of view, in terms of its accuracy, precision, availability and also how different factors such as the number of satellites in view and their geometry might affect the positioning accuracy.

2. SmartNet and the Master Auxiliary Concept (MAC)

Currently, SmartNet comprises a total of about 153 CORS that are fairly evenly distributed across the whole country as shown in Figure 1. Since July 2007 Leica Geosystems has been also offering the SmartNet service to Ireland and Northern Ireland. Although the majority of the CORS are owned by OSGB, 18 CORS are managed by Ordnance Survey Ireland and Ordnance Survey Northern Ireland and 20 CORS are owned by Leica. Eight Leica stations are GPS and GLONASS enabled receivers.

Figure 1: SmartNet CORS as of 15 August 2007 (Leica Geosystems 2007).

Receivers at the CORS collect raw GNSS data from the satellites and pass them through dedicated communication lines or the Internet to a network Control Centre (CC). At the CC a Leica NRTK software suite called GPS Spider processes the observations as per the MAC technique in order to produce the NRTK corrections. These are then broadcast to the service's subscribers via GSM/GPRS under the Networked Transport of RTCM via Internet Protocol (NTRIP) standard or via GSM without the need of any particular protocol.

SmartNet is based on MAC, which is the most recently developed NRTK GPS technique, developed through joint research carried out by Leica Geosystems and Geo++ in 2001 (Euler et al. 2001). MAC is the basis of the RTCM 3.1 format message which is the new standard for Differential GNSS that fully supports NRTK GPS (RTCM 2006).

A fundamental requirement of MAC is that the phase measurements from the CORS are reduced to a common ambiguity level. Euler et al. (2001) state that "two reference stations are said to be on a common ambiguity level if the integer ambiguity for each phase range (satellite-receiver pair) has been removed (or adjusted) so that when double differences are formed the integer ambiguity cancels".

Once the common ambiguity level has been achieved, full raw observation and coordinate information for one reference station (called the master station) and correction differences and coordinate differences for all other stations in the network (called auxiliary stations) are transmitted to a rover station (Zebhauser et al. 2002). Brown et al. (2005b) explain that "depending on its processing capabilities the rover may use the correction difference information to simply interpolate the error at its location or to reconstruct the full observation information from all reference stations in the network". The rover position is then calculated using double differenced carrier phase.

3. Quality assessment methodology

Several static and kinematic tests were carried out in order to evaluate the positional quality of SmartNet. The dedicated static tests were to evaluate the accuracy, precision and availability of the SmartNet NRTK GPS solutions, whereas the kinematic tests were intended to assess only their accuracy (when compared with a more accurate solution) and availability.

All the tests had a general objective, i.e., to examine the influence of several factors on the SmartNet solutions, such as the number of GPS satellites in view and their geometry, and the age of the NRTK corrections (AoC) when they were received at the rover receiver.

As can be seen in Table 1, a total of eight static tests were performed (TS1, TS2, TS3, TS4, TS5, TS6, TS7 and TS8). Two kinematic tests (TK1 and TK2) were carried out, one of which was designed to evaluate the accuracy and availability of SmartNet on a road section in a built-up area (TK1) in the Nottingham city centre.

The NRTK method or correction type used during tests is also listed in Table 1. SmartNet can offer three different correction services, i.e. Broadcast-MAX, Auto-MAX (MAX) and i-MAX. More details about these services can be found in Burbidge (2006). As a way of assessing the performance of different correction types, it was planned to use a particular message type each time. However, due to the Broadcast-MAX correction service not being activated, it was not possible to test it. Thus only message types Auto-MAX (TS3, TS4 and TS6) and i-MAX (TS1, TS2, TS5, TK1 and TK2) were used.In addition, TS7 and TS8 were performed using conventional single reference RTK in order to compare their results against those from the NRTK GPS positioning tests.

Table 1: Details of the tests that were performed using different correction services.

Test	**Network Sercice**	**NRTK method**	**Obs. method**	**Cut off angle**	**Obs. rate (Hz)**
TS1	SmartNet	I-MAX	Static	10°	1
TS2	SmartNet	I-MAX	Static	10°	1
TS3	SmartNet	MAX	Static	10°	1
TS4	SmartNet	MAX	Static	10°	1
TS5	SmartNet	I-MAX	Static	10°	1
TS6	SmartNet	MAX	Static	10°	1
TS7	SmartNet	Conv. RTK	Static	10°	1
TS8	UoN/Leica	Conv. RTK	Static	10°	1
TK1	SmartNet	I-MAX	Kinematic	0°	20
TK2	SmartNet	I-MAX	Kinematic	0°	20

This investigation was mainly intended to evaluate the quality of the SmartNet services from the end users' point of view; therefore, the majority of the tests were carried out using the service “as it is”. This means that, as SmartNet is a commercial NRTK service in Great Britain, the corrections received during the tests were the same as any other subscribers would have received if using the service at the same location and time.

However, as the CORS configuration of the SmartNet network included a reference station (RS) located about 10km (KEYW) from the rover site (see Figure 2), a new CORS configuration was especially created for some of these tests by removing KEYW from the NRTK solution. The nearest RS to the rover site was then located about 49km away, which could be considered a typical configuration for a NRTK GPS application (see Figure 3).

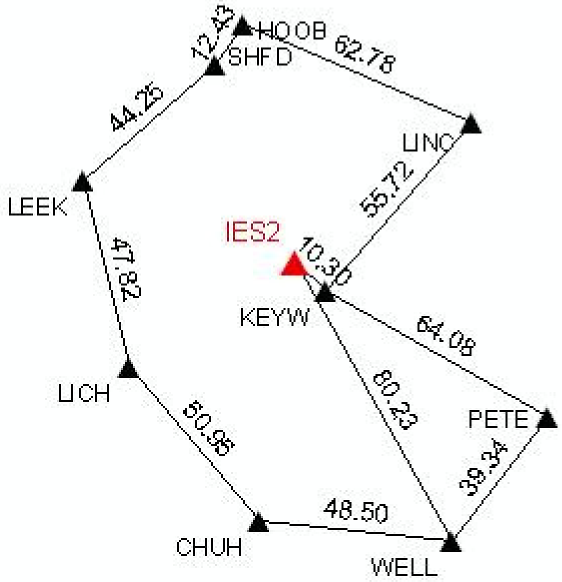

Figure 2: A SmartNet CORS configuration used during the tests TS1, TS2, TS3, TS4, TK1 and TK2. Except for kinematic tests (TK1 and TK2), the rover site location is indicated in red (IES2) with the nearest reference station (KEYW) located at 10.30km, the farthest (WELL) located at about 80.23km and the average distance between CORS is about 47.32km.

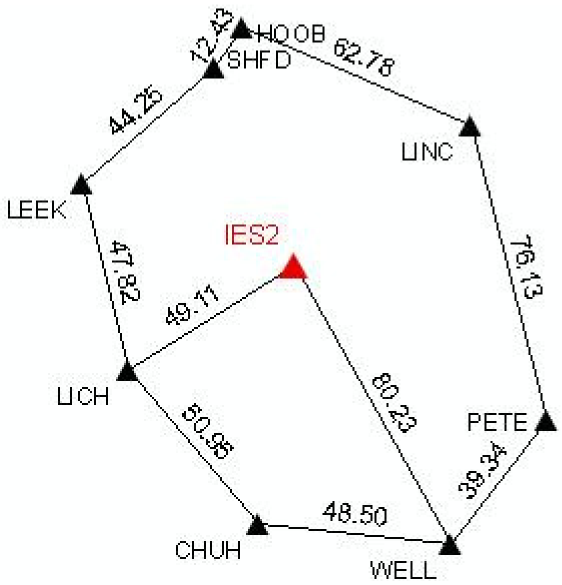

Figure 3: A sparser SmartNet CORS configuration used during TS5 and TS6. The distance of the rover site (IES2) from the nearest reference station (LICH) is 49.11km, and the farthest site (WELL) is located at about 80.23km, and the average distance between CORS is about 47.78km.

As already mentioned, two conventional RTK tests were also performed. A short baseline test called TS7 used KEYW as the reference station (see Figure 2), and its results could be directly compared against those from TS1, TS2, TS3 and TS4. On the other hand, TS8 used LNC1 as the RS, which is one of the reference stations of the testbed facility of a joint initiative of the University of Nottingham and Leica Geosystems (Meng et al. 2007b). Use of LNC1 created a long baseline (53.66km) for a conventional RTK GPS solution, the results of which could be compared against those from TS5 and TS6 (see Figure 4).

Figure 4: A long baseline used during static test TS8. The rover site location (IES2) with a reference station (LNC1) located 53.66km away.

Static tests were all performed using the facility within the IESSG building with a geodetic antenna installed on the roof of the building. Figure 5 shows the general equipment configuration for the static tests. The signal from an AT503 antenna was split by means of an antenna signal splitter and shared by two geodetic GPS receivers.

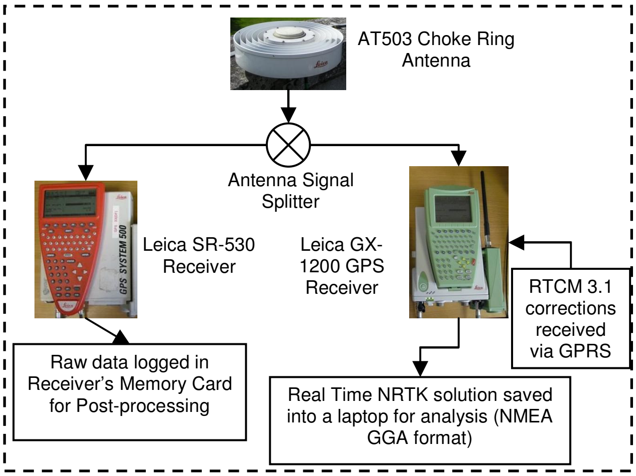

Figure 5: Equipment configuration used for the static tests.

One receiver was a Leica GX-1200 dual-frequency geodetic GPS receiver which can receive NRTK corrections from SmartNet via a GPRS data link. This GPRS service is provided by Vodafone, which is a well established UK mobile phone company with a good coverage in the Midlands region. The GX-1200 receiver was, at the same time, connected to a laptop logging real time NMEA GGA data.

A second receiver (a Leica SR-530) was also used during the tests in order to log raw observations for post-processing. The purpose of the post-processed solution was to compare the NRTK results not only with the true coordinates but also with another kinematic solution in order to check for biases or other errors that could have affected GPS observations.

Although the AT503 antenna was located on the roof of the IESSG building, the receivers and the GPRS data link were, during most tests, placed indoors in the Geodesy Lab of the Institute. This Lab has good mobile phone coverage and therefore no GPRS communications problems were experienced.

For both kinematic tests a Leica AX1202 dual-frequency antenna was used. The configuration of the equipment was very similar to that used for the static tests, except that the raw observations were additionally logged onto the memory card of the GX-1200 receiver and subsequently post-processed to provide the "true" position trajectory.

Most static tests lasted for about 24 hours, while kinematic tests were performed for about one hour. The detailed observation dates, times and duration are showed in Table 2.

Table 2: UTC start and finish time for each static and kinematic test, including their duration.

Test	**UTC Start Time**		**UTC Finish Time**		**Duration**
	Date	**Time**	**Date**	**Time**	**hh:mm:ss**
TS1	29/05/08	12:00:00	30/05/08	12:00:00	24:00:01
TS2	28/02/08	13:00:00	29/02/08	13:00:00	24:00:01
TS3	01/03/08	13:00:00	02/03/08	13:00:00	24:00:01
TS4	06/08/08	09:46:00	07/08/08	09:45:59	24:00:00
TS5	23/07/08	13:51:00	24/07/08	13:51:00	24:00:01
TS6	12/08/08	09:09:00	13/08/08	09:09:59	24:01:00
TS7	05/08/08	09:21:00	06/08/08	09:20:59	24:00:00
TS8	04/08/08	09:37:00	05/08/08	08:38:59	23:02:00
TK1	07/06/07	10:17:00	07/06/07	11:34:59	01:18:00
TK2	07/06/07	13:39:00	07/06/07	14:32:59	00:54:00

4. Positional quality of the NRTK GPS service

In order to evaluate the quality of the NRTK service the collected data were analysed under the following assumptions: the total error in a GPS observation results from the sum of different error components (such as the receiver clock offset, the satellite clock offset, the orbit error, the ionospheric and the tropospheric biases, etc.) and the resulting total error have approximately a normal distribution, whether or not the component errors are normally distributed.

Therefore, common statistical formulas for normal distributed data were employed in the analysis. The first step was to filter outliers. The data was processed at a 99.7% confidence level to eliminate all the outliers.

4.1 SmartNet accuracy and precision

Accuracy can be defined as how far the coordinates calculated during testing are from the true values (Feng and Wang 2007). Therefore, for each coordinate component, East, North, and Height, the accuracy was calculated. The total accuracy of a respective test was determined as the average of the accuracy values at each epoch. On the other hand, precision is a degree of repeatability (or closeness) that repeated measurements display, and is therefore used as a means to describe the quality of the data with respect to random errors (Rizos 1999). It was represented by the standard deviation (SD) of the solutions (3 sigma, about 99.7% of solutions).

The accuracy and precision obtained during the tests is summarised in Table 3. The results in this table are based on epochs with valid NRTK observations. As can be seen, TS1, TS2, TS3 and TS4 had the best accuracy and precision of all the tests, with most values at the millimetre level. At the same time, results from the sparse SmartNet CORS configuration tests (TS5 and TS6) showed better accuracy and precision than TS8 (conventional long baseline RTK test). The accuracy and precision of the kinematic tests were at the centimetre level.

Table 3: Accuracy (Ave.) and precision (SD) in centimetres obtained during both static and kinematic tests, for the East, North and Height coordinate components.

Test	East		North		Heigth	
	Ave.	SD (+/-)	Ave.	SD (+/-)	Ave.	SD (+/-)
TS1	0.08	0.43	-0.42	0.83	-0.76	1.17
TS2	0.06	0.47	-0.68	0.86	-0.89	1.17
TS3	0.04	0.84	-1.15	1.47	-1.70	1.52
TS4	-0.12	0.61	-0.54	1.11	-0.62	1.33
TS5	0.11	0.75	0.77	1.64	1.02	2.27
TS6	0.42	0.77	0.02	1.75	0.37	2.42
TS7	-0.29	0.64	-0.93	1.42	-1.05	1.57
TS8	1.62	0.79	-2.64	2.36	2.09	2.79
TK1	-1.05	1.44	-3.53	2.22	1.60	4.68
TK2	-1.11	1.62	-3.52	2.70	2.35	5.07

The accuracy obtained from each test for the East coordinate component can be seen in Figure 6. During NRTK static tests (including those from the sparse SmartNet configuration, TS5 and TS6) the East accuracy was better than 1cm for an average of 87% of the NRTK epochs; clearly much better than the long baseline conventional RTK solution (TS8), which had better than 1cm accuracy during only about 18% of the NRTK epochs.

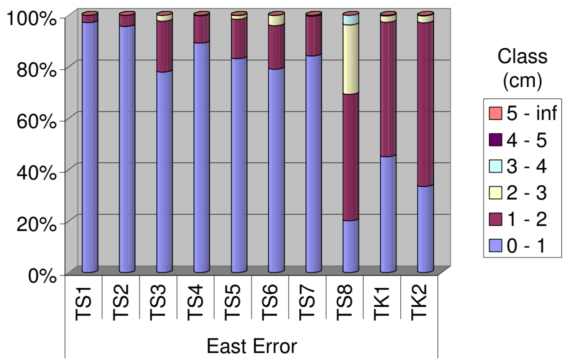

Figure 6: Accuracy of solutions from each static and kinematic test for the East coordinate component (cm).

The same pattern was also observed in the North coordinate component results (see Figure 7) and in the Height coordinate component results (see Figure 8). In general, NRTK GPS results were more accurate than conventional RTK GPS solutions.

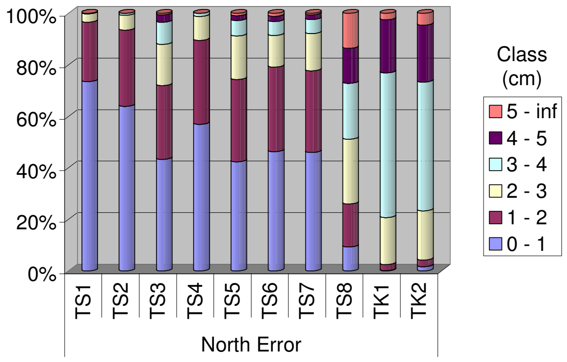

Figure 7: Accuracy of solutions from each static and kinematic test in the North coordinate component (cm).

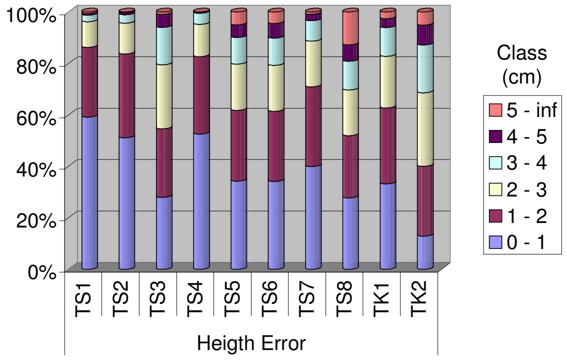

Figure 8: Accuracy of solutions from each static and kinematic test for the Height coordinate component (cm).

4.2 The availability of the service

The availability was determined as the percentage of observations from which a NRTK

GPS solution (integer ambiguities resolved) was obtained during a test (Brown et al. 2005a). This is a vital index for the good performance of the SmartNet service. The accuracy and precision of the position results directly depend on whether the solution obtained is NRTK or not.

A summary of the availability found during the tests is given in Table 4. As can be seen, the availability of the NRTK service during static tests was always over 97.74%. The highest availability was obtained during TS3 (99.77%), while both conventional RTK tests (TS7 and TS8) also showed high availability values over 99.80%. The lowest availability levels for static NRTK tests were observed during TS5 (98.54%) and TS6 (97.74%). These tests were performed using the sparse SmartNet CORS configuration, which might indicate the additional difficulties that NRTK faces when resolving ambiguities at the rover side for sparse CORS configurations.

Table 4: Number of possible NRTK epochs and actual epochs in which a NRTK solution was achieved, including the availability during each test.

Test	Possible Epochs	Actual Epochs	Availability (%)
TS1	86401	85535	99.00
TS2	86401	85678	99.16
TS3	86401	86205	99.77
TS4	86400	85735	99.23
TS5	86401	85135	98.54
TS6	86460	84506	97.74
TS7	86400	86224	99.80
TS8	82920	82777	99.83
TK1	93599	50905	54.39
TK2	64799	40736	62.87

Figure 9 shows the availability results. It is possible to see that about 1.4% of epochs during TS5 and about 2% during TS6 were differential GPS (DGPS) solutions, that when added to the NRTK epochs (availability) accounts for nearly 100% of the total possible epochs (see Table 4) for these two tests, indicating that the correction message was still being received.

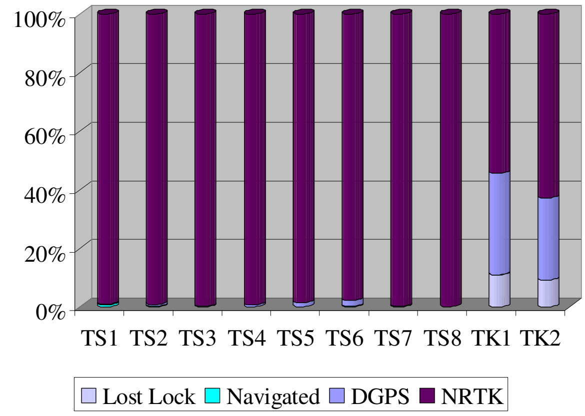

Figure 9: Percentage of solution types during static and kinematic tests, including availability of NRTK observations.

A characteristic of the SmartNet service is that when a NRTK solution is not possible due to the ambiguities not being fixed, the solution switches to DGPS; of course, only if the corrections are still being received. Therefore, because most of the epochs apart from NRTK were DGPS, it can be inferred that problems with the GPRS data link did not cause the availability to drop during TS5 and TS6.

Nonetheless, the presence of DGPS solutions does not indicate that all the required correction messages were received. In GSM/GPRS (TCP) communication the data is Cyclic Redundancy Check (CRC) checked, it is not error checked. Therefore, data can be received but might not be correct or complete. The correction messages are formed by pseudoranges and phases. When pseudoranges are used, each epoch gives a solution independently of prior or later observations. Phase solutions need more observation data to resolve integer ambiguities. Thus, if some phase data of satellites are missing due to the communication link this will have a bigger impact on integer fixing. Hence, further investigation needs to be carried out in order to check not only the availability but the correctness and completeness of the RTCM message as received at the rover device.

Factors such as low number of satellites in view, constellation geometry, and unreliable observations could have affected the ambiguity resolution process during these two tests.

Table 4 and Figure 9 also show the availability achieved during kinematic tests. On average, NRTK solutions were obtained only about 58% of the time, which is considerably lower than that which was achieved during static tests (over 97%). Due to the routes travelled during both kinematic tests the availability of TK2 was about 8% better than that of TK1.

Except for an extra route in a built-up area in the Nottingham city centre during TK1, the same trajectory was travelled during both kinematic tests. The data collection started at the IESSG car park, continued on major roads to junction 26 of the M1 Motorway, then went south on the M1 to junction 24, and came back by the same route to the IESSG car park where the data collection finished. Additionally, during TK1, some urban roads forming a ring around the Nottingham city centre were covered before returning back to the IESSG car park. Figure 10 shows the 2D and 3D root mean square error (RMSE) observed during TK1. It is evident that there are many gaps when a NRTK solution was not possible. In particular, the availability in the built-up area is much lower than for the rest of the route. Nevertheless, as can also be seen, most of the achieved NRTK epochs had 2D and 3D RMSE better than 5cm.

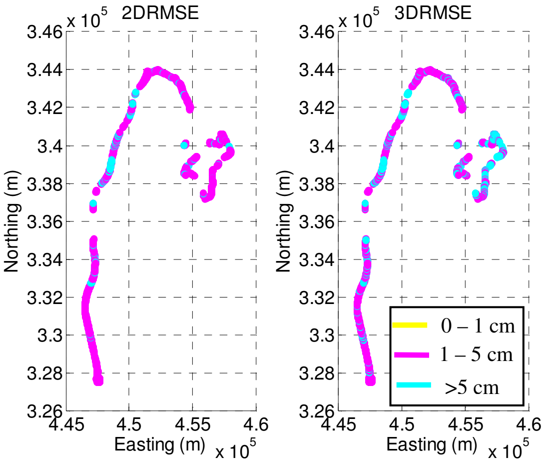

Figure 10: 2D and 3D RMSE errors observed during TK1, represented over the route covered during the test.

Many factors were found to cause the lack of availability during the kinematic tests:

- GPS signal blockage and multipath when passing under flyover bridges, which are very common along the M1 motorway (refer to Figure 11). The signal blockage and multipath caused the ambiguity fix to be lost and therefore the NRTK solution could not be obtained. This situation occurred several times while on the M1 and was clearly perceived during the tests by the beeps of the rover receiver.

Figure 11: View of one flyover bridge from the test car during TK1 (M1 Motorway). Such bridges caused GPS signal blockages along the M1.

- The M1 Motorway is a very busy route for heavy lorries which, when passing next to the test car, also produced similar effects as those caused by the flyover bridges. Figure 12 shows two lorries next to the test car when stopped at a traffic light at junction 24 of the M1. Those lorries effectively were mobile obstacles producing signal blockage and dynamic multipath when they were next to the test vehicle.

Figure 12: Lorries on the M1 Motorway blocked GPS signals and potentially caused dynamic multipath.

- In the built-up area the availability was severely affected by the typical factors found in an urban canyon environment when using GPS. Tall buildings, narrow roads and tree canopies caused signal blockage, shadowing, and multipath.
- The high percentage of DGPS epochs in the solutions (see Figure 9), even on occasions when the right conditions were presented for fixed ambiguity

solutions (more than five satellites in view and uninterrupted reception of the RTCM message), might suggest some problems in the cycle slip detection/repair and/or ambiguity resolution algorithms. However, although this assumption needs further investigation, these algorithms have always demonstrated high robustness during previous research (Brown et al. 2005a; Meng et al. 2007b).

4.3 The availability of accuracy

The availability of accuracy was denoted in this research as the percentage of NRTK observations with accuracy better than 5cm. A summary of the results is presented in Figure 13, in the order East, North and Height. In general, it is apparent that the static tests from the normal SmartNet CORS configuration (TS1, TS2, TS3 and TS4) presented more accurate results, with the accuracy for more than 98% of the epochs being better than 5cm for all three coordinate components. I-MAX tests (TS1 and TS2) showed slightly more accurate results than MAX tests (TS3 and TS4). However, the accuracy during these four tests was on average better than those obtained from the short baseline conventional RTK test TS7. The results from TS7 were very similar to those achieved from the sparse SmartNet configuration (TS5 and TS6), which were significantly better when compared with the long baseline conventional RTK solution TS8. These results show that the NRTK GPS solutions are in general better than the conventional RTK GPS solutions even when the observation was made under ideal conditions, such as for baselines less than 20km in length.

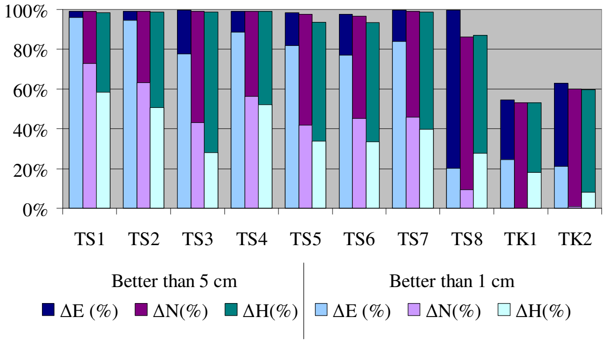

Figure 13: Percentage of the solutions with accuracy better than 5cm (dark colours) and 1cm (light colours).

On the other hand, kinematic tests had much lower accuracy availability with only around 50% of the total possible solutions having an accuracy better than 5cm.

4.4 The influence of the number of GPS satellites in view on the NRTK GPS solutions

Figure 14 clearly shows the relationship between the number of GPS satellites used in the solution and the accuracy of the positioning solutions. That is, the solutions became less noisy as the number of satellites increased, and the accuracy decreased when the number of satellites was 6 or less. For instance, at about epoch 50000 the number of satellites peaked at 11 and the solutions were clearly more accurate. However, at epoch 15000 when the number of satellites was about 5, the solution was very noisy.

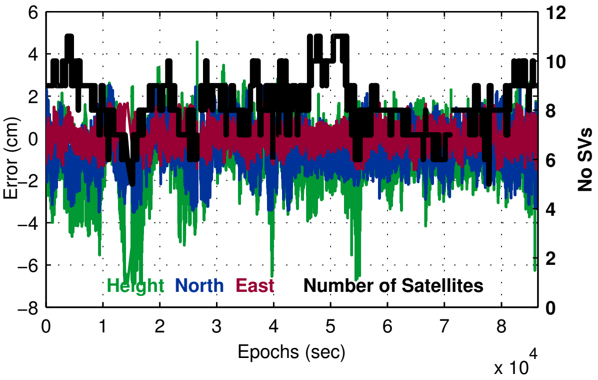

Figure 14: Influence of the number of GPS satellites on the solution for the East, North and Height coordinate components during TS1.

4.5 The influence of the horizontal dilution of precision (HDOP) on the planimetric accuracy

The influence of HDOP on the accuracy of the East and North components during TS2 can be seen from Figure 15. Even though the HDOP values were below 4 for most of the time, which could be considered good, it is evident that from epochs 60000 to 70000, when the HDOP was always below 1.5, the East and North errors were very steady, with values between -3.00 and -1.50cm. But at about epoch 23000, when the HDOP peaked at about 4.4, the planimetric errors showed higher noise.

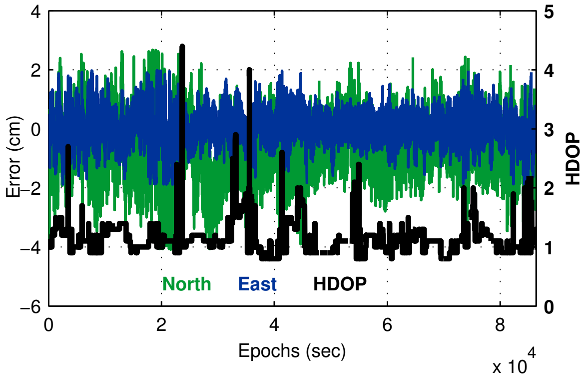

Figure 15: Influence of HDOP on the East and North errors during TS2.

4.6 The influence of the vertical dilution of precision (VDOP) on the height component

Figure 16 is the relation between VDOP and the vertical errors during TS3. As with the HDOP and planimetric coordinates, it is again evident that when the VDOP values are good, e.g. about 1.5 in epoch 55000, the height solutions are less noisy than when the VDOP peaked at about epoch 35000.

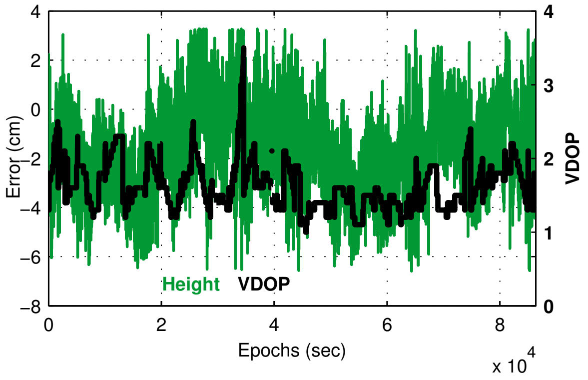

Figure 16: Influence of VDOP on the height error during TS3.

4.7 The influence of the age of correction (AoC) on the NRTK GPS solutions

Even though the influence of the AoC on the accuracy of the solutions is not as apparent as the factors above, e.g. number of satellites in view, HDOP and VDOP, Figure 17 shows how the accuracy became noisier when the AoC went over one second. However, it does not seem to be a rule, as it can also be seen that even if the AoC was about one second during some periods of TS6 the solutions also had considerable noise.

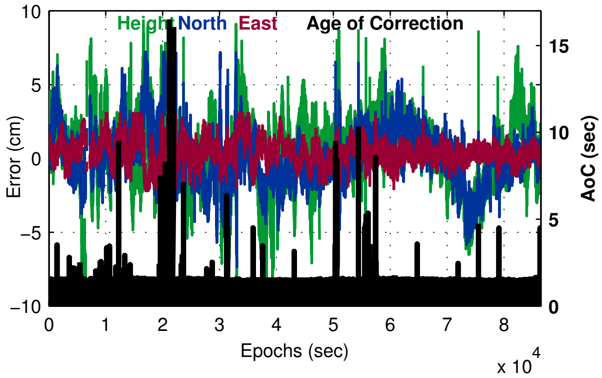

Figure 17: Influence of the AoC on the East, North and Height errors during TS6.

4.8 The relationship between the coordinate quality (CQ) value output by the receiver and the actual 3D RMSE

The Leica GPS receiver used during these tests can display an estimated value of the error for every epoch during observation. Figure 18 shows a time series of this CQ against the actual 3D errors obtained during TS5. As can be seen, the CQ follows the same pattern as the actual errors observed for each epoch. However, in most cases, CQ tends to underestimate the actual errors. Nevertheless, it seems to be a reasonably good indicator of the accuracy of the solutions while in the field.

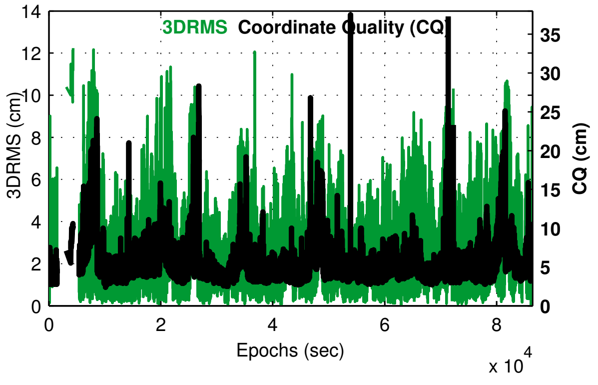

Figure 18: Relationship between the coordinate quality (CQ) value output by the receiver and the 3D RMSE during TS5.

5. Conclusions

This research demonstrated that SmartNet (NRTK GPS) can offer centimetric positioning accuracy and precision (3-sigma) to its end users. In general, during static tests, the NRTK observations from both CORS configurations were more accurate and precise than those achieved from the conventional short and long baseline RTK solutions.

The availability of the static NRTK observations was always above 97.74% which ensured an average accuracy better than 5cm over 98% of the time for all three coordinate components.

During the static tests, the accuracy of the solutions was affected by factors such as low number of satellites in view, high HDOP and VDOP and high AoC. It was evident that a low number of satellites caused a decrease of the accuracy, and in the worst case the loss of the NRTK service. This is because, in order to solve for the integer ambiguities, at least the same five satellites are required to be observed at both ends of a baseline, i.e., the master station and the rover site; and in order to maintain the solution at least four satellites are required. Also, high HDOP, VDOP and AoC values were directly related to lowered positioning accuracy.

Kinematic tests, however, showed a much lower availability of the NRTK solution, and resulted in accuracy being better than 5cm only about 50% of the time. The lack of availability during the kinematic tests was mainly caused by GPS signal disturbances and possibly the interruptions of the GPRS communication link. Signal blockage, shadowing and also multipath caused by static (flyover bridges, buildings, etc.) and mobile obstacles (e.g. lorries) along the test routes directly affected the availability by causing disruption of the NRTK solution. The same factors, in addition to the common mobile phone coverage problems, could have also affected the GPRS wireless link by interrupting the delivery of the NRTK correction messages and therefore causing a high AoC, which led to gaps in the NRTK solution availability.

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