

# Performance Assessment of a GPS Network RTK Service

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**Key words:** network RTK GPS, corrections, service, GPRS, performance.

## SUMMARY

Network RTK (NRTK) GPS positioning is considered the most appropriate solution to the problems faced by single baseline based RTK GPS which accuracy is highly affected by the distance dependent errors such as satellite orbital and atmospheric biases. NRTK GPS employs GPS raw observations gathered from a network of CORS (Continuously Operating Reference Stations) in order to create models that can mitigate these errors acting within the area covered by the CORS. This technique has been considerably developed and tested during recent years and the accuracies as good as or even better than that can be achieved with conventional RTK GPS are normally met.

Currently, there are several operating commercial NRTK services around the world. In Great Britain (GB), for instance, Leica Geosystems in partnership with Ordnance Survey GB has been offering NRTK GPS corrections to its clients since 2006. This service is called SmartNet and it can provide centimetric and continuous accuracy to its subscribers. However, in the same way the advantages that NRTK GPS offers to the GPS community are well known, it is also clear that NRTK GPS faces its own problems due to factors such as low GPS satellites availability, wireless data link coverage, etc., which affect the positioning solution through introducing inaccuracy and instability in the NRTK results.

The research presented in this paper reports the initial results on the investigation of the SmartNet service from the end users' point of view which was carried out in order to create a snapshot of the service's performance leading onto a recent PhD studentship jointly awarded by UK's EPSRC (Engineering and Physical Sciences Research Council) and Leica Geosystems to conduct comprehensive research into NRTK GPS Quality Control measures at the IESSG (Institute of Engineering Surveying and Space Geodesy). Several static and kinematic tests were performed during the months of June, July and August. Tests were carried out with the same type of equipments and in the same way any SmartNet subscriber would have used the service.

Centimetric accuracy was generally attained during both static and kinematic tests. This high accuracy was only affected by some level of unavailability of wireless data link and GPS signal blockage which caused the losses of the NRTK solution. Additionally, the influence of the number of satellites in view, HDOP and age of corrections over the accuracy and stability of the NRTK GPS solution was also investigated during this research.

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## 1. INTRODUCTION

Conventional RTK (RTK) GNSS positioning is a technique that allows centimetre level accuracy observations in real time by effectively differencing away similar errors and biases caused in the carrier phase observations of receivers at both end of a baseline (Reference Station and Rover) by atmospheric effects and GNSS satellites orbit errors (distance dependent errors). However, this differentiation works well only when the baseline length is not greater than about 20 km; but as soon as the baseline length increase over these recommended limits, the distance dependent errors change causing the magnitude of the errors in the observations of both receivers to be different so that these errors cannot be effectively cancelled (high accuracy is then lost). This phenomenon is called Spatial Decorrelation of Errors and is the main limitation of RTK GPS positioning.

Although throughout the years many ways to overcome the drawbacks of RTK GPS have been investigated and implemented, it is only with NRTK GPS that the RTK technique has been drastically improved. NRTK GPS overcomes the decrease in RTK 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.

Taking advantage of the benefits NRTK GPS brings to the GPS users such as surveyors, which include but are not limited to longer baseline length, no need of known points and two dual frequency receivers it therefore decreases surveying time and costs but increases performance. Many NRTK commercial services have been established in different countries in the last few years. Such is the case of SmartNet which is operated in GB by Leica Geosystems in partnership with Ordnance Survey Great Britain (OSGB) since January 2006. Assessment of its service forms the sole study object of this paper.

This paper describes an initial stage of a research that is jointly funded by the EPSRC and Leica Geosystems which is currently being carried out at the IESSG and investigates into GNSS NRTK quality control measures. The preliminary studies covered in this paper include the analysis of the actual performance of the SmartNet service from the final user's point of view, in terms of its accuracy, precision, integrity, availability, repeatability and also how different factors such as the number of satellites in view and their geometry might affect the service.

## **2. THE NETWORK RTK GPS SERVICE**

### **2.1 Master Auxiliary Concept (MAC)**

MAC is the most recently developed NRTK GPS technique and has its origins in a jointly research carried out by Leica Geosystems and Geo++ in 2001 and in this research a proposal for a new message standard that would allow NRTK GPS corrections to overcome the RTCM 2.3 format drawbacks was made [Euler et al., 2001].

RTCM 2.3 is a standardised message format for precise positioning using baseline approaches that allows proper interoperability between different manufacturers' equipment [RTCM, 2001]. However, this message standard does not support the use of data from a network of CORS.

After many discussions the RTCM Special Committee 104 finally approved and published the RTCM 3.1 format in 2006, which is based on the MAC technique and is a new standard for Differential GNSS that fully supports NRTK GPS [RTCM, 2006].

A fundamental requirement of MAC is that the phase ranges 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 ambiguities for each phase range (satellite-receiver pair) have been removed (or adjusted) so that when double differences are formed the integer ambiguities cancel'.

Once the common ambiguity level has been achieved, full raw observation and coordinate information for one reference station called master station and for all other stations in the network which are identified as auxiliary stations, correction differences and coordinate differences 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'. Rover position is then calculated using double difference carrier phase.

### **2.2 SmartNet**

Currently, SmartNet comprises a total of about 142 CORSs distributed as shown in Figure 2-1. Since July 2007 Leica Geosystems has been also offering the SmartNet service to Ireland and Northern Ireland. Therefore, although the big majority of CORSs are owned by OSGB, the total number of stations includes about 18 CORSs managed by Ordnance Survey Ireland and Ordnance Survey Northern Ireland, in addition to about 20 owned CORSs, and some of which (about 8) are GPS and GLONASS enabled receivers.



**Figure 2-1:** SmartNet CORSs as on 15 Aug. 2007 [Leica Geosystems, 2006].

Receivers at the CORSs collect raw GNSS data from the satellites and pass them through dedicated communication lines or internet connections to a network Control Centre (CC). At the CC a Leica software suite called GPS Spider is in charge of processing the observations as per the MAC technique in order to produce the NRTK corrections for their subsequent broadcast to the service's subscribers.

The NRTK GPS corrections from SmartNet are finally delivered to its users via GPRS under the NTRIP standard or via GSM without the need of any particular protocol. Therefore, SmartNet users can employ any mobile phone networks which offer GSM or GPRS services with good signal coverage of the geographic area where they are supposed to be working in.

### 2.3 Max and i-Max

Although SmartNet is specially designed to work under the MAC approach and therefore with the RTCM 3.1 format, it also supports old rovers that only accept the RTCM 2.3 message. Consequently, SmartNet corrections can be divided into two types depending on the RTCM format they broadcast through: MAX (Master-Auxiliary Corrections) and i-MAX (Individualised Master-Auxiliary Corrections).

MAX are the corrections as specified by the MAC concept and are available only through the RTCM 3.1 message format which due to its recent introduction might not be supported for older GNSS receivers.

After the ambiguities in all the CORSs within a cluster (group of CORSs with a common ambiguity level) have been fixed, a cell of stations (small group of CORSs within the cluster) is then selected in order to contribute in the creation of the MAX corrections to be delivered to a determined rover. The way the stations forming the cell are selected directly depends on

two factors, i.e., the location of the rover and the communication link being used for data transmission.

If the data transmission link used between the rover and the CC is a two-way system so that the rover can send its approximate location to the CC in an NMEA GGA format when it first connects to the system, Spider will automatically select the most appropriate set of CORSs to form the cell and subsequently produce the NRTK corrections [Brown et al., 2005a].

Normally, the cell is formed by the 6 CORSs with the shortest 3D distances from the rover. From these 6 stations the nearest one is selected as the master and the remaining 5 stations are configured as the auxiliary stations [Burbidge, 2006]. This correction message service is called Auto-MAX and due to its characteristics usually produces the best set of corrections for a determined rover while minimizing the amount of data in the message [Brown et al., 2005a].

On the other hand, preconfigured cells could also be available within the system in order to serve the users with one-way communication links. Spider's operators might create as many cells as needed based on the size of the cluster. In addition, the number of CORSs in the cell should try to optimize the amount of data delivered in the message. This correction service is called Broadcast-MAX and being a broadcast service is the essence of the MAC approach. Users should connect to the broadcast service that is most related to their location.

The i-MAX correction service is specially designed in order to support users with old GPS rovers that do not support the new RTCM 3.1 network message format.

i-MAX is strictly a two-ways communication service, in which the rover sends its approximate location to the CC via NMEA GGA message. As soon as Spider receives the rover position an optimum cell is created based on the same criteria of Auto-MAX. Once the CORSs forming the cell are identified the software determines the network corrections for the region and, in this case, Spider interpolates the correction to find the errors at the rover site and applies them to the CORS selected as the master station (which is the nearest to the rover). The corrections are then sent to the rover who solves for its final position as in a conventional RTK solution.

### **3. RESEARCH METHODOLOGY**

#### **3.1 The Main Objectives of the Tests**

The static tests were designed in order to evaluate the accuracy, precision, availability, integrity and repeatability of the SmartNet NRTK solutions, whereas the kinematic tests were intended to assess only their accuracy, availability and integrity.

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

Table 3-1 summarises the static tests carried out during the research and main testing objectives. A total of seven static tests were performed and of which four were specially designed to assess the repeatability of the NRTK correction service of SmartNet.

<b>Static Tests</b>	<b>Objectives</b>
TS1	Evaluate accuracy, precision, availability and integrity.
TS2	Evaluate accuracy, precision, availability and integrity.
TS3	Evaluate accuracy, precision, availability and integrity.
TS4.1	Evaluate accuracy, precision, availability integrity and repeatability.
TS4.2	
TS5.1	Evaluate accuracy, precision, availability integrity and repeatability.
TS5.2	

**Table 3-1:** Static Tests and Their Main Objectives.

Table 3-2 includes a summary of kinematic tests. Two kinematic tests were performed; one of them particularly designed to evaluate the accuracy, availability and integrity of SmartNet in a trajectory that covers a built-up area.

<b>Kinematic Tests</b>	<b>Objectives</b>
TK1	Evaluate accuracy, availability and integrity including an urban canyon area.
TK2	Evaluate accuracy, availability and integrity.

**Table 3-2:** Kinematic Tests and Their Main Objectives.

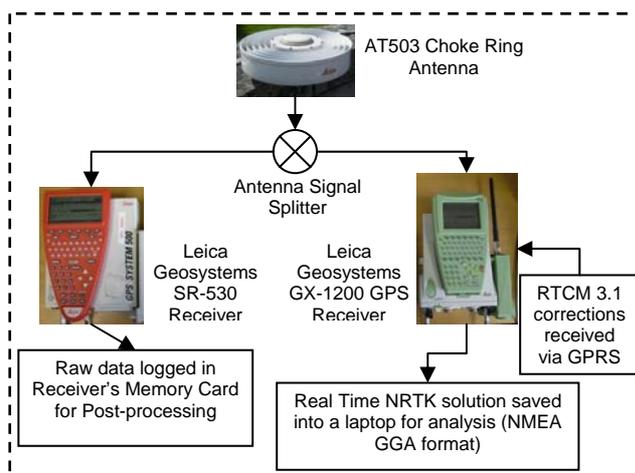
### 3.2 The Configuration of the Tests

Static tests were all performed using the facility within the IESSG building with a geodetic antenna installed on the roof of the building as shown in Figure 3-1.



**Figure 3-1:** An AT503 Choke Ring Antenna Located at a Known Point on the Roof of the IESSG Building.

Figure 3-2 shows a general equipment configuration for the static tests. The signal from the AT503 antenna was split by means of an Antenna Signal Splitter and shared by two GPS geodetic types of receivers at the same time.



**Figure 3-2:** Equipment Configuration Used for the Static Tests.

One receiver was a Leica Geosystems GX-1200 Dual Frequency GPS Geodetic 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 good coverage in the Midland region. The GX-1200 receiver was, at the same time, connected to a laptop logging real time NMEA GGA data.

A second receiver (Leica Geosystems SR-530 Dual Frequency GPS) was also used at the same time in order to log raw observations for post-processing. The idea of having also a

post-processed solution was to compare the NRTK results not only with the true coordinates but also with another solution in order to check for biases or other kind of errors that could have been affecting GPS observations at the tests location and time.

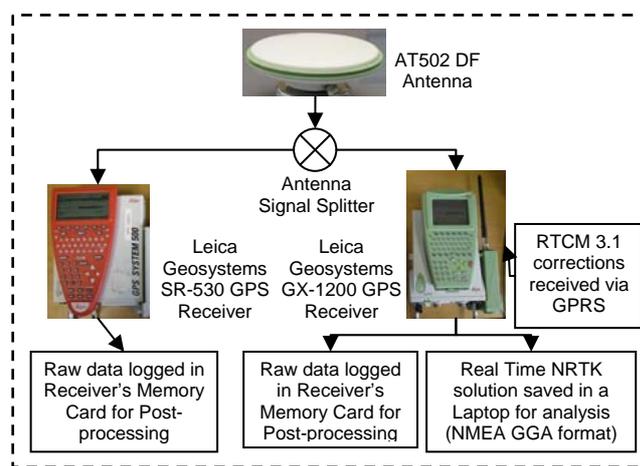
Although, as mentioned before, the AT503 antenna was located on the roof of the IESSG building, the receivers and the GPRS data link were, during most tests, placed indoor in the Geodesy Lab of the Institute. This Lab presents good mobile phone coverage and therefore no GPRS communications problems were experienced due to the data link being indoors. However, in order to make the research as a most realistic one as possible and investigate different working scenarios, TS2 was performed completely outdoor with receivers and data link all installed on the roof of the IESSG building.

For both kinematic tests, TK1 and TK2, a Leica Geosystems AT502 dual frequency antenna was used. The antenna was installed on the roof of a vehicle as shown in Figure 3-3.



**Figure 3-3:** AT502 DF Antenna Installed on the Roof of a Car for the Kinematic Tests.

Aside from the raw observations being also logged in the GX-1200 receiver during both kinematic tests in order to be subsequently post-processed and considered as the “actual” values during results analysis, as shown in Figure 3-4, the configuration of the equipments was very similar to the used during static tests.



**Figure 3-4:** Equipment Configuration Used for the Kinematic Tests.

### 3.3 Data Collection

Static and Kinematic tests were all performed during the months of June, July and August 2007. Although no ionospheric activity was monitored, in general, there was a good weather with clear skies and temperatures ranging from 12 to 23 °C during tests.

As mentioned before, this investigation intended to evaluate the SmartNet services from the end users' point of view; therefore, the service was tested "as it is". This means that, as SmartNet is an actual commercial NRTK service in Great Britain, there was not access to the set up of corrections or CORSs. Therefore, the corrections received during testing, were the same as any other subscribers would have received if using the service at the same location, day and time.

Table 3-3 shows the settings used by the GPS receivers during data collection.

Receiver Parameters	Configuration	
	Static	Kinematic
Elevation Mask	0°	0°
Data logging	1 Hz	20 Hz
Maximum GDOP	None	None
Number of Observations	1 per sec.	20 per sec.

**Table 3-3:** Parameters Used in the Static and Kinematic Tests.

Date, and duration of data collection are summarised in Table 3-4 for both, static and kinematic tests.

Test	UTC Time		Date	GPS Time (sec)		Dur. (min)
	Start	End		Start	End	
TS1	13:35:00	15:34:59	19/07	394514	401713	120
TS2	10:10:00	11:39:59	24/07	209414	214813	90
TS3	08:35:00	16:34:59	16/08	376514	405313	480
TS4.1	16:55:00	18:44:59	15/08	320114	326713	110
TS4.2	16:55:00	18:44:59	16/08	406514	413113	110
TS5.1	10:45:00	13:44:59	16/08	384314	395113	180
TS5.2	10:45:00	13:44:59	17/08	470714	481513	180
TK1	10:17:00	11:34:59	07/06	382634	387313	78
TK2	13:39:00	14:32:59	07/06	394754	397993	54

**Table 3-4:** Static and kinematic tests data collection.

Also important is the NRTK message types of the corrections at which the GPRS data link is used to transport during tests. As mentioned before, SmartNet can offer three diverse correction services, Broadcast-MAX, Auto-MAX and i-MAX. As a way to assess the performance of the different correction types, it was planned to connect to a particular message each time. However, as shown in

Table 3-5, due to it not being activated at the time of this investigation, it was not possible to try the Broadcast-MAX corrections thus only Auto-MAX and i-MAX were tested.

Tests	NRTK Correction Types
TS1, TS2, TS5.2, TK1 and TK2	i-MAX
TS3, TS4.1, TS4.2 and TS5.1	Auto-MAX

**Table 3-5:** NRTK correction service used during tests.

### 3.4 Data Analysis

The data analysis involves statistical analysis of the observations based on a thoroughly studied theory that when it is used in GPS observations it can be summarised as follows: 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 tropospheric biases, etc. and has approximately a normal distribution, whether or not the components errors are normally distributed [Mikhail and Gracie, 1981].

Therefore, common statistical formulae for normal distributed data were employed during analysis. The first step in the data analysis stage was to filter the data from outliers. Outliers are basically observations too big from the mean values that could be considered as being caused by gross errors or other anomalies and therefore were eliminated from the data. The data was processed at a 99.7% confidence level by eliminating all the observations (outliers) that are large that 3 times of the SD (Standard Deviation - Sigma).

Accuracy can be defined as how far the coordinates computed during a test are from the true values. Therefore, for each coordinate component (E, N, and H) the accuracy was calculated as the difference between the observation and the actual value. The two and three dimensional accuracies were calculated by using the well known 2DRMSE (Two Dimensional Root Mean Square Error) and 3DRMSE (Three Dimensional Root Mean Square Error) formulae respectively. Additionally, the total accuracy of a respective test was determined as the average of the accuracy at each epoch.

Precision is the degree of repeatability (or closeness) that repeated measurements display, and is therefore a means of describing the quality of the data with respect to random errors [Rizos, 1999]. It was represented by the SD of the observations (1 Sigma, about 68% of observations).

Availability was determined as the percentage of observations in which a NRTK solution (Integer Phase Ambiguities resolved) was obtained during testing [Brown et al., 2005a].

Integrity was evaluated as the percentage of observations during which the NRTK solutions were available at accuracy level better than 5 cm.

Repeatability was calculated as the difference in the percentage of observations during which the NRTK solutions were available at a accuracy level better than 5 cm in two different tests carried out under similar conditions [Gordini et al., 2006].

By using the same statistical formulae the influence of the following factors in the performance of the service was also evaluated during this research:

- Number of GPS satellites in view.
- Satellite geometry in terms of HDOP (Horizontal Dilution of Precision).
- AoC of the NRTK correction message when received at the rover.

## 4. THE NRTK GPS SERVICE PERFORMANCE

### 4.1 Accuracy and Precision

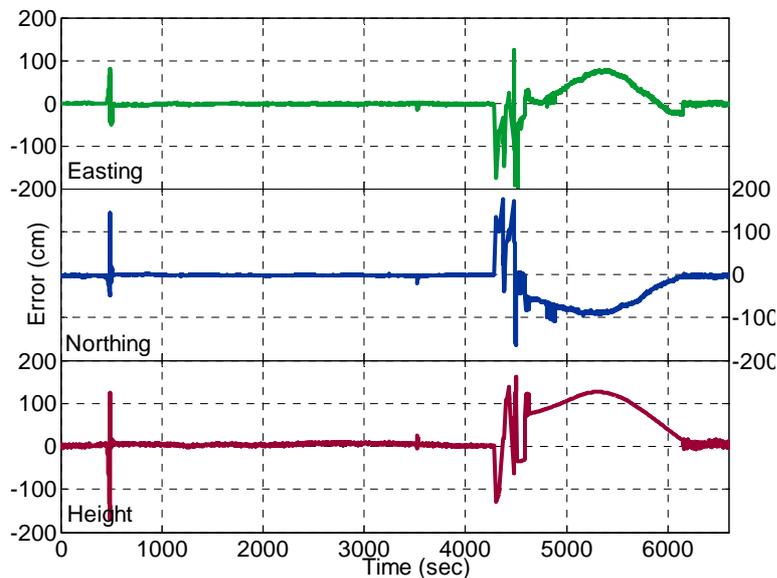
The accuracy and precision obtained during tests is summarised in Table 4-1. The results in this table are based on epochs with valid observations and include all types of solutions such as Stand-alone, DGPS and NRTK.

Test	Accuracy (cm)			2D RMSE	3D RMSE	Precision (+/- SD cm)		
	$\Delta E$	$\Delta N$	$\Delta H$	(cm)	(cm)	E	N	H
TS1	-1.03	-3.27	4.36	3.43	5.55	0.13	0.50	0.62
TS2	-0.98	-3.72	1.68	3.85	4.20	0.05	0.11	0.33
TS3	-0.67	-3.69	5.03	3.75	6.27	3.15	5.20	9.57
TS4.1	5.11	-16.69	24.75	17.45	30.29	24.91	30.50	42.09
TS4.2	-1.59	-3.14	3.47	3.52	4.94	3.38	3.05	6.19
TS5.1	-0.98	-3.20	4.06	3.35	5.26	1.79	3.37	5.40
TS5.2	-1.60	-2.97	4.34	3.37	5.50	1.23	2.41	3.89
TK1	-3.05	-7.35	-8.69	7.96	11.78	7.80	11.00	31.33
TK2	-1.51	-2.92	1.96	3.29	3.83	6.28	10.22	14.61

**Table 4-1:** Accuracy and Precision Obtained during both Static and Kinematic Tests (All Epochs).

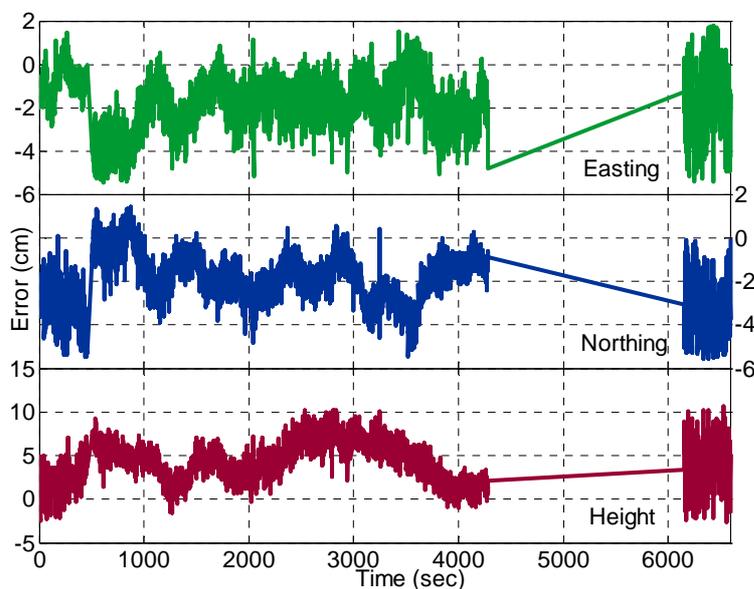
As can be seen, aside from TS4.1, centimetric accuracy in the order of 4.0 cm was achieved in the planimetric coordinates (2DRMSE) and of about 4.5 cm in the height ( $\Delta H$ ). Also, E, N and H precisions ranging from 0.05 cm to 7.80 cm, 0.11 cm to 11.00 cm and 0.33 cm to 31.33 cm were achieved respectively.

Figure 4-1 shows the accuracy achieved during TS4.1. It is very clear that between epoch 4000 and the end of the test, an event took place which forced the solution to produce errors of up to +/-200 cm.



**Figure 4-1:** ENH Errors during TS4.1 (All Epochs).

Only epochs where a fixed phase solution was achieved (NRTK Epochs) during TS4.1 are shown in Figure 4-2. As it is evident there are not NRTK solutions during the time period when the event mentioned above occurred which means that ambiguities were not fixed in that period thus explaining why large errors were presented in TS4.1.



**Figure 4-2:** ENH Errors during TS4.1 (NRTK Epochs).

Evidently, the accuracy during TS4.1 was in the centimetre level when a proper NRTK solution was achieved.

Therefore, although centimetric accuracy was met in most tests when accounting All Epochs as demonstrated in

Table 4-1, a better image of the accuracies and precisions that are achievable by using SmartNet can be gained by looking at

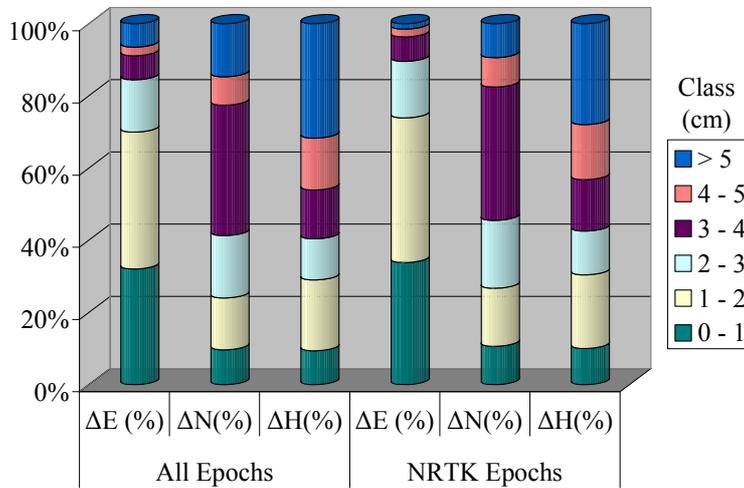
Table 4-2. This table summarises the accuracy and precision obtained only when a proper NRTK solution was achieved.

Test	Accuracy (cm)			2D	3D	Precision (+/- SD cm)		
	$\Delta E$	$\Delta N$	$\Delta H$	RMSE (cm)	RMSE (cm)	E	N	H
TS1	-1.03	-3.27	4.36	3.43	5.55	0.13	0.50	0.62
TS2	-0.98	-3.72	1.68	3.85	4.20	0.05	0.11	0.33
TS3	-1.17	-2.97	3.61	3.19	4.82	1.24	2.04	3.72
TS4.1	-1.82	-2.02	4.19	2.72	4.99	1.23	1.23	2.38
TS4.2	-1.60	-3.07	3.40	3.46	4.85	2.80	2.66	5.40
TS5.1	-1.12	-2.71	3.56	2.93	4.61	1.13	1.86	3.91
TS5.2	-1.56	-2.91	4.34	3.30	5.45	1.14	2.01	3.59
TK1	-1.05	-3.53	1.60	3.68	4.02	0.48	0.74	1.56
TK2	-1.11	-3.52	2.35	3.69	4.38	0.54	0.90	1.69

**Table 4-2:** Accuracy and Precision obtained during both, Static and Kinematic Tests (NRTK Epochs ONLY).

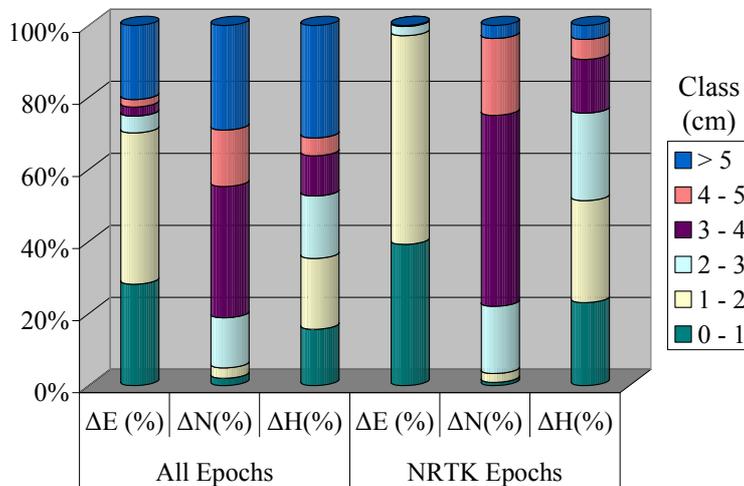
Even though it is clear that the accuracy improved to an average of -1.27 cm in the Easting, -3.08 cm in the Northing and 3.23 cm in the Height, it was the precision which showed the highest improvements during the tests from an averages of +/-5.41 to +/- 0.97 cm in the East, +/-7.37 cm to +/-1.34 cm in the North and from +/-12.7 cm to +/- 2.58 cm in the Height.

Such improvements in the accuracy and precision of the observations can also be seen in Figure 4-3 which shows how the percentage of observations with accuracy better than 5 cm increased when accounting only for NRTK epochs.



**Figure 4-3:** Percentage of Observations during Static Tests with Accuracy better or worst than 5 cm.

As shown in Figure 4-4 an even better improvement was obtained during kinematic tests with only less than 5% of valid NRTK observations over 5 cm error.



**Figure 4-4:** Percentage of Observations during Kinematic Tests with Accuracy better or worst than 5 cm.

In general, as seen in Table 4-1,

Table 4-2 and Figure 4-4 during the kinematic tests the All Epochs solution of TK2 presented better accuracy and precision than TK1. This is due to an urban canyon being included in the route during TK1 which caused signal lost in many occasions

## 4.2 Availability

Availability resulted to be a vital factor for the good performance of the SmartNet service. As demonstrated above, the accuracy and precision of the results directly depend on whether the solution obtained was NRTK or not. A summary of the availability found during tests is shown in

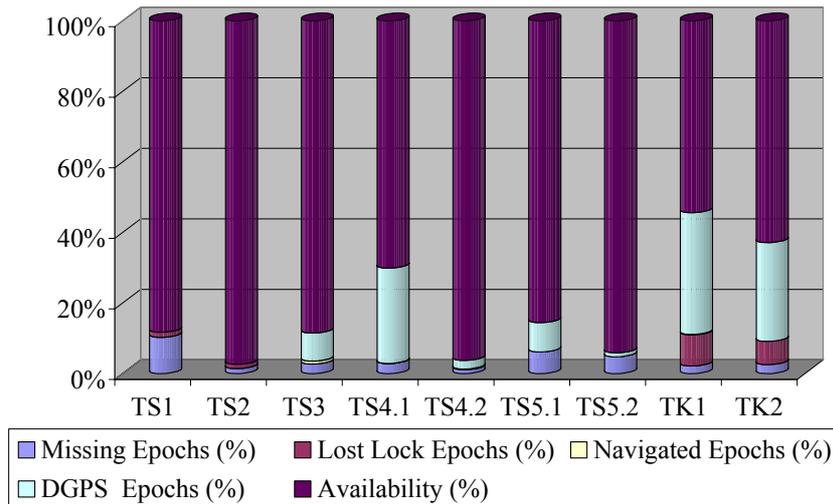
Table 4-3.

Test	Possible Epochs	NRTK Epochs	Availability (%)
TS1	7200	6356	88.28
TS2	5400	5257	97.35
TS3	28800	25490	88.51
TS4.1	6600	4628	70.12
TS4.2	6600	6354	96.27
TS5.1	10800	9241	85.56
TS5.2	10800	10164	94.11
TK1	93599	50905	54.39
TK2	64799	40736	62.87

**Table 4-3:** NRTK Availability during tests.

As can be seen in the table above, apart from TS4.1, the availability of the NRTK service during static tests was always over 85%. The highest availability was presented during TS2 (97.35%) and although it was the only static test performed completely outdoors, it is not possible to conclude that the use of the GPRS data link indoors caused the lack of availability in some of the tests. This is mainly because during two indoor tests, TS4.2 and TS5.2, high availability levels of 96.27% and 94.11% respectively were also achieved.

Figure 4-5 shows the detailed availability results. TS4.1 and TS4.2 were specially designed to evaluate the repeatability of the service and therefore were performed during the same time but at consecutive days. Consequently, approximately the same number of satellites and geometry should have been available during those tests; in addition, there were apparently similar weather conditions. However, although the same sort of availability should have been experienced during both tests, it is possible to see that TS4.1 presented about 26% of DGPS epochs whereas TS4.2 only about 2.42% which largely made the difference between the actual availability seen during both tests.

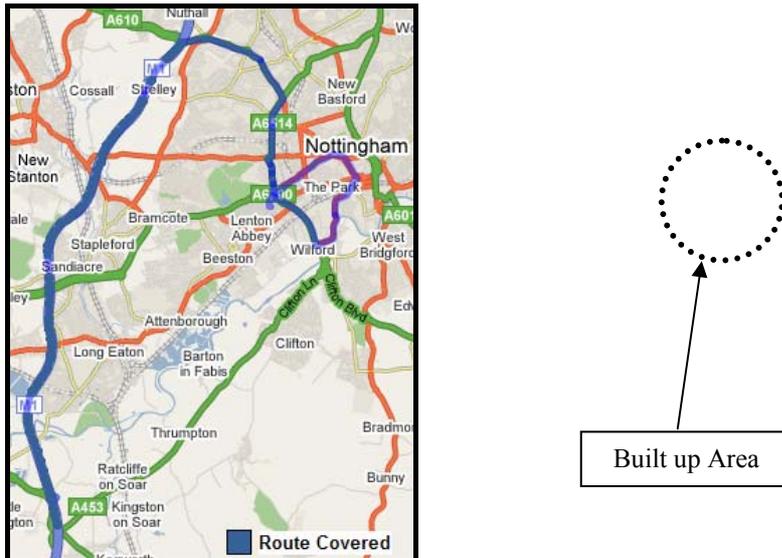


**Figure 4-5:** Detailed percentage of observations performed under the different solution types during tests.

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 the large majority of epochs apart from NRTK were DGPS, it is not possible to say that problems with the GPRS data link caused the availability during TS4.1 to drop. Therefore, aside from communicational problems, what could have impeded the ambiguities during TS4.1 of being solved? Factors such as low number of satellites in view, constellation geometry, high ionospheric activity and problems in the completeness of the corrections could have caused this anomaly.

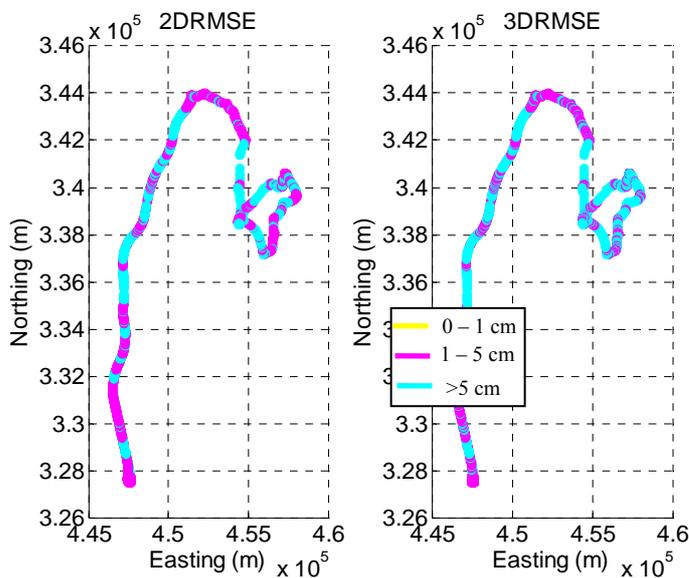
Figure 4-5 also shows the availability seen when performing kinematic tests. In average, only about 58% of the time NRTK solutions were obtained which is considerably lower than that achieved during static tests (over 85%). Due to the route travelled during both tests the availability of TK2 was about 8% better than that of TK1.

Aside for an extra route formed by a built up area in the Nottingham City Centre covered during TK1, during both kinematic tests the same trajectory was travelled. The data collection started at the IESSG car park, continued through the A6514 until the A610 where the car headed to the junction 26 on the M1, then went all the way down to the junction 24 of the M1, and came back by the same route to the IESSG car park where the data collection finished. Additionally, during TK1, some roads (Derby Rd., Maid Marian Way, Wilford Rd., Queens Dr., and A52) forming a ring around the Nottingham City Centre were covered before returning back to the IESSG car park. A sketch of these trajectories is shown in Figure 4-6.



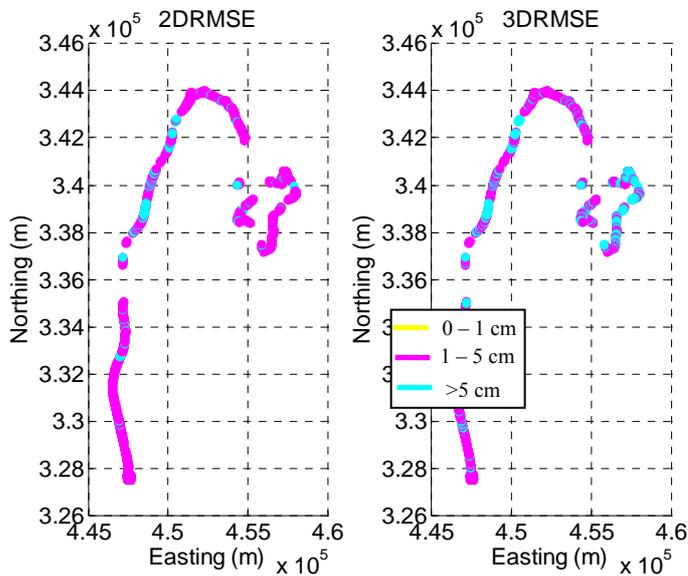
**Figure 4-6:** Sketch of the Routes Covered during Kinematic Tests.

Figure 4-7 shows the 2D and 3D RMSE errors observed during TK1, representing over a scatter of the route covered during the test. As can be seen, most of the built up area saw errors higher than 5 cm. The rest of the trajectory which was mainly formed by a part of the M1 motorway in the Midlands showed better results with errors between 1 and 5 cm in several observations.



**Figure 4-7:** TK1 2D and 3D RMSE Errors as Observed in the Covered route (All Epochs)

Figure 4-8, on the other hand, shows the same information as above but includes only the NRTK epochs. It is evident that there are many gaps in which a NRTK solution was not possible; particularly, the availability in the built up areas is much lower than in the rest of the route. Nevertheless, most of the achieved NRTK positioning accuracy were under 5 cm error.



**Figure 4-8:** TK1 2D and 3D RMSE Errors as Observed in the Covered Route (NRTK Epochs).

Many factors were found to cause the lack of availability during the kinematic tests and they are listed as follows:

- GPS signals blockage and surely high amount of multipath were originated when passing through flyover bridges which are very common along the M1 motorway (refer to
- Figure 4-9). The signal blockage and multipath caused the ambiguity fix to be lost and therefore the NRTK solution. This situation occurred several times while in the M1 and was clearly perceived during the tests by the beeps of the rover receiver.



**Figure 4-9:** View of Flyover Bridges from the Car during TK1 (M1 Motorway).

- The M1 motorway is a very busy route for heavy lorries which when passing next to the testing car they also produced similar effects as those caused by the flyover bridges. Figure 4-10 shows two lorries next to the testing car when stopped at a traffic light at the junction 24 of the M1. Those lorries worked as a mobile obstacle producing signal blockage and dynamic multipath when they are next to the testing vehicle.

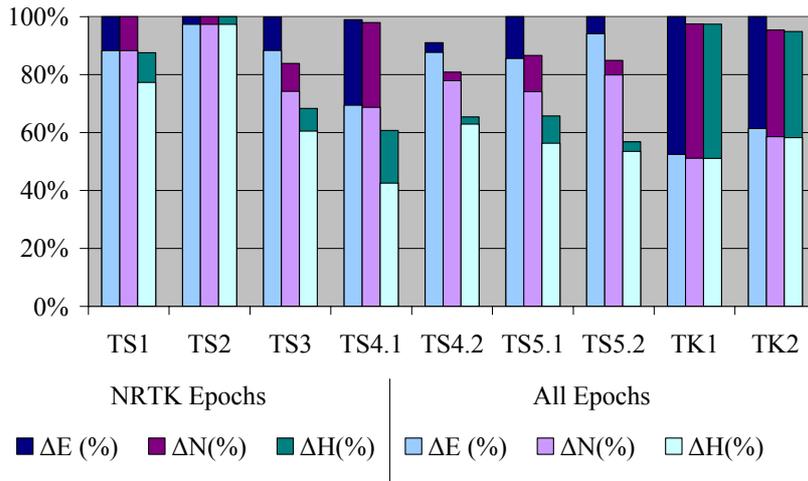


**Figure 4-10:** Lorries in the M1 Motorway Blocked GPS Signals and Caused Dynamic Multipath.

- In the built up area the availability was severely affected by the common factors found in an urban canyon environment when using GPS. Tall buildings, narrow roads, trees canopies were a constant during TK1 and the consequences were signal blockage and shadowing and multipath.

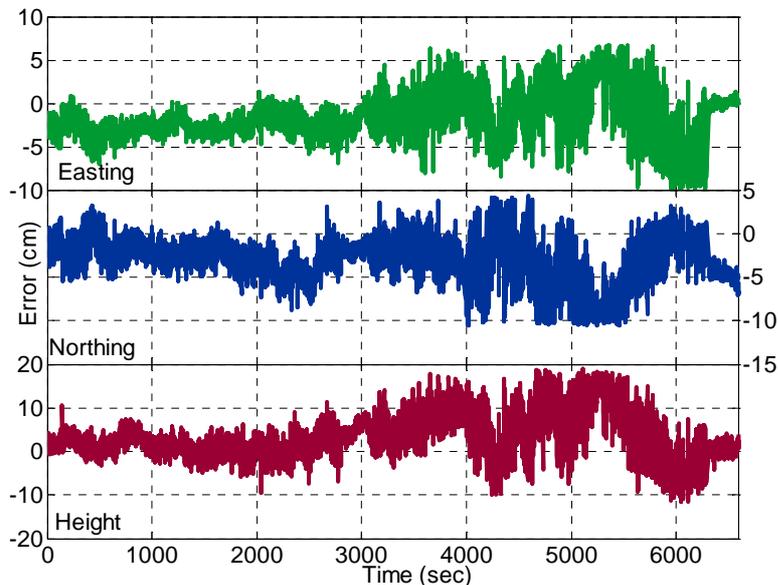
### 4.3 Integrity

Integrity, as mentioned before, was evaluated in this research as the percentage of NRTK observations with accuracy better than 5 cm. A summary of integrity results is presented in Figure 4-11. In general, averages of 98.87% in the Easting, 91.90% in the Northing and 77.41% in the Height were obtained when accounting only NRTK Epochs. However, as expected, when considering All Epochs the integrity dropped to averages of 80.50% in the Easting, 74.45% in the Northing and 62.17% in the Height.



**Figure 4-11:** Percentage of observations with errors better than 5 cm (Integrity).

An outstanding integrity of 100% in all the coordinates was obtained during TS2. Such a result contrasts with the integrity achieved in TS4.2 which was one of the worst of all the tests. However, when looking at Figure 4-12 it is evident that TS4.2 accuracy was not too low. The Easting coordinate was only 9% of the time worst than 5 cm and the figure shows that, when it was over 5, it was not higher than -10 cm. The Northing coordinate, although being about 20% of the time worst than 5 cm, did not go above -12 cm. On the other hand, the Height was about 35% of the time over the 5 cm target but the highest error seen during that time was only about 20 cm.



**Figure 4-12:** ENH Errors during TS4.2 (NRTK Epochs).

#### 4.4 Repeatability

Repeatability was considered in this research as how similar the integrity results of two different tests was. Two pairs of tests were specially designed in order to evaluate the

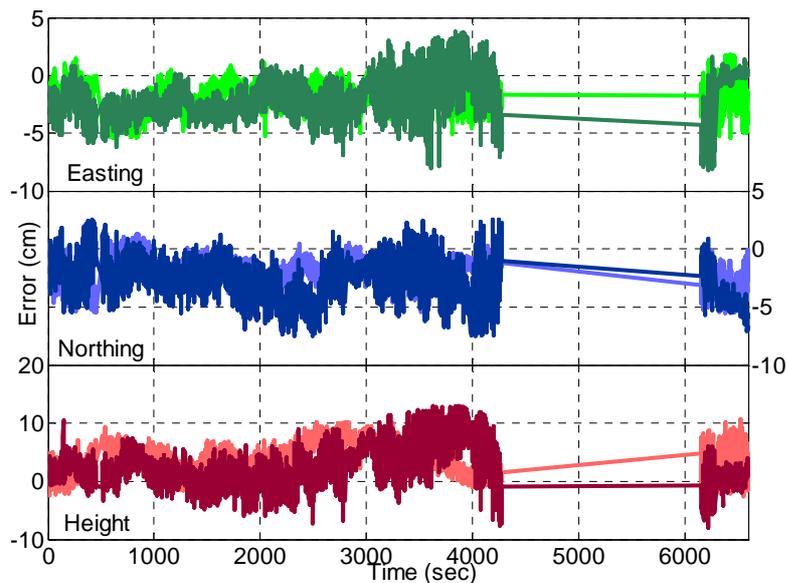
repeatability of SmartNet service, TS4.1 – TS4.2 and TS5.1 – TS5.2. If the integrity found during these tests was similar, when the Integrity of one of the tests within the couple is divided by the Integrity of the second test, the result should be very close to 1. The result from this division is called in this paper “Repeatability Factor” and is shown in Table 4-4.

Test	NRTK Epochs			All Epochs		
	$\Delta E$ (%)	$\Delta N$ (%)	$\Delta H$ (%)	$\Delta E$ (%)	$\Delta N$ (%)	$\Delta H$ (%)
TS4.1/TS4.2	1.09	1.21	0.93	0.79	0.88	0.68
TS5.1/TS5.2	1.00	1.02	1.16	0.91	0.93	1.05

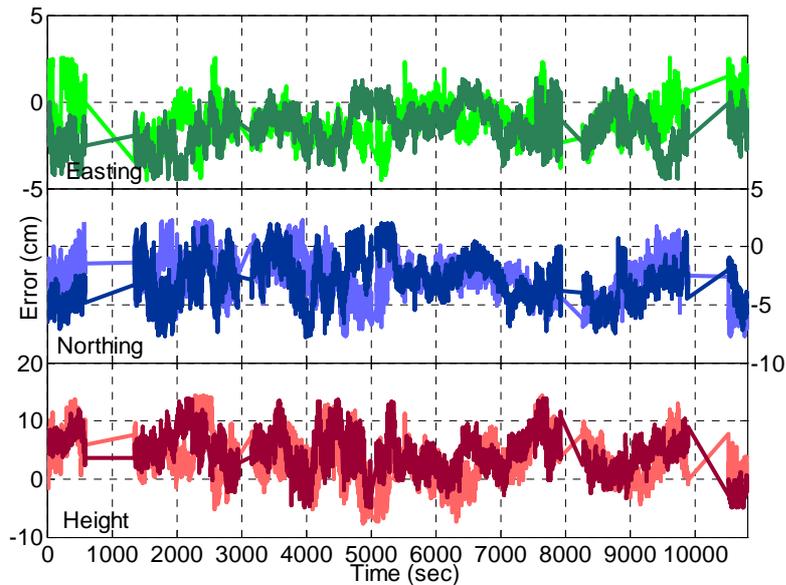
**Table 4-4:** Repeatability Factors Results.

Repeatability as high as 1 was achieved in the Easting coordinates during TS5.1 - TS5.2 and as low as 1.21 in the Northing coordinates of TS4.1 - TS4.2. In average, high repeatability factors of 1.08 in the first pair and 1.06 in the second pair were obtained.

In addition to the repeatability factor measure, by looking at Figure 4-13 and Figure 4-14, it is possible to confirm that the accuracy of the mentioned tests was repeatable at the centimetre level.



**Figure 4-13:** Repeatability between TS4.1 (Light Colour) and TS4.2 (Dark Colour). There are 4331 common epochs of a total of 6600 epochs.



**Figure 4-14:** Repeatability between TS5.1 (Light Colour) and TS5.2 (Dark Colour). There are 8233 common epochs of a total of 10800 epochs.

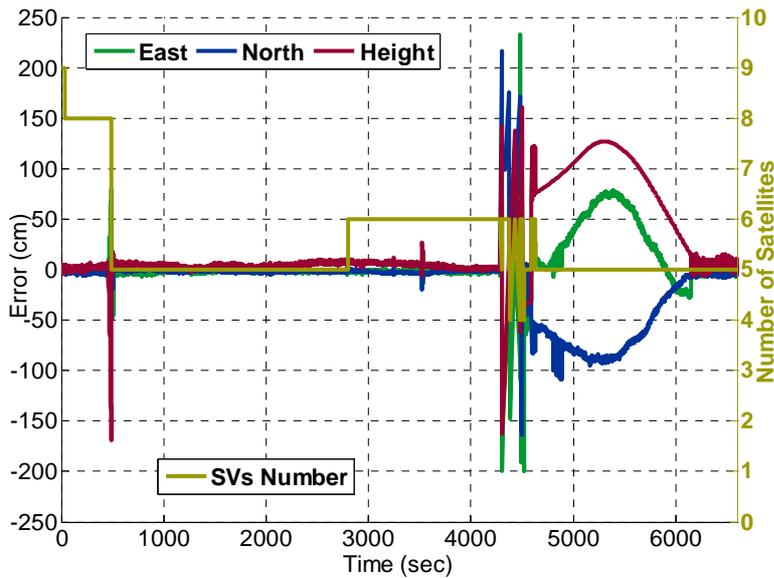
Meanwhile,

Figure 4-14 also shows that both services Auto-Max (TS5.1) and i-Max (TS5.2) produced observations with centimetre level accuracy.

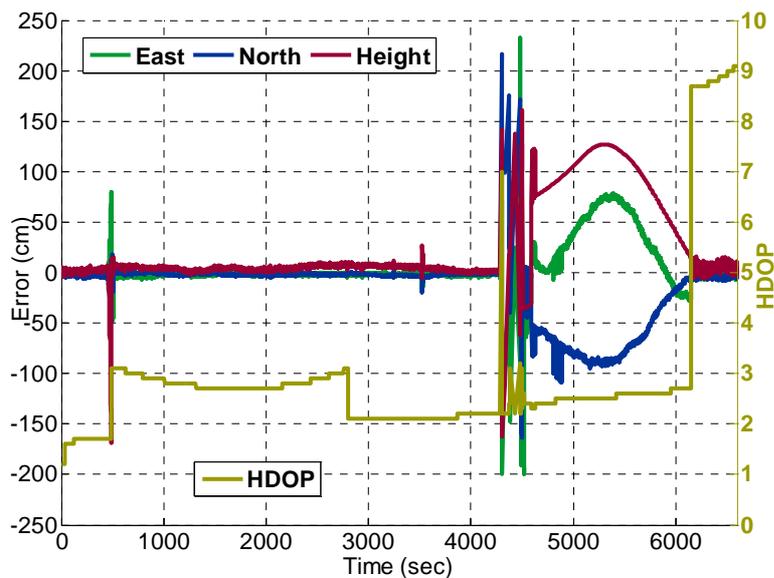
#### 4.5 Influence of the Number of GPS Satellites in View and their Geometry

Figure 4-15 and

Figure 4-16 show the values of the mentioned factors during TS4.1 which as explained before presented a low accuracy and availability. It is clear that at about epoch 4300 when the NRTK solution started to be lost, the number of satellites in view dropped to 4 and the HDOP went up to about 7. This situation seems to be cyclical during some period of time with new satellites rising and therefore the satellites geometry changing which obviously caused the lost in the NRTK solution and a drop in the observations accuracy.

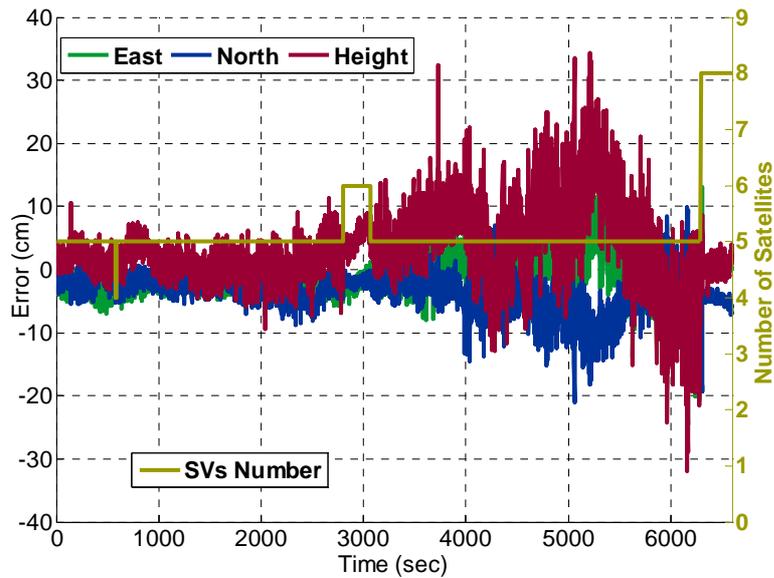


**Figure 4-15:** Influence of the Number of GPS satellites in View over the Errors during TS4.1 (All Epochs).

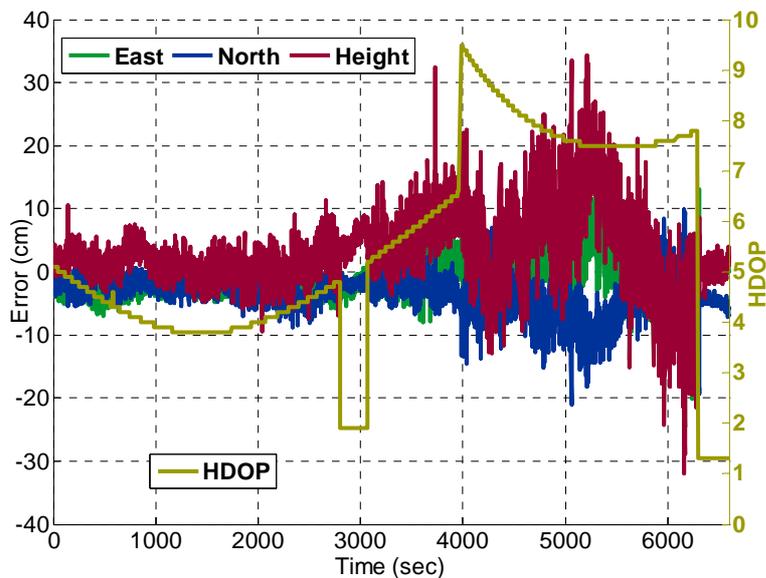


**Figure 4-16:** Influence of the HDOP over the Errors during TS4.1 (All Epochs).

Figure 4-17 and Figure 4-18 are evidences that the accuracy during TS4.2 started to drop at about epoch 3000 due to a sharply increase in HDOP which went from about 2 to 9 in a few minutes. The fall of HDOP took place when there were only 5 satellites in view which were sure forming a bad geometry. As soon as the number of satellites increased to 8 toward the end of the test HDOP value dramatically decreases to about 1.2 and also did the accuracy.



**Figure 4-17:** Influence of the Number of Satellites in View over the Errors during TS4.2 (All Epochs).



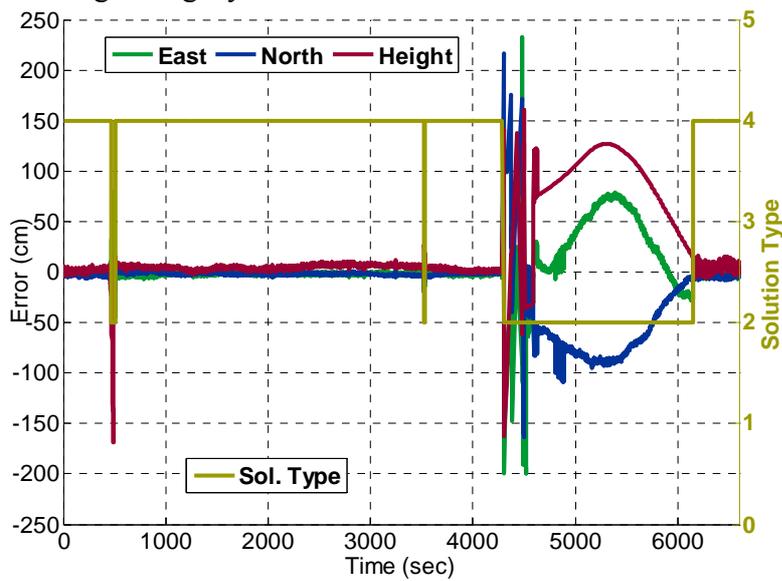
**Figure 4-18:** Influence of the HDOP over the Errors during TS4.2 (All Epochs).

#### 4.6 Age of Correction

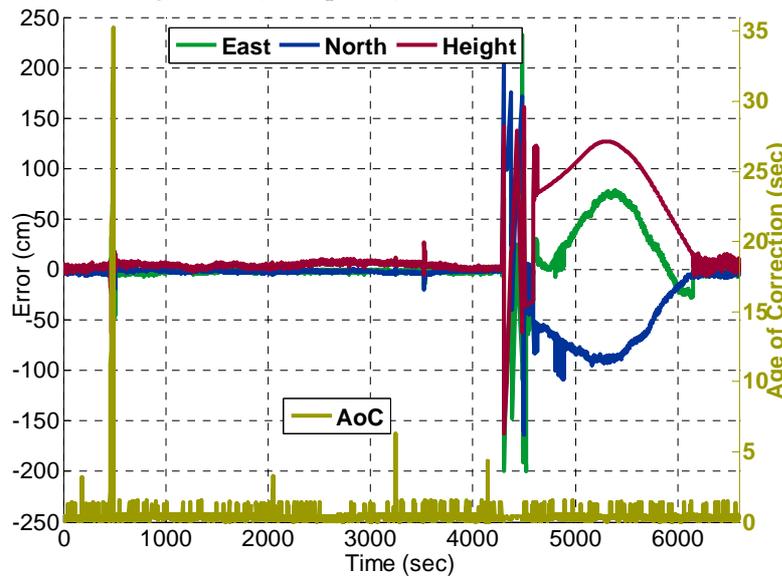
The influence of the AoC over the accuracy of the solution is not as clear as per the two factors above. Rather than directly influencing the accuracy, the AoC affects the Types of Solutions. As demonstrated in Figure 4-19 and

Figure 4-20 as soon as the AoC was older than about 10 sec the NRTK solution was replaced by a DGPS solution which could have dropped to a Stand-alone solution if the AoC was older than about 60 sec. The effect of the Types of Solutions over the SmartNet performance was implicitly discussed in the Availability; nevertheless, it can be said that only when the

solution achieved was NRTK the service provided centimetric accuracy and precision and also high integrity.



**Figure 4-19:** Influence of the Type of Solution (1 = Stand Alone, 2 = DGPS and 4 = NRTK) over the Errors during TS4.1 (All Epochs).



**Figure 4-20:** Influence of the AoC over the Errors during TS4.1 (NRTK Epochs).

## 5. CONCLUSIONS

This research demonstrated that SmartNet can offer high accuracy in an order of 1.27 cm in the Easting, 3.08 cm in the Northing and 3.23 cm in the Height to its general users. Similar results were obtained in the precision (1-sigma), which was of centimetre level when the integer ambiguities were fixed ( $\pm 0.97$  cm in the East,  $\pm 1.34$  cm in the North and  $\pm 2.58$  cm in the Height).

The availability of the NRTK solution was the main drawback faced during tests. The centimetric accuracy and precision mentioned above were achieved during about 90% of the time in static tests and 58% during the kinematic tests. The values of integrity and repeatability obtained from the system were also excellent only when NRTK was available.

The lack of availability seen during the kinematic tests was mainly caused by GPS signal disturbances and in a lower extends by the interruptions of the GPRS communication link. Signal blockage, shadowing and also possibly multipath caused by static (flyover bridges, buildings, etc.) and mobile (lorries, etc.) obstacles along the testing routes directly affected the availability performance by causing the lost of the NRTK solution. The same factors, in addition to common mobile phone coverage problems, also influenced the GPRS wireless link by interrupting the delivery of the NRTK correction messages and therefore caused a high AoC which originated breaks in the NRTK solution.

On the other hand, during static tests, the gaps in the service were caused by the problems directly related to the GPS system. Low number of satellites in view and high HDOP values were substantially influencing the solutions. It was clearly evident that a low number of satellites originated the loss of the NRTK service; this was because in order to solve 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 rover site, and to keep the solution four satellites are needed. Also, high HDOP values were directly related to the low accuracy which caused the interruption of the NRTK solution. It was also observed how some epochs went from NRTK to DGPS immediately after the HDOP had suffered sharply increases due to changes in the constellation and therefore also introducing inaccuracies in the observations.

It is important to mention that since the tests presented in this paper were carried out a series of upgrades to SmartNet have been performed. These upgrades have seen the receivers and antennas within SmartNet's CORS replaced to support multiple GNSS constellations such as GPS, GLONASS and future GALILEO. The general performance of SmartNet is expected to improve after these upgrades have been completed.

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