EVALUATING THE PERFORMANCE OF NRTK GPS POSITIONING FOR LAND NAVIGATION APPLICATIONS

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BIOGRAPHY

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Mark Burbidge is the UK GNSS Network and Technical Support Manager for Leica Geosystems. Mark started his career in electronic engineering as an apprentice with a flight simulation company, before landing a job with a survey manufacturer in 1990. Since then Mark has held several technical positions within land surveying manufacturers, receiving first hand training in Japan, Europe and America. For the past 5yrs Mark has specialised in GPS/GNSS and more recently Networked GNSS. Mark was the first person in the UK to complete the Spatial Data Management NVQ 4, with RICS and after further studies, has gained the RICS designation as Chartered Land Surveyor and full membership of the Institution of Civil Engineering Surveyors. He has also been part of the RICS Geomatics faculty board, the RICS Mapping and Positioning Panel and is now the FIG commission 5 UK representative, for positioning and measurement.

ABSTRACT

Network RTK (NRTK) GPS positioning is a technique that can offer centimetric accuracy in real time by employing GPS raw carrier phase observations gathered from a network of CORS (Continuously Operating Reference Stations) in order to create models that mitigate the distance dependent errors acting within the area covered by the CORS.

This technique has been considerably developed and tested during recent years and in 2006 the Radio Technical Commission for Maritime Services (RTCM) introduced a new RTCM standard-10403.1 (RTCM version 3.1) for differential GNSS services which regularizes the use of GNSS observations from CORS for the production of NRTK corrections.

In Great Britain (GB), Leica Geosystems in partnership with Ordnance Survey GB is offering a NRTK GPS correction service to its clients called SmartNet which works under the RTCM version 3.1 standards. SmartNet is currently able to offer two kinds of NRTK GPS corrections: i-MAX which is specially designed to support subscribers with old GPS receivers based on the previous RTCM version 2.3 standards and Auto-MAX that is a realization of the newest RTCM 3.1 standard.

NRTK have until now been particularly used for surveying applications; however, the introduction of the new standard together with the development and improvement of the NRTK concept and the realization of the technique through operation of commercial services such as SmartNet have significantly increased the possibilities of using NRTK in a broader range of applications such as land navigation.

NRTK can effectively position users within an area covering a few hundreds of square kilometers or as

is the case of SmartNet in bigger areas covering whole countries. The coverage of a particular network is only limited by the number of available CORS and the quality of the wireless data link used in order to transmit the corrections to the users. Such a coverage advantage gives NRTK users a much improved positioning flexibility and mobility which makes this technique especially suitable for navigation applications.

This research investigates the performance of the NRTK GPS service offered by SmartNet when it is used for vehicle positioning. Road tests were carried out in order to evaluate the quality of NRTK based on important performance measures such as accuracy, mobility and availability.

Keywords. Network RTK GPS, land navigation, road surveying, intelligent transport systems, performance, availability and mobility.

1. INTRODUCTION

The successful use of GPS positioning in land navigation applications such as in Satnav devices has been constrained to the Standalone GPS technique which can offer an accuracy of only a few metres to tens of metre level. However, such accuracy is not enough for applications in which precise knowledge of vehicle position is required. For instance, kinematic land applications such as precise navigation, lane based traffic or fleet management, active cruise control and self parking systems that require continuous high accuracy vehicle position have been limited to controlled environments where conventional RTK GPS can be used.

Conventional RTK GPS 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 satellites 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 differentiation 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 above drawbacks of conventional 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 can offer many other advantages such as much longer baseline length, no need of setting up any project based reference stations and use of two dual frequency receivers; therefore, significantly decreasing costs but increasing performance and flexibility.

Taking advantage of the mentioned NRTK's benefits, many NRTK commercial services have been established in different countries in the past few years. Such is the case of SmartNet which is operated in the UK by Leica Geosystems (UK) in partnership with Ordnance Survey Great Britain (OSGB) since January 2006. SmartNet works under the new RTCM version 3.1 standards and can also support subscribers with old GPS receivers based on the previous RTCM version 2.3 standards.

SmartNet offers NRTK GPS service across all the UK allowing centimetric accuracy as demonstrated for several static and kinematic trials (Meng et al. 2007). The coverage of this high accuracy is only limited by the number of CORS and the availability of the mobile phone network signals that allow the wireless transmission of the NRTK correction messages from a data centre to the final users via GPRS.

Such a broad coverage and high accuracy would surely open the path to allow the use of NRTK GPS in massive kinematic road applications where accurate awareness of the vehicle location is needed. This paper describes the preliminary results of the studies being carried out at the IESSG in the University of Nottingham that include the analysis of the actual positional quality of the NRTK GPS SmartNet service from an end user's point of view, in terms of its accuracy, availability and mobility when employed in real time road vehicle positioning.

2. SMARTNET AND ITS POSSIBLE USE IN REAL TIME ROAD VEHICLE POSITIONING

Currently, SmartNet comprises a total of about 142 CORS that are situated fairly evenly in the whole country as shown in Figure 1. Since July 2007 Leica Geosystems has been also offering the SmartNet service in Ireland and Northern Ireland. Although the majority of 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. 8 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 software suite called GPS Spider is responsible for processing the observations and producing the NRTK corrections as per the MAC technique which is the most recently developed NRTK GPS technique and has its origins from a jointly research carried out by Leica Geosystems and Geo++ in 2001 (Euler et al. 2001). MAC is the base for the RTCM 3.1 format message which is the new standard for Differential GNSS that fully supports NRTK GPS (RTCM 2006). As mentioned before, support for subscribers with old GPS receivers is also provided by SmartNet in the form of the i-MAX correction messages which can work under the 2.3 RTCM standards. Once the NRTK corrections have been produced they are broadcast to the service's subscribers via GPRS under the NTRIP standard or via GSM without the need of any particular protocol.

The coverage of any NRTK GPS service is only limited by the number of CORS and the availability of mobile phone networks capable of allowing GSM or GPRS connections. By having all the UK territory covered with CORS (as can be seen in Figure 1), SmartNet for instance, can allow high 3D positional accuracy in all the UK's areas where a wireless GSM or GPRS connection can be established. Past tests have demonstrated that the SmartNet's 3D achievable accuracy is normally better than 5 cm (Aponte et al. 2008).

Many Intelligent Transport Systems (ITS) applications such as precise vehicle navigation, lane based traffic or fleet management, active cruise control and parking guidance and information require real time high rate accurate knowledge of the vehicle position. Such a requirement would be undoubtedly met by a NRTK positioning service as SmartNet. By fitting vehicles with dual frequency GPS receivers capable of accepting RTCM correction messages via GSM/GPRS, SmartNet could help position and track them at the lane level which, as mentioned by Meng et al. (2008), is the current bottleneck for precise ITS applications.

3. PERFORMANCE ASSESSMENT METHODOLOGY

Two preliminary kinematic tests, T1 and T2, were carried out recently in order to evaluate the general performance of SmartNet when employed for vehicle positioning applications. The objectives and configuration used for each test are shown in Table 1. Although in different ways, both tests were intended to assess the accuracy of the NRTK positioning solution. T1's real time positions were plotted in Google Earth (http://earth.google.com) which allowed knowing the position of the vehicle to the lane level. On the other hand, T2's results were compared with a more accurate solution produced with an integrated Inertial Measurement Unit (IMU) and post-processed GPS platform.

Table 1: Configuration of the performed tests including test objective, NRTK method used and parameters for cut off angle and observation rate in Hz.

Test	Objective	NRTK method	Cut off angle	Obs. rate (Hz)
T1	Accuracy (against digital map), availability and mobility.	I-MAX	10	1
T2	Accuracy (against IMU/GPS), availability and mobility.	I-MAX	10	1

All the tests had a general objective, i.e., to examine the availability and mobility of NRTK on kinematic vehicle applications.

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 (Burbidge 2006). However, only the service called i-MAX was used during tests as it is the only NRTK correction message currently available for all kind of users e.g. those with old and new receivers.

As a preliminary investigation, these tests were mainly intended to evaluate the performance of the SmartNet service from the end users' point of view; therefore, both tests were carried out using the service "as it is". This means that, as SmartNet is an actual commercial NRTK service in Great Britain, there was no free access to the set up of the corrections or the CORS. Therefore, the corrections received during testing, were the same as any other subscribers would have received if using the service at the same location, and under other external environments. The location of the closest SmartNet CORS to the route covered during tests is shown in Figure 2.

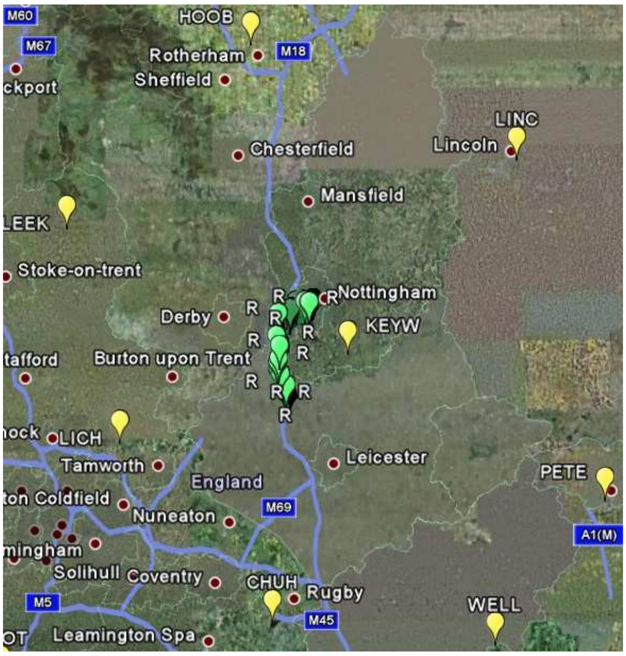

Figure 2: SmartNet CORS configuration used during both tests (icons in yellow, HOOB, LINC, LEEK, LICH, CHUK, WELL, PETE and KEYW). Vehicle route is indicated in green. The average distance between CORS is about 47.32 km.

T1 covered a total trajectory of about 92 km from the IESSG car park on the University Park campus in Nottingham up to junction 23 in the M1 and back to the IESSG car park. In order to best understand the NRTK performance results, the data collected during T1 was divided in four tracks. Tracks 1 and 2 corresponded to the return route covered from junction 25 up to junction 23 in the M1. This trajectory was travelled twice and therefore Track 1 corresponds to the first journey and Track 2 to the second one (each journey covered about 37 km). These two tracks would help to understand the performance of NRTK GPS on a busy Motorway such as the M1. Tracks 3 and 4 covered respectively a semi-urban route from the IESSG car park up to junction 25 in the M1 and then the return journey and had a distance of about 9 km each.

T2 on the other hand, was all considered as a Motorway environment and covered a distance of roughly 32 km from a car park in Toton Ln (B6003) closes to junction 25 down to junction 23 and then back to end just before arriving again at junction 25.

The detailed observation dates, times and duration are showed in Table 2. T1 lasted for 01:20:00 (hh:mm:ss) including all the tracks and T2 had a duration of roughly 30 minutes.

Table 2: Start and finish UTC time for each test including their duration.

Test	UTC Start Time		UTC Finish Time		Duration
	Date	Time	Date	Time	hh:mm:ss
T1	20/05/08	13:46:00	20/05/08	15:05:59	01:20:00
T2	08/07/08	12:23:20	08/07/08	12:53:07	00:29:48

Both tests were performed using the IESSG's surveying van as the probe vehicle. This van is especially equipped for road testing (Figure 3).

Figure 3: IESSG's surveying van.

The equipment configuration used during tests T1 and T2 can be seen in Figure 4. The GPS signal from a Leica AX1202 antenna was read by a Leica 1200 dual frequency geodetic type of GPS receiver.

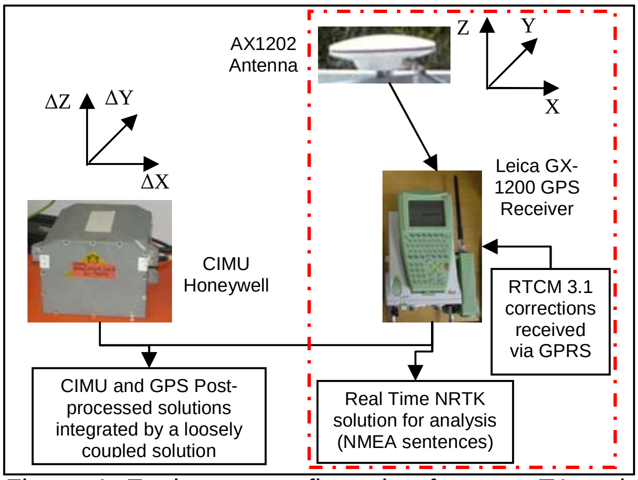

Figure 4: Equipment configuration for tests T1 and T2. T1 equipments' configuration enclosed in red dashed line.

The receiver used a GPRS data link in order to receiver the NRTK corrections from SmartNet. The GPRS service is provided by Vodafone which is a well established UK mobile phone company with a good coverage in the Midland region in the UK. The real time NRTK solution and the raw GPS observation for post-processing were all stored for subsequent analysis. The configuration above was used for both tests.

Additionally, T2 included the use of a CIMU Honeywell IMU logging real time data referred to the GPS antenna position. This data was combined with the post-processed GPS solution using a loosely coupled integration in order to get the 'true' coordinates that were subsequently used as a reference to analyse the accuracy of the NRTK positioning solution. The integrated IMU/GPS benchmark was expected to have an accuracy level of a few centimetres when no GPS outages were presented.

4. THE AVAILABILITY AND MOBILITY OF THE NRTK GPS SERVICE

The availability was determined as the percentage of observations in which a NRTK GPS solution (integer ambiguities resolved) was obtained during a test (Brown et al. 2005). As predictable this is a vital index for the good performance of the SmartNet service. The accuracy of the observations directly depends on whether the solution obtained is NRTK or not.

Table 3 shows the detailed availability results. It is possible to see that about 45% of the epochs observed in the Motorway were NRTK solutions (T1-1, T1-2 and T2) which is not much better than the average of NRTK epochs (41.5%) obtained in the semi-urban tracks (T1-3 and T1-4). Except for T1-3, that presented a high percentage of Lost Lock (29,86%) and Standalone position epochs (20.86%), most of the observations obtained, aside from NRTK, were Differential GPS (DGPS) which accounted for 36.50% of total solution.

Table 3: Detailed percentage of observations performed under different solution types during the tests including availability of NRTK observations.

Test	Track	Lost Lock	Standalone	DGPS	Availability
T1	1	16.41	0.48	37.83	45.29
	2	9.58	0.00	39.60	50.82
	3	29.86	20.86	15.57	33.71
	4	12.34	0.00	36.76	50.90
T2	-	7.44	0.00	52.80	39.77

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 correction messages are still being received. Therefore, because most of the epochs apart from NRTK were DGPS, it is not completely possible to say that problems with the GPRS data link caused the availability to drop during tests.

Furthermore, the age of the correction message (AoC) received at the rover could also help to understand whether the drop in the availability is related to the RTCM message reception. The GPS receiver used during tests can only solve the ambiguities for RTCM messages with an AoC lowest than 10 sec whereas there could be a DGPS solution when the AoC is between 10 and 60 seconds old. Table 4 contents the type of solution that could have been achieved during the tests with the available AoC. As can be confirmed when looking at the cited table, the low availability of the NRTK solution shown in Table 3 might has not been induced by missing RTCM correction messages. Aside from T1-3, the available messages were in theory capable of providing a NRTK solution over 84% of the time which is about twice the actual number of solutions in which the ambiguities were fixed. Only during T1-3 the lack of correction message can be demonstrated by the elevated number of stand alone solutions (navigated) which was over 20%.

Table 4: Detailed percentage of observations that could be theoretically performed under different solution types during the tests according to the AoC. Availability (NRTK) requires AoC 0 to 10 sec; DGPS requires AoC 10 to 60 sec; Navigated requires AoC > 60 sec or empty; Lost Lock means that no information was collected.

Test	Track	Lost Lock	Standalone	DGPS	Availability
T1	1	16.41	0.6	1.43	81.56
	2	9.58	0.85	3.94	85.63
	3	29.86	20.86	2.43	46.85
	4	12.34	0.77	3.86	83.03
T2	-	7.44	0.17	6.21	86.18

Nonetheless, the AoC does not indicate that all the required data is 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 be not correct or complete. The correction message is formed by pseudoranges and phases. When pseudoranges are used each epoch gives a solution independently of prior or later observations. Phases need more data during a certain period else a main factor for missing fixed solutions. Thus, if some phases of satellites are missing due to the communication link it will have a bigger impact on integer fixing compared with DGPS solution. Therefore, 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.

Many factors were found to cause the lack of availability during the 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 5). The signal blockage and multipath caused loss of track to the GPS signal and therefore the ambiguity fixes to be lost. This situation occurred several times while on the M1 and is clearly noted in Table 3 which shows the high percentage of Loss of Lock.

Figure 5: View of a typical flyover bridge from the probe van during tests (M1 Motorway). These bridges caused GPS signal blockage along the M1.

- The M1 motorway is a very busy route for heavy lorries which when passing next to the testing van also produced similar effects as those caused by the flyover bridges. Figure 6 shows two lorries next to the testing van when stopped at a traffic light at the junction 23 in the M1. Those lorries worked as a mobile obstacle producing signal blockage and dynamic multipath when they were next to the testing vehicle.

Figure 6: Lorries in the M1 Motorway blocked GPS signals and potentially caused dynamic multipath.

- In the semi-urban tracks (T1-3 and T1-4) the availability was affected by the common factors found in this kind of environments when using GPS. Buildings, trees canopies caused signal blockage and shadowing, and multipath.

- The high percentage of DGPS epochs presented in the solutions (see Table 3), even in occasions when the right conditions were presented in order to have fixed ambiguity solutions (more than five satellites in view and uninterrupted reception of the RTCM message), might suggest some problems in the cycle slips and/or ambiguity resolution algorithms; however although this assumption needs further investigation, the questioned algorithms have always demonstrated high robustness during previous research (Brown et al. 2005; Aponte et al. 2008). Additionally and what is suspected to be the main cause of the high number of DGPS epochs, the 1200 GPS receiver used as rover during this research is a geodetic receiver whose algorithms are designed for high precision surveys which means that it aims for accurate and reliable fixes rather than producing a fix for each epoch.

Figure 7 shows the typical problem saw when passing down fly over bridges at the M1 motorway. It is possible to see that when travelling in the south direction the solutions obtained were NRTK up to just before passing down the bridge when the lock to the GPS signals was lost and recovered after about 5 seconds once out of the bridge. However, the solution obtained immediately after the bridges resulted to be a DGPS epoch most of the time. Given that there were not other obstacles after the bridge the NRTK solution was normally recovered after about 5 - 15 seconds. In many opportunities the NRTK solution was not recovered but after more than 15 seconds or in some occasions after a few minutes. It is also possible to see in Figure 7, when travelling in the north direction, how sometimes the NRTK solution was lost even a few seconds before passing through the bridges.

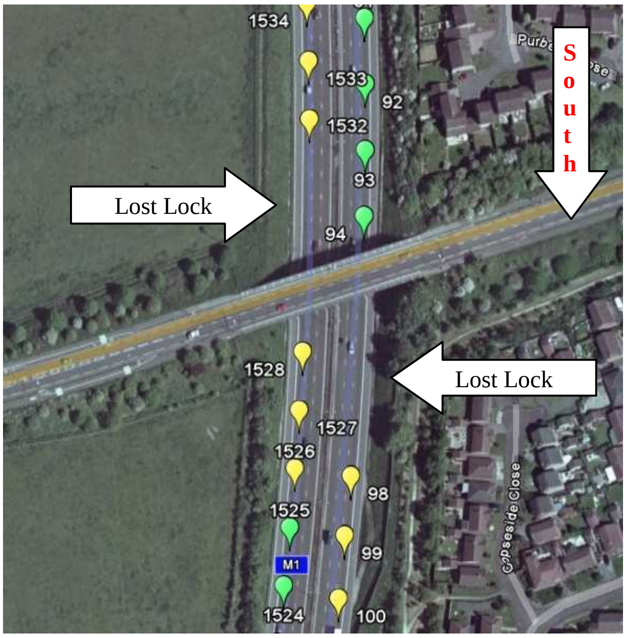

Figure 7: Typical problem faced during tests. Fly over bridges caused GPS signal blockage and therefore lost of lock (NRTK epochs in green and DGPS icons in yellow).

In terms of mobility, the NRTK solution demonstrated to be very acceptable. Although with the interruptions described above, SmartNet allowed high rate fixed positions in all the environments tested and at any speed the probe van travelled at (between 0 and 70 mph).

5. THE ACCURACY OF SMARTNET IN VEHICLE POSITIONING

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 X, Y, and Z the accuracy was calculated. The total accuracy of a respective test was determined as the average of the accuracy 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 observations (1 Sigma, about 68% of observations).

However, the concepts above could be applied only for T2 results, which is the tests where a more accurate and precise solution (IMU/GPS integration) was also produced. Nevertheless, the accuracy during T1 was studied by plotting the observations in Google Earth which, as can be seen in Figure 8 can help to identify the positional accuracy at the line level. During tests the probe van was kept in the slow line (outside line) which can be clearly identified on Google Earth.

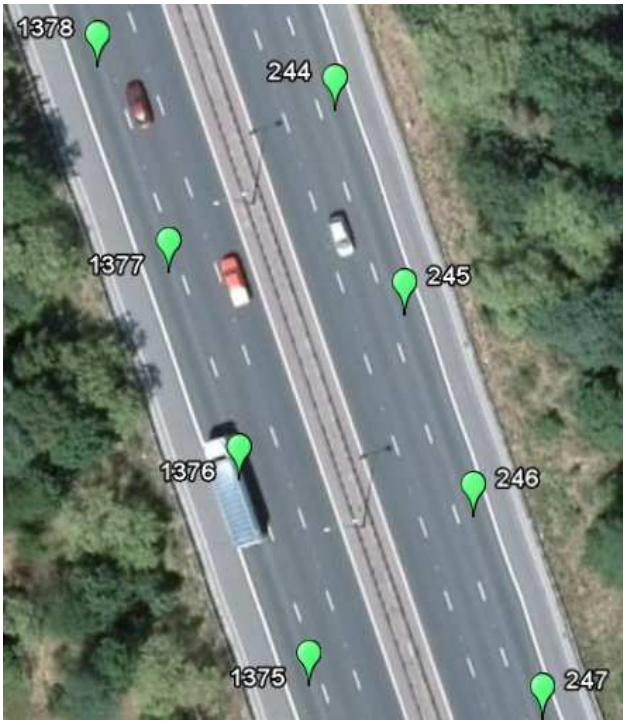

Figure 8: Typical positioning results during T1. Accuracy of the observations is at the line level when using Google Earth (NRTK epochs in green).

The accuracy and precision obtained during T2 are summarised in Table 5. This table contains the results from all the epochs e.g. Standalone, DGPS and NRTK (All) and from only valid NRTK observations (NRTK). As can be seen, the accuracy and precision of the NRTK epochs is always in the centimetre level (below 1 metre). Such an accuracy contrast with the All epochs solution which, although the mean is in the metre level, the Sd is always a few tens of a metre. The latest is more or less the same sort of accuracy that is currently achieved with the standalone GPS used for land navigation applications (Satnavs). This sort of accuracy does not allow the precise ITS applications to be performed. The accuracy of the NRTK epochs, on the other hand, will definitely allow the real time positioning of the vehicles to be at the line level which would definitely open the market for the precise ITS applications.

Table 5: Accuracy (Ave.) and precision (Sd) in metres obtained during T2 for the X, Y and Z coordinates.

Epochs	Coordinates					
	X		Y		Z	
	Mean	Sd +/-	Mean	Sd +/-	Mean	Sd +/-
All	1.06	19.66	1.73	36.05	-0.55	14.48
NRTK	0.24	0.80	-0.31	0.68	-0.13	0.59

A time series of the errors obtained during T2 can be seen in Figure 9. It is clear that 3D errors (RMSE) can be as high as 3.7 metres and that there are NRTK outages of up to roughly 4 continuous minutes (between epochs 1335 and 1575). Such an outage would restrict the use of NRTK in ITS applications where an uninterrupted positioning solution is required.

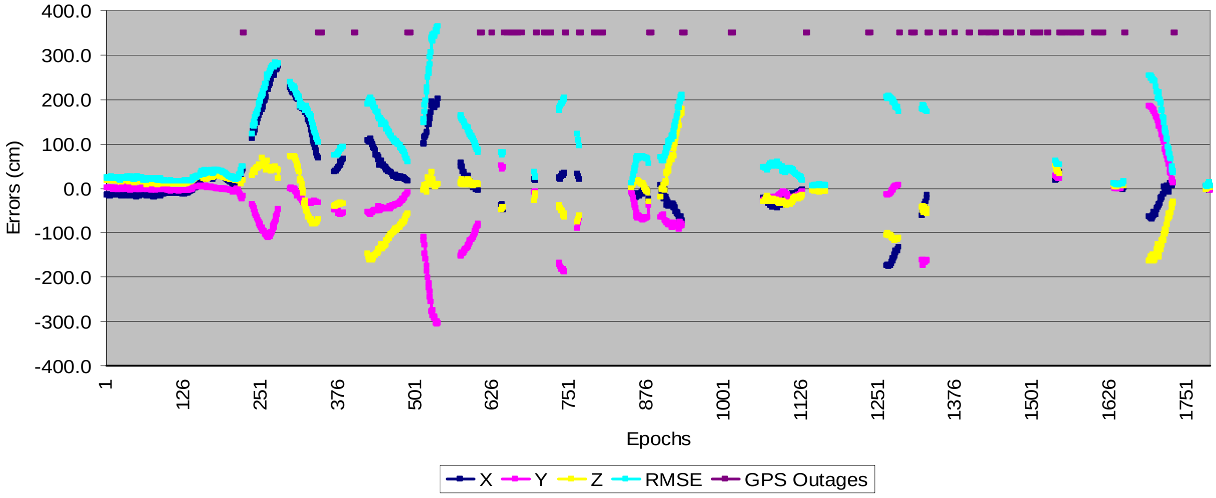

Figure 9: Time series of errors during T2.

It is also possible to see in Figure 9 that, when GPS signals outages where presented, the positional accuracy decreased. However, the accuracy improved again when tracking of the GPS signals was recovered. This seems to have been caused by a typical error of the IMU/GPS integrated solution, whose accuracy decreases as the GPS solution is not feed into the integration. However, although that for this paper the IMU/GPS solution is considered as the actual coordinates with zero errors, it is important to carry out further investigation in order to definitely establish the actual accuracy of NRTK in these sorts of kinematic tests.

Furthermore, the quality of the NRTK solution can also be seen in Figure 10. Epochs 341, 342 and 342 are NRTK and IMU/GPS solutions overlapped. Epochs 344 and 345 are only IMU/GPS due to the fixed ambiguities solution being lost when passing down the bridge. Then, from epochs 346 to 350 DGPS solutions were obtained which were evidently drifted related to the IMU/GPS solution. The NRTK solution was then recovered from epoch 351 as well as the high accuracy that it provides (overlapped NRTK and IMU/GPS epochs).

Figure 10: Typical positioning results during T2 (NRTK epochs in green, DGPS epochs in yellow and IMU/GPS epochs in pink).

6. CONCLUSIONS

This paper demonstrated that SmartNet (NRTK GPS) can offer the lane level positional accuracy that precise ITS applications require. The lack of availability of the NRTK observations however, could currently constrain its use to applications where uninterrupted tracking of the vehicles is not paramount or to areas with clear open skies and none or few obstacles (bridges, etc.)

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REFERENCES

Aponte, J., Meng, X., Dodson, A., Moore, T., Hill, C., Burbidge, M. (2008). Performance Assessment of a GPS Network RTK Service. IN Proceedings of ENC-GNSS 2008, Toulouse, France, Apr. 22-25, 2008.

Brown, N., Geisler, I. and Troyer, L. (2005). *RTK Rover Performance using the Master-Auxiliary Concept*. IN Proceedings of *The International Symposium on GPS/GNSS*, Hong Kong, Dec. 8-10, 2005. Hong Kong: HKPU.

Burbidge, M. (2006). *Introducing SmartNet-UK, the first Leica Geosystems commercial Network RTK Correction service*. IN Proceedings of *XXIII FIG Congress*, Munich, Germany, Oct. 8-13, 2006.

Euler, H.-J., Keenan, C. R., Zebhauser, B. E. and Wübbena, G. (2001). *Study of a Simplified Approach in Utilizing Information from*

Permanent Reference Station Arrays. IN Proceedings of *ION GPS*, Salt Lake City, Utah, USA, Sept. 11–14, 2001. Salt Lake City: The Institute of Navigation.

Feng, Y. and Wang, J. (2007). *Exploring GNSS RTK Performance Benefits with GPS and Virtual Galileo Measurements.* IN Proceedings of ION NTM, San Diego, CA, USA, Jan. 22-24, 2007. San Diego: The Institute of Navigation.

Leica Geosystems (2007). *SmartNet Website* [Online]. Great Britain: Leica Geosystems. Available at: http://smartnet.leica-geosystems.co.uk/SpiderWeb/frmIndex.aspx [Cited 01 Aug. 2007].

Meng, X., Dodson, A., Moore, T. and Roberts, G. (2007). *Towards Ubiquitous Positioning (UbiPos): A GNSS Perspective*. IN Proceedings of *ION NTM*, San Diego, CA, USA, Jan. 22-24, 2007. San Diego: The Institute of Navigation.

Meng, X., Yang, L., Aponte, J., Hill, C., Moore, T. and Dodson, A. (2008). Development of Satellite Based Positioning and Navigation Facilities for Precise ITS Applications. IN Proceedings of The 11th International IEEE Conference on Intelligent Transportation Systems 2008 (ITSC2008). Beijing, China, Oct. 12-15, 2008.

Rizos, C. (1999). *How Good is GPS?* [Online]. Sydney, Australia: The University of New South Wales. Available at: http://www.gmat.unsw.edu.au/snap/gps/gps_survey/chap2/241relb.htm [Cited 09 Aug. 2007].

RTCM (2006). *RTCM Standard 10403.1 for Differential GNSS (Global Navigation Satellite Systems) Services - Version 3.* Virginia, USA: RTCM.

Wanninger, L. (2004). *Introduction to Network RTK* [Online]. Dresden, Germany: International Association of Geodesy. Working Group 4.5.1: Network RTK. Available at: http://www.network-rtk.info/intro/introduction.html [Cited 01 Aug. 2007].

Wegener, V., and Wanninger, L. (2005). *Communication Options for Network RTK* [Online]. Dresden, Germany: International Association of Geodesy. Working Group 4.5.1: Network RTK. Available at: http://www.network-rtk.info/wegener/communication.html [Cited 13 Aug. 2008].