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GNSS-based Road User Charging

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The last few years have seen a rapid growth of applications based on positioning information provided by satellite positioning systems. In transport management and control, satellite positioning has proven to be the most promising means for spatial location data collection. With the GPS modernisation programme well underway, and the recent developments of the Galileo project, even more GNSS-based applications are to be expected in the future. One such GNSS-based application is the use of position and velocity information as the prime input to a road user charging (RUC) scheme. However, navigation in urban environments raises a number of problems. Most important are the difficulties related to signal obstruction by features such as tall buildings, urban canyons, bridges and trees, as well as the effects of multipath caused by signal reflections from buildings and other vehicles. Given the inevitable limitations of road trials, the use of simulation modelling to assess the present and future satellite positioning systems' performance to support urban RUC seems indispensable. The main objective of the research undertaken at the University of Nottingham Institute of Engineering Surveying and Space Geodesy (IESSG), and the Nottingham Centre for Infrastructure (NCI), was to develop a tool to simulate GPS for Satellite Positioning-based Road User Charging (SPRUC). In this regard, an existing GPS simulator was modified to rectify one of its major weaknesses, namely the inability to address properly the change in non-static GPS measurements with respect to changes in built environment. For this purpose, state-of-the-art Geographic Information Systems (GIS) software was used to complement the simulator, and consequently a seamless interface between the two software has been developed. Finally, in order to provide a prime input to the simulator, field tests have been undertaken and significant amounts of GPS data were collected. Statistics were also derived for positioning accuracy and signal availability so that the results from the simulation modelling can be validated against those from the undertaken road trials.

KEY WORDS

1. GNSS. 2. Road user charging.

1. INTRODUCTION.

SPRUC is a next generation Electronic Fee Collection technology, which remedies the key disadvantage of the widely used, so-called Dedicated Short-Range Communication (DSRC) approach: namely its inflexibility to the upgrading of infrastructure. It has been shown that SPRUC could be feasible even with advertised GPS accuracy (Kakihara *et al.*, 1999). However, research such as that by Wood and Mace (2001) reveals that in urban GPS positioning the advertised accuracy can deteriorate immensely due to signal obscuration and multipath.

A RUC scheme normally involves either cordon, time or distance-based charging (Transport & Travel Research Ltd, 2000 and Cheese and Klein, 1999). The last method is increasingly being viewed as most feasible, but equally efficient and fair. The distance travelled is measured by means of continuous GPS tracking or by engaging a non-tracking device, such as a simple odometer, when the vehicle reaches a particular point of interest. Although continuous tracking has the benefit of enabling the provision of more Location Based Services (LBS) to the user, the key advantage of the latter technique is that it is expected to attract less privacy concerns. Nevertheless, both techniques rely on real-time location data provision.

Urban RUC schemes involve the definition of a charging area, usually surrounding the city centre, and therefore involve the definition of a charging zone(s), such that motorists are charged for entering, or driving within the charging area, depending on the exact type of RUC scheme being operated. The points where roads cross the zone boundary are termed charging points (CPs), and the accurate determination of vehicles passing through CPs is vital to an RUC scheme's operational performance, whether it is done using the DSRC or GNSS approach. The limitations of GNSS, in the context of implementing urban RUC, may lead to significant inaccuracies as well as gaps in GNSS availability. These inaccuracies, and/or a signal loss, could mean that the user might get charged even when outside the charging area or vice versa. Hence, there is a need to investigate the accuracies and signal availability available today so that an area of confidence around the charging sites can be estimated to facilitate reliable charging.

2. FIELD TESTS AND RESULTS.

To study the operation of GPS in urban SPRUC as well as to provide inputs to the simulator, experiments were carried out in the city of Nottingham during 2002. A hypothetical distance-based charging scheme, facilitated by 32 CPs, was set up and the GPS measurements were taken around the defined CPs. The CPs followed the existing, so-called "Inner Traffic Area", which provided an opportunity to place the points at locations with less severe positioning conditions. These points are here referred to as open CPs. In addition, two imaginary charging points within the city centre were defined in order to address the issue of GPS positioning under unfavourable conditions (e.g. near tall buildings, in urban canyons, etc.), which might occur at certain CPs on a charging zone boundary. Due to privacy considerations, the investigated hypothetical scheme envisaged charging by means of vehicle positioning at the CPs and their immediate vicinity only, and did not include vehicle tracking within the charging area.

The testing was conducted by means of floating car data collection. In this regard five out of the above mentioned 34 CPs were selected; three of them were open ones, and the remaining two were the non-open CPs in the city centre. Twenty runs at a time (10 inbound and 10 outbound) through each of the five CPs were undertaken. The testing included low-cost standalone GPS code pseudoranging as well as differential carrier phase ranging in order to get the "true position(s)". In this regard Garmin 48 and Leica GPS500 receivers were used for the low-cost standalone and precise positioning respectively. Both receivers were connected to separate antennas such that the Garmin receiver used a simple patch antenna and a Leica AT502 dual frequency antenna was used for the Leica receiver. Both the antennas were mounted on the survey car roof 54 cm apart.

Although a high precision geodetic receiver was used to establish the "ground truth", the receiver has still demonstrated a degree of susceptibility with respect to ambiguity resolution. Consequently, the kinematic solution could not be provided at every epoch and code pseudoranges had to be used as well. To compensate for the related inaccuracies, the recorded positions were validated against the digital map(s) using ESRI ArcView 3.2 and ArcMap 8.3 GIS software, eliminating all the positions which did not follow the expected path.

As said earlier, a Garmin receiver was used for low-cost standalone measurements. However, the receiver was primarily set up to log the RINEX data/files which were then processed as standalone by the P4 (Pseudorange and Phase Post-Postprocessor) software. That is to say, the idea was to emulate the receiver's readings, contained within the internal Garmin TrackLog data, using P4 given that it provides better processing capabilities. The difference between the TrackLog measurements and those from P4 was also analysed, however this will not be further discussed in the paper.

The tests were designed to include changes in satellite constellation as well as the differences between the day-time and night-time positioning performance. With respect to the former, two separate trials were undertaken to address the issue of the constellation change such that the measurements in the second trial (April trial) used signals from the satellites different to the satellites used in the first trial (March trial). In order to address the differences in the day-time and night-time positioning performance, another two trials (March and April replica trials) were undertaken in such a way that the satellite geometry used in the first two trials (March and April trials) was emulated as closely as possible in the night. Although it could be argued that the night-time positioning issue does not need to be addressed, as it is expected the road users would not be charged when driving in un-congested conditions, such trials were conducted chiefly to address the issue of signal multipath from other traffic. Therefore overall, a total number of 400 runs was undertaken.

As said earlier, privacy issues have driven the idea of vehicles being tracked merely as they approach and leave the CPs. Hence, only those segments of the runs which roughly correspond to the 100 m distance either side of each CP were analysed. The accuracy and signal availability – given by the frequency and the duration of signal loss – were then assessed for the entire segment as well as for the CP itself. Table 1 provides the overall positioning accuracy and signal availability statistics for all four

Table 1. Accuracy and signal availability statistics.

CP ID	CP1	CP2	CP3	CP4	CP5
Accuracy 100 m [m]					
Average	5·61	5·22	5·87	13·27	17·03
Max	68·31	25·99	41·68	55·41	224·73
R95	13·94	15·25	11·03	32·07	44·58
Overall:		Average = 5·55 m R95 = 13·59 m		Average = 15·05 m R95 = 39·67 m	
Accuracy at CP [m]					
Average	4·79	4·60	5·68	14·57	25·53
Max	13·71	17·17	14·80	51·33	42·67
Overall:		Average = 5·00 m		Average = 15·09 m	
Signal loss [s]					
Average	2·67	2·00	2·50	3·59	3·91
Max	9	2	3	16	29
Overall:		TL/RD* = 3·73%		TL/RD = 38·29%	

* TL = Total signal Loss.
RD = Route Duration.

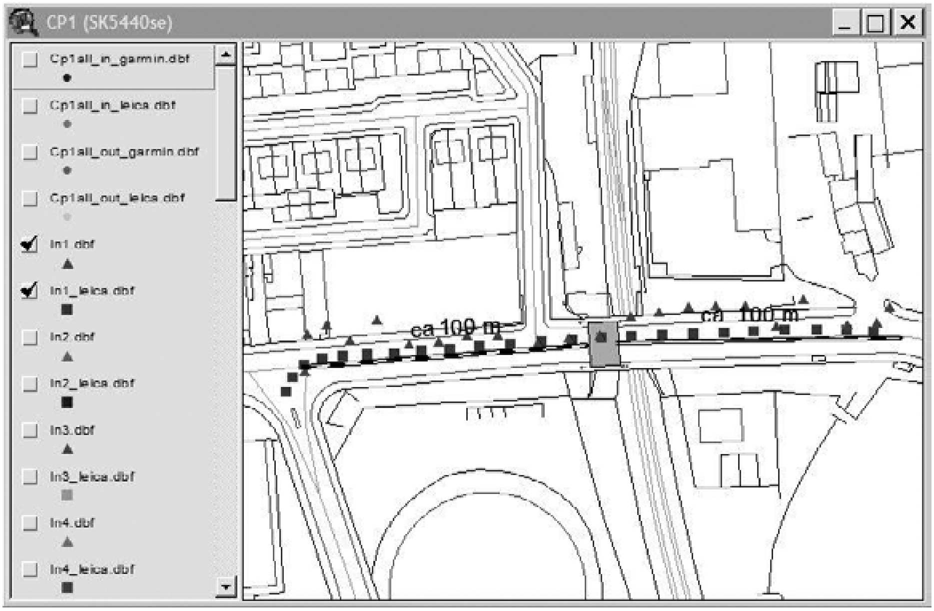

Figure 1. ArcView screen of an open CP.

trial periods. Rows denoted as "Average" and "Max" provide average and maximum errors respectively, for a given CP.

In addition, Figures 1 and 2 provide typical examples of the ArcView screen for an open and a non-open CP respectively. The square dots represent the true positions, whereas the triangular dots represent positions recorded by the low-cost Garmin receiver and processed as stand-alone. The polygons in the middle of the analysed road

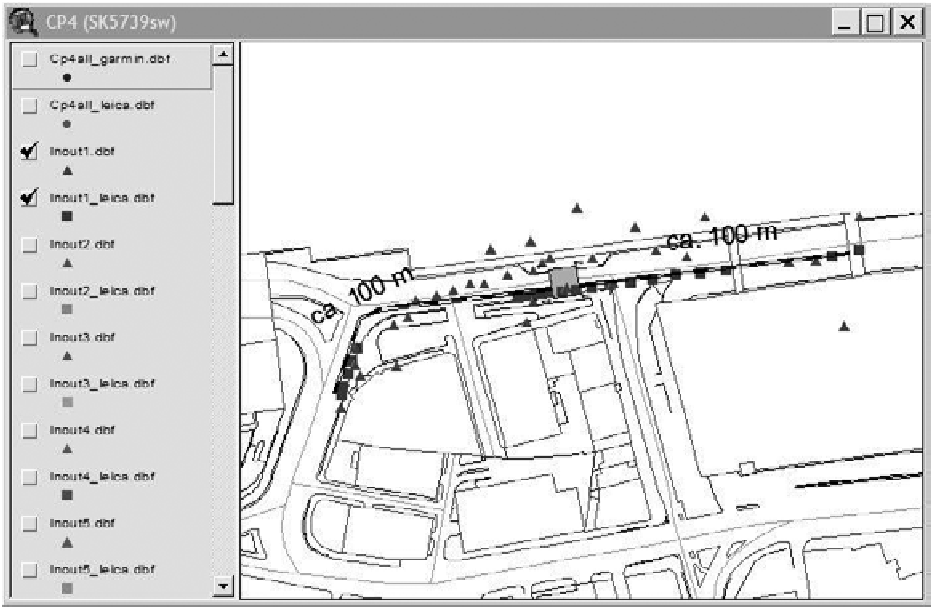

Figure 2. ArcView screen of a non-open CP.

segments are virtual toll booths with the initial length set to 10 m. The position of each polygon was precisely calculated by the static carrier phase positioning of the vertices.

3. ACCURACY DISCUSSION.

Although the term *accuracy* is being used, in reality, it was the difference between the Garmin and the corresponding Leica positions which was assessed. However, to ascertain how accurately a system has determined a point's coordinates, normally another system with an inherently higher accuracy than the one being tested is employed to provide the "ground truth" (Langley, 1991 and van Diggelen, 1998). In this regard the data collection and analysis methodology used follows the common technical practice. Nevertheless, it could be argued that, in our trials, such a comparison demonstrates consistency rather than accuracy, given that both the reference and the tested measurements originate from the same system: GPS.

To further investigate accuracy, it is advantageous to estimate the theoretical distribution of the recorded positional differences. However, the differences taken from non-static observations are likely to be biased, given that the accuracy of the reference point, at a given epoch, cannot be assessed from more than one measurement, making the number of measurements to assess the error distribution from, almost irrelevant. Given the above considerations, although other accuracy measurements may have been employed to indicate the error distribution (Bowditch, 1984 and van Diggelen, 1998), in our trials the horizontal 95 per cent accuracy (R95) measure was seen as most appropriate. It also best portrays a RUC scheme's efficiency as to the number of vehicle entries recorded.

As can be seen from Table 1, 95% of the recorded positional differences, which fall within the observed road segments, were less than roughly 15 m at all open sites (CPs 1–3). This may indicate that the minimum length of the polygon representing virtual

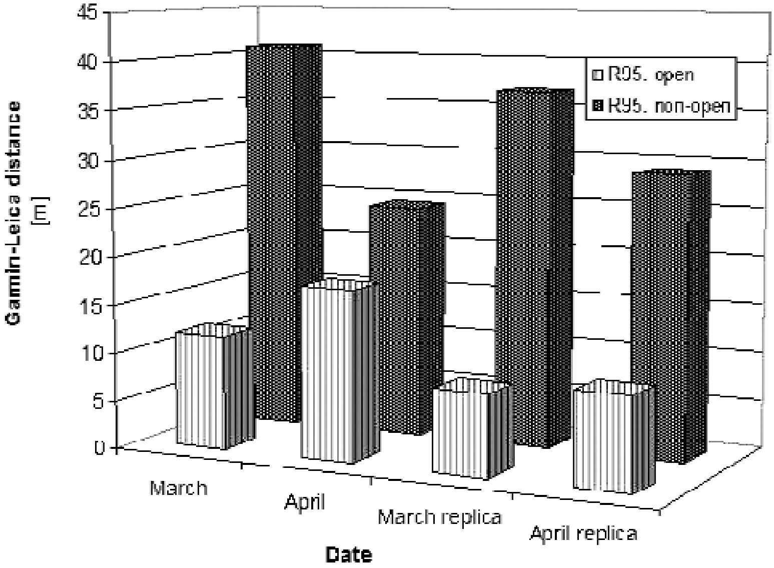

Figure 3. Day/night-time differences in R95 positioning accuracy for the entire road segments.

tollbooths should be 15 m. If the average accuracies at all open and non-open sites are compared, it can be seen that the accuracy at non-open sites (CPs 4, 5) is roughly three times worse in "Accuracy 100 m" and "Accuracy at CP" cases. Given the maximum values of the measured differences, it is reasonable to assume that a 100 m area of confidence, either side of each open CP, would provide reliable charging. It should however be noted that the above figures have ±54 cm tolerance given the distance between the antennas. Finally, given the small number of recorded measurements which fall inside the virtual toll booths, the R95 measure at the CPs was not assessed. With respect to the signal availability, given the maximum open site signal loss of nine seconds, a 120 m gap without the positioning service is to be expected. That is, if the duration of the signal loss is translated into distance travelled, it results in 120 m distance with the supposed vehicle speed of 48 km/h (30 miles per hour). Coupled with the total signal loss/route duration ratio, this further underpins the estimated length of the area of confidence. However, one should be careful with the time/distance conversion as a signal loss can occur while the vehicle is stationary.

4. MULTIPATH FROM OTHER VEHICLES.

As said earlier, to address the issue of signal multipath from other vehicles, two night-time trials were undertaken. The histogram shown in Figure 3 provides information about the original March and April trials' accuracies compared with the accuracies from the correspondent replica trials. The replica trials results showed expected improvements in accuracy at open CPs, due to less ionospheric error and/or errors caused by signal multipath from other traffic. On the other hand, the accuracies at non-open sites exhibited much less (March replica) or even no improvements (April replica) in accuracy, thus suggesting that signal obstruction from surrounding buildings was the main source of error and that the errors caused by the ionosphere and signal multipath from other traffic can be ignored.

5. GPS DATA SIMULATOR.

The Navigation System Simulator has been developed at the IESSG over the last 10 years. It is a software-based tool which has been extensively used and tested in different research areas, and in this particular research it was used to generate GPS measurements which correspond to the real data capture during the road trials. In order to generate GPS data, the program has a detailed error model that includes both system and environmental models, and is able to model the characteristics of different quality GPS receivers. A seed trajectory, the so-called Dynamics file, is input for the vehicle borne receiver, which in this case was based on the real trajectory of the vehicle from the trials. The generated data may be processed through the same software used to process the real data. As said earlier, the environmental models do have their limitations, and the obscuration and signal multipath models, which are critical to this particular application, are recognised weaknesses and are currently undergoing further development.

Figure 4 provides the flow chart of the GPS data generation process facilitated by the most recent upgrade of the simulator. The arrows indicate points where modifications were made to the original code to enable data from the GIS module to be read. The data generation flow is controlled by the so-called control file in which different simulation parameters are contained. These include: the locations of the dynamics, ephemeris and output files, simulation interval, receiver quality, output format, error models activation flags and many other vital information. As can be seen from the flow chart, the simulator is capable of simulating both static and kinematic GPS receiver measurements. Currently, up to five receivers can be processed in one run, though only one of these may be assigned the kinematic label. As indicated earlier, for kinematic receivers a dynamics file needs to be provided. It is an ASCII file which contains the receiver's position given in WGS84 coordinates, its velocity and attitude, and finally the satellite visibility data.

As will be explained later, the visibility data, provided by the GIS module, contain the IDs of all the satellites which are in view at a particular epoch. The data are read only if one of the receivers whose readings are to be simulated is designated as kinematic. As the simulator loops through the epochs given by the simulating interval, it is forced to disregard the satellites which are either designated as blocked, unhealthy or below the elevation mask (Figure 4).

6. THE NEWLY DEVELOPED GIS MODULE.

Satellite visibility directly affects the receiver performance accuracy. Providing the optimal number of available tracking channels a receiver possesses, the effect of the line-of-sight (LoS) obstructions to satellites, in non-static applications such as urban RUC, can generate gross errors in receiver output. Signal reflection from the surrounding surfaces leads to the situation where readings from a shadowed satellite are included in the final solution. Hence, manual exclusion of the satellite, within the dedicated software, may look a natural remedy. This is further encouraged by the fact that transport applications normally operate as two-dimensional environments, thus requiring fewer satellites in view to provide a position.

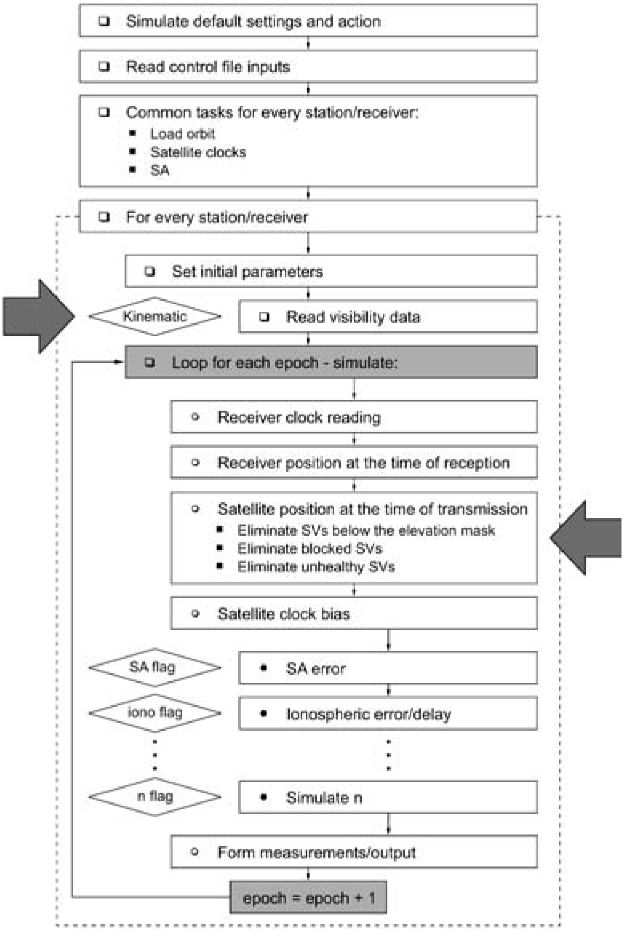

Figure 4. Data generation flow chart.

Given the way the simulated data are generated, and given that the dynamic nature of the signal blockage in non-static measurements requires the LoS analysis to be undertaken for each of the epochs to be simulated – and therefore contained in the dynamics file – the dynamics file seemed a logical interface between the GIS module and the simulator. As stated earlier, the filtering is facilitated by excluding the measurements from blocked satellites from further processing once the visibility data are read. In this regard the list of satellites to be excluded at the given epoch is supplied via an extra line in the dynamics file.

To complement the simulator with the GIS module developed, the ESRI ArcMap software was used. First, a GIS model of the urban environment had to be provided. The model included buildings/obstacles that may obscure the satellites, such that the simulated GPS measurements were filtered through the model. The model was developed by overlaying the buildings on top of the Digital Terrain Model (DTM) of the researched area. To acquire the DTM, Ordnance Survey Land-Form PROFILE® data were used. A Triangulated Irregular Network was created from the data with the height accuracy of ±2·5 m (Ordnance Survey, 2003). Although some could argue about the coarseness of the DTM, given the demands for positioning accuracies in transport applications of low or medium magnitude (Drane and Rizos, 1998), such accuracy should allow for a reliable investigation to be undertaken into the feasibility of a proposed SPRUC scheme.

The building layer in ArcMap was created by extruding the building plan view for the corresponding relative heights. The absolute and relative heights of the buildings were acquired from a separate field trial which included the use of carrier phase GPS and conventional surveying. In this regard a geodetic Leica GPS500 receiver was used to establish the reference point coordinates which were then used by the Leica TPS1000 total station. The heights were acquired by first measuring the horizontal distance between the instrument (total station) and the reflector placed at the building front (facade). The instrument was then pointed at the roof apex/top, such that the horizontal angle from the previous measurement remained the same, and the vertical angle was recorded. Assuming that the two points taken lie perpendicular to each other, the measured relative height is given by:

$$h_b = h_i + d \cos \alpha \tag{1}$$

where:

h_b = building relative height
h_i = instrument relative height
d = horizontal distance between the instrument and the reflector
α = vertical angle.

The GIS module is realised in the form of a new ArcMap template, making the application easy to disseminate. The template adds a new toolbar to the main ArcMap screen, which can be activated and deactivated by the user. The following data manipulation and analysis tools are provided by the toolbar:

- *Trajectory input tool*: enables outputs from both Leica SKI-Pro (GPS processing software used for Leica data processing) and P4 to be read and records displayed as a new ArcMap layer. The tool utilises the QUEST Geodetic Software Solutions GIQ 6.0 dynamic link library (DLL) for the WGS84 to OSGB36 coordinate transformation. That is, in order to overlay the trajectory outputs from both Leica SKI-Pro and P4 on top of the map data used, the WGS84 coordinates used by the GPS processing software had to be converted into the UK National Grid coordinate referencing system (namely OSGB36) in which the Ordnance Survey Land-Line® map data used were displayed. The tool enables the user to choose which records are to be displayed and includes a number of different safety mechanisms designed to prevent accidental data corruption.
- *Ephemeris input tool*: enables the ephemeris data to be read and displayed. Currently, the tool only supports the *sp3* ephemeris format. Again, to make the ephemeris data compatible to the map data, satellite coordinates had to be converted into the local reference grid using the GIQ 6.0 DLL. However, given that the DLL does not operate with altitudes as high as those of the satellites, the positions of the satellites had to be scaled down prior to their conversion into the local grid. This was done by first establishing the LoS vector $\vec{a}$ between a reference point on the ground – given by the position of the survey car at the beginning of each run – and the satellite (see Figure 5). The correspondent unit vector

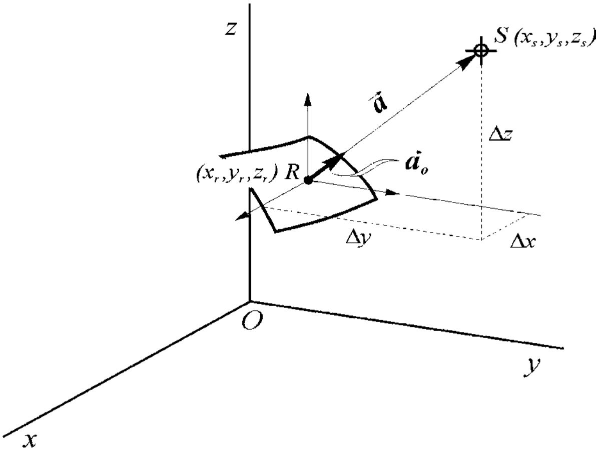

Figure 5. Satellite LoS vector scaling.

$\vec{a}_o$ was then calculated and a scaling parameter k was introduced such that the final scaled S' position of the satellite is given by:

$$\begin{bmatrix} x_s' \\ y_s' \\ z_s' \end{bmatrix} = \begin{bmatrix} x_r \\ y_r \\ z_r \end{bmatrix} + k \begin{bmatrix} x_o \\ y_o \\ z_o \end{bmatrix} \tag{2}$$

It could be argued that such acquired positions of the satellites may not be applicable for all the vehicle positions recorded, given that the referencing was done using the same reference point on the ground for all the satellites in view. Moreover, the ephemeris data is given in 15 minute epochs which normally exceeds the duration of a run, causing the same ephemeris data to be used for more than one run. Nevertheless, given the altitude of the satellite orbits, the change in $\vec{a}_o$ is expected to be very small with respect to the movements of both the satellites and the vehicle, and therefore can be disregarded. The tool allows for choice between several scaling parameters.

- *Satellite visibility tool*: the most critical part of the application. It undertakes the LoS analysis between the vehicle antenna and all the satellites in view, for each vehicle location contained in the trajectory file. For this, the tool requires the Digital Elevation Model (DEM) of the researched area in the form of a Triangulated Irregular Network (TIN). The tool adds a new column into the trajectory attribute table with the records containing IDs of the satellites in view at the correspondent epoch/vehicle location. Again, different safety features are provided to prohibit tool misuse. Also, the tool requires the 3D Analyst extension to be loaded otherwise it is automatically disabled.
- *Create/Modify dynamics tool*: creates new and/or modifies existing dynamics files. The former is done using the correspondent attribute table, providing the trajectory has already undergone a visibility analysis. The latter provides a powerful facility to repeat the use of real trajectory inputs to simulate the effects of changes in satellite constellation. First a dynamics file is read following the user being offered the opportunity to modify the existing GPS week and GPS time-of-week (TOW) values. If modified, the change in these values means a

change in satellite constellation, hence a new visibility analysis needs to be undertaken in order to get correct visibility data. Consequently, the satellite visibility tool is called; in this case modified to read the vehicle locations from the dynamics file instead of the attribute table. Both create and modify tools read/store dynamics files in the simulator-friendly *dat* format.

- *Interpolate position tool*: interpolates missing positions in the trajectory file. As discussed earlier, signal blockage can produce "gaps" in GPS availability. These gaps mean that the vehicle location cannot be provided for every epoch in the trajectory. Although both the ArcMap application and the simulator can allow for such an incomplete trajectory to be processed, best results are produced if the dynamics file contains the data for all the epochs within the simulation interval. Hence, the tool interpolates the missing positions from a polyline provided by the user, which represents an approximate vehicle trajectory between the known locations surrounding the "gap". Again, different safety mechanisms are included to prevent the user from inputting erratic approximate trajectories.

7. SIMULATION RESULTS. To test the new GIS module and its interface with the simulator, runs undertaken at CP4 were simulated for all four trial periods, and the results were then compared with the receiver readings from the correspondent road trials. Although this originally included the total number of 80 runs to be simulated, some of the runs had to be disregarded. That is, on a few occasions poor positioning conditions caused too many gaps in the vehicle trajectory to be interpolated and/or a lack of the known vehicle positions to interpolate the missing positions from. Hence, it seemed sensible to exclude those runs from further analysis.

Instead of utilising the accuracy and signal availability criteria used in the real data analysis discussed earlier, the number of satellites logged at a given epoch criterion – here referred as the number of visible satellites – was used for the simulated vs. real data comparison. Using this criterion, if the results from the simulated runs are compared with those from the road trials, some discrepancies may occur. That is, the modelled number of visible satellites can be either equal, greater or less than the number of satellites visible during the trials. In this respect, four scenarios may be contemplated, namely:

- *The modelled number of visible satellites is greater than the correspondent number from the trials*. This may suggest that the GIS model used was over simplified and therefore not able to address the signal blockage issue accurately enough. If true, a more accurate/inclusive DEM needs to be used.
- *The modelled number of visible satellites is less than the correspondent number from the trials*. This could mean a clear indication of a signal multipath at a given epoch but equally …

  … it may again suggest the coarseness of the DEM model used.
- *The modelled number of visible satellites is equal to the correspondent number from the trials*. The application properly addresses the signal blockage issue.

Figure 6 shows the correspondent numbers of visible satellites from the simulated and real data plotted against the overall number of records (epochs) analysed. As can be seen from the figure the simulated data closely follow the pattern in which the real data are distributed. For the sample of nearly 2000 epochs, the average simulated vs.

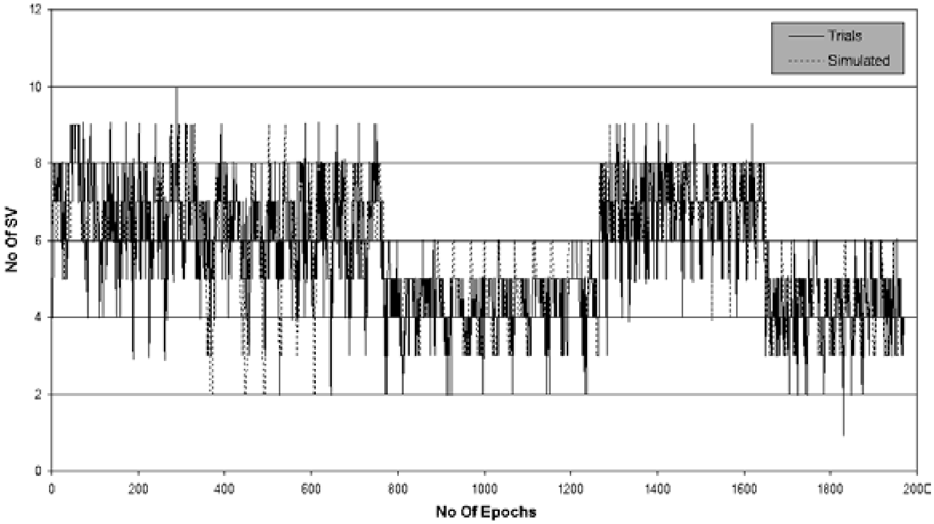

Figure 6. Number of visible satellites in real and simulated data.

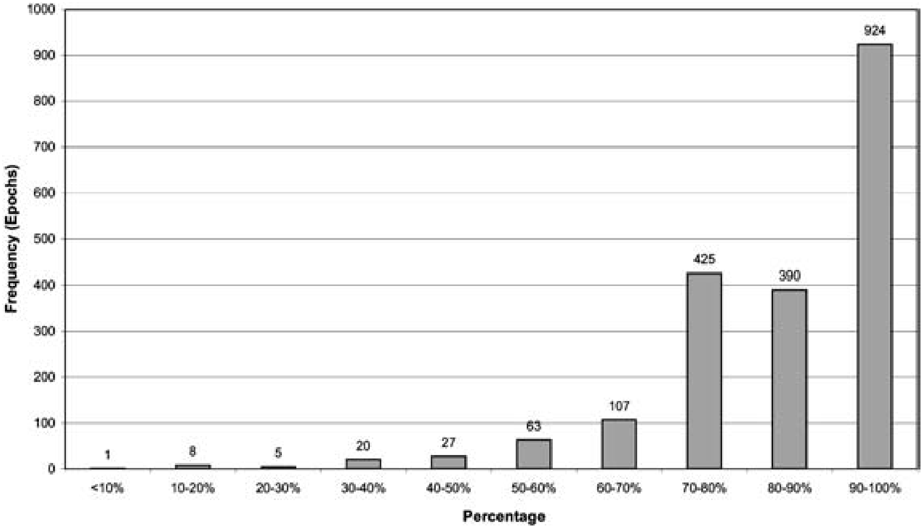

Figure 7. Real vs. simulated data satellite ID matching.

real data difference in the number of satellites is 0·9 with the standard deviation of 0·86. Clearly, in order to regard the application as sound, apart from the number of visible satellites, satellite ID matching needs to be investigated as well. In this regard Figure 7 provides absolute frequencies of the different matching levels given in percentage intervals. It can be seen that almost half the simulated records more than 90 per cent match the corresponding records from the road trials. Equally, 70 per cent or higher matching occurs for nearly 90 per cent of the simulated records.

8. CONCLUSIONS. The road trials provide a good indication of the levels of GPS accuracy, availability and integrity available today in urban environments.

However, these can only provide a snapshot of a few roads on a sample day(s). Hence, the use of simulation modelling is suggested in order to quantify GPS positioning performance over an entire urban area, over a significant period of time. The GIS-supported simulator developed at the IESSG provided results which suggest that the tool is capable of simulating the GPS measurements accurately enough. However, further testing needs to be undertaken in order to validate the tool fully. This will include the tool being tested at a new researched area with respect to the number of visible satellites criterion as well as the positioning accuracy and signal availability criteria. The research also revealed that urban SPRUC, facilitated by the low-cost standalone GPS positioning, might be feasible provided the charging points have open locations. Although signal loss can be expected, the total signal loss/route duration ratio is likely to be low. Hence the potential mis-positioning may be remedied by lengthening the virtual tollbooths or by introducing low-cost signal blockage/multipath modelling such as the one proposed. In addition, it has also been shown that, at open sites, the virtual tollbooths of 15 m length coupled with the 100 m area of confidence should provide reliable positioning for charging.

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