# Challenges for integrity in navigation of high precision

M. J. Paśnikowski, E. Domínguez, *GMV, Spain*;
E. Aguado, D. Lowe, M. Pattinson, M. Hutchinson, *NSL, United Kingdom*;
G. Seco-Granados, J. Salcedo, D. Egea, *UAB, Spain*;
D. Naberezhnykh, TRL, United Kingdom;
F. Dovis, Politecnico di Torino, Italy;
J.P. Boyero, I. Fernandez, European Commission, Belgium

## BIOGRAPHY

**Maciej Jerzy Paśnikowski** received his M.Sc. degree in 2013 from Warsaw University of Technology in geodesy and cartography. Currently, he is a PhD student at UAB and is working at GMV since 2013 as satellite navigation engineer in GMV. His work is focused on the navigation in harsh urban environments, and the possible trade-off between existing navigation techniques.

**Enrique Domínguez** received a M.Sc. degree in Telecommunications Engineering in 2000 and a Master in Space Technologies in 2009, both from the Polytechnic University of Madrid. He joined GMV in 2000 working first in the development of EGNOS and Galileo and since 2009 in GNSS software receivers, multi-sensor fusion algorithms and integrity algorithms.

**L. Enrique Aguado** is a Principal Project Manager at NSL. He received a Ph.D. in Electrical Engineering from the University of Manchester, UK. He has been involved in Galileo-related R&D since 2002 with his current work focussed on robust positioning technologies.

**David Lowe** is a Principal Navigation Engineer at NSL. He received a PhD in Engineering Surveying and Space Geodesy from the Univ. of Nottingham, UK. He has been involved in GNSS navigation technologies, researching GNSS for aircraft precision approach and landing, deformation monitoring, sea-level determination and land navigation with emphasis on the rail domain.

**Gonzalo Seco-Granados** holds a PhD degree from Univ. Politecnica de Catalunya (UPC) and an MBA from IESE, Universidad de Navarra. Since 2006, he is associate prof. at the Dept of Telecom. Eng. of UAB and head of the SPCOMNAV group.

**José A. López-Salcedo** received the M.Sc. and Ph.D. degrees in Telecommunication Engineering in 2001 and 2007 from UPC. He joined UAB and the SPCOMNAV group as an assistant prof. in 2006, and since 2013 he is an associate prof.

**Daniel Egea** received the M.Sc. in Electrical Engineering in 2012 and the M.Sc. degree in Micro and Nano Electronics Engineering in 2013, both from Universitat Autònoma de Barcelona (UAB). Currently, he is a Ph.D. student at the SPCOMNAV group, of UAB and his research is focused on signal-level GNSS integrity.

**Denis Naberezhnykh** received the BSc. degree in Physics from the Royal Holloway, University of London and is the Head of Low Carbon Vehicle and ITS technology at TRL. He has worked on numerous tests for the evaluation of GNSS-based vehicle OBUs.

**Fabio Dovis** received a Master degree in Electronics Engineering in 1996, and a PhD in Electronics and Communications Engineering in February 2000, at Politecnico di Torino. He is currently assistant professor at the Department of Electronics and Telecommunications of Politecnico di Torino. He strongly contributed to the creation of the NavSAS group. His research focuses on the design of algorithms and architectures for satellite navigation receivers.

**Juan Pablo Boyero** is since 2012 working at the EC in the definition of the evolution of the Galileo and EGNOS missions. Before he worked within the Galileo System Performance area and acting both as System Prime as well as Technical Support to System Prime. He holds a M.Sc. by the Escuela Técnica Superior de Ingenieros de Telecomunicación of the Universidad Politécnica de Madrid. He also passed the course on Safety Critical Systems by the University of Oxford, UK.

**Ignacio Fernandez** is currently responsible for the Galileo Commercial Service at the EC. He is an ICAI (Madrid) engineer, has a Ph.D. in Electronic Systems by Aalborg University and a MBA by London Business School.

## ABSTRACT

Providing integrity to precise positioning navigation techniques utilizing carrier-phase measurements, like Precise Point Positioning (PPP) and Real-Time Kinematic (RTK), is still a challenge. Whereas these methods can provide centimetre-level positioning accuracy, their use has been limited mainly for static and kinematic positioning solutions, with less employment for general navigation purposes. Both techniques are dependent on external information which has to be considered in the integrity monitoring process.

For RTK, a differential method, the external information could be the distance to a reference station, its coordinates, or the atmospheric effects, for which the associated reliability needs to be considered.

The nature of PPP as an absolute technique demands considering a reference frame, estimating several parameters and eliminating others - estimated in a different process- which requires the convergence of the solution. As it was mentioned in [Laínez and Romay, 2013], all of these factors influence the integrity and reliability in PPP methods.

The use of carrier-phase in both techniques allows higher achievable accuracy, but also causes their vulnerability on cycle slips and loss of lock of satellite signal. These problems occur extensively in harsh environments, especially in urban scenarios. High precision navigation techniques were not intended for road or urban environments, but their performance in these scenarios in aspects of navigation and integrity can be analysed and improved.

In this article different road scenarios will be analysed, both in motorway and urban scenarios, in terms of navigation and integrity performance of precise positioning techniques. The data utilised in the paper were collected for the IGNSSRX project purposes. The analysed scenarios were challenging for the evaluated techniques, with a significant number of elements obstructing the sky view, causing cycle slips both in motorway and urban conditions.

Performances of navigation and integrity of high accuracy algorithms will be assessed in relation to the characterization of pseudorange, Doppler, C/N0, and carrier-phase observables, in motorway and urban environments. The discontinuities and gaps in the observables, especially in carrier-phase measurements, impact not only the navigation convergence and accuracy but also the integrity of the solution. To identify integrity threats, the distribution of the errors of the observables will be analysed. Subsequently, the identified outliers will be examined in terms of their magnitude, frequency of occurrence, ambiguity resolution, and clock errors. In the carrier-phase measurements, the analysis will be focused on the L1 frequency as raw signal samples in this band have been recorded exhaustively in all the scenarios of interest.

## INTRODUCTION

The topic of integrity for RTK and PPP techniques is scarcely described in the existing literature. Carrier-phase measurements are able to provide higher accuracy, but on the other hand, they are much more complex to process. This is the result of ambiguity reconstruction, a process which demands determining the unknown value of full wavelengths to use carrier-phase as a distance measurement.

The necessary operation for both RTK and PPP techniques is the resolution of the ambiguity, integer (IAR, or Integer Ambiguity Resolution) or floating. In the RTK method, the ambiguity is computed in a relative way, with respect to a reference station, allowing reducing significantly common errors. The distance between the reference station and the receiver is crucial, as well as commonly tracked satellites. Double differences of observations for baselines below 20 km can be simplified and residual errors from troposphere and ionosphere can be neglected.

The PPP method requires estimation of biases, which causes a long convergence time of the ambiguity resolution algorithm. Its added value is in the fact, that it is a global solution, allowing the user to obtain position with only one receiver without using reference stations.

Both PPP and RTK techniques are aimed at providing high accuracy positioning solutions in essentially open-sky environments. They are very sensitive to LoS losses, especially PPP, which needs to start a new convergence phase every time the number of available LoS decreases below 5 or 4.

This paper summarizes the work on the analyses of PVT integrity for RTK/PPP which have been carried out under the Integrity GNSS Receiver project. The Integrity GNSS Receiver (IGNSSRX) is a European Commission funded project developed between 2012 and 2015 by a consortium including GMV, NSL, TRL and UAB, with three main objectives:

a) The development of two platforms to capture and store GNSS radio frequency signal samples and a reference trajectory from representative low-, medium- and high-end sensors in terrestrial applications.

b) An extensive data collection campaign aiming to characterize error sources, magnitudes and probabilities for two important GNSS terrestrial application areas: automotive and pedestrian users.

c) The research and development of techniques and algorithms to mitigate the integrity threats in the two terrestrial environments studied using the collected data, thus allowing reliable terrestrial applications within these domains.

The outcome of first two goals was presented in [Domínguez et al. 2014]. This paper presents the results fulfilling the part of the third objective, and referring to the characterization of integrity threats based on the analysis of GNSS observables utilized by algorithms of high precision navigation techniques. The other results of the whole project are described in [Domínguez et al. 2015], [Egea-Roca et al. 2015a], [Egea-Roca et al. 2015b].

In the following parts of this paper a short description of utilized precision navigation techniques will be presented, specifically in relation with the constrained scenarios, such as urban ones. Next, the real data analysis performed on the data collected during the IGNSSRX project will be described, with the main focus on the carrier phase observations, as their quality influences the precise positioning techniques performance and their solution quality. Finally, the conclusions from the analysis will be presented in the end of the article.

The tools used in the analysis were RTKLIB and magicPPP. RTKLIB is an open source program package for standard and precise positioning with GNSS. It supports all currently operating satellite systems, various positioning modes, multiple standard formats and protocols and is highly configurable, through GUI and CUI APs. The second tool, magicPPP, is software developed by GMV as a part of magicGNSS package. This tool allows for processing double frequency data, with multiple configuration options, in various modes. Its main distinct feature in comparison with RTKLIB tool is the real, not integer, ambiguity estimation process, as well as the built-in implementation of the integrity algorithm providing protection levels for the obtained position. The lack of an integrity algorithm in RTKLIB software caused the urge of developing and implementing a preliminary integrity algorithm for this tool, based on the assumptions used in preliminary magicPPP integrity algorithm. For both tools, GMV's magicODTS products were utilized to supply precise GNSS satellites' orbits and clocks to PPP navigation solution.

Conclusions and recommendations extracted from these analyses will be used to define and propose improvements for carrier phase processing in the algorithms of high precision navigation with integrity. The results will help in development of magicPPP and, if possible, RTKLIB in positioning, navigation and integrity approach.

## HIGH PRECISION NAVIGATION TECHNIQUES IN URBAN SCENARIOS

### Real Time Kinematics (RTK) and Integer Ambiguity Resolution

RTK is a type of kinematic relative positioning method. By differencing observables between receivers, between satellites and between time can result in eliminating common errors between them, e.g. relating to satellite and receivers' clocks. In the principle of the kinematic method, one receiver remains fixed, while the other one moves, and its position is to be determined for arbitrary epochs. In real-time situations, the ambiguity solution has to be solved immediately, thanks to observations from the fixed receiver and knowing its position. Decorrelation of error sources limits this method to about 20 km baselines. In WARTK (Wide Area RTK, [Hernández-Pajares et al., 2004]) implementing ionospheric corrections allows a fast decorrelation and preserving integer nature of ambiguities. RTK and WARTK need time for convergence, up to several minutes, allowing for solutions of baselines up to 20 and 400 kilometres respectively.

The horizontal accuracy if 1σ level of RTK solution in good observation conditions and with properly solved ambiguities, for 5 tracked satellites in open-sky conditions, can be given as 5 cm + 5 ppm, depending on the length of the baseline [Hofmann-Wellenhof et al. 2008].

The ambiguity resolution process has therefore a crucial influence on the accuracy of the solution. When the ambiguity is estimated as an integer value, the convergence time for the solution shortens. The description of techniques providing Integer Ambiguity Resolution is presented in [Kim et al 2000]. The Integer Ambiguity Resolution process involves three major steps. The first one is the generation of potential integer ambiguity combinations, possibly considered by algorithm. This is done in the search space, the volume of uncertainty surrounding the antenna location. In static positioning, search space can be realized in float ambiguities, while for kinematic positioning it is constructed by code range solution. Decreasing the size of the search space would increase efficiency of calculations, which is important for kinematic solutions.

The second step is the identification of correct integer ambiguity combinations. The key aspect in this step is having enough redundant satellites, as the criterion used by many of the techniques is based on the minimization of the sum of the squared residuals in a least squares adjustment approach.

The third step is the validation of the ambiguities. It can be done by the ambiguity success rate, depending on following factors: observation equations, precision of observables and the method of integer ambiguity estimation itself.

Potential difficulties in IAR process can be placed in several issues:

- Assumption of normal distribution of the residuals; errors like multipath, orbit errors, atmospheric errors influence it, and this is the main reason of failure of solution for long baselines
- Decision on statistical significance of ambiguity decision, as the integer ambiguity combination fitting the measurements in the best way should be significantly better than all the others.

In urban scenarios, the IAR process will be therefore much harder, because of presence of multipath and NLOS observations caused by high power signal reflections, reduced LoS signal visibility and frequent geometry changes due to signal blockage. The urban and suburban propagation channels were described e.g. in [Lehner and Steingass, 2005] and [Steingass and Lehner,. 2008].

### Precise Point Positioning (PPP)

PPP is the method of absolute positioning using accurate orbital and clock data provided by external sources, along with dual frequency code pseudoranges and/or carrier phase observations. The determined parameters are the position, receiver clock error, tropospheric delay and ambiguities. Taking into account more effects like Sagnac effect, solid earth tides, ocean loading atmospheric loading, polar motion earth orientation effects, crustal motion, antenna phase center models and antenna phase wind-up allow for refining the model and improving resulting accuracy. Weighting of observations allows for improving further the accuracy.

PPP theoretically allows an easier detection of anomalous behaviours. The key issue influencing the solution is the quality of reference data (orbits and clocks) and dual frequency observations. Problematic aspects in this technology are:

- Observability of some parameters is poor, resulting in high correlations, especially critical in convergence process
- Systematic errors in orbits and clock product can influence the position, while isolated ones can lead to discontinuities difficult to be detected and mitigated
- Environment obstruction can cause problems in convergence and in recovery process. Current PPP tools are working in developing gap bridging techniques to overcome from these situations (state of the art); this is the case of *magicPPP*, which is in a continuous improvement process, including the integrity algorithm that generates the PLs.
- Communication losses in real time scenarios can lead to degradation of solution (while RTK needs a real time communication link with the base station, PPP can withstand much longer communication losses).

After the analysis made in [Lainez and Romay 2013] based on the PPP algorithm and service developed in GMV, the main indicators for PPP integrity issues can be stated as following:

- As PPP is based on absolute positioning, the lack of definition of the terrestrial reference frame can lead to some errors
- Covariance indicators from PPP estimation filter have to be taken into account
- Residuals from phase measurements are providing valuable information, especially in urban or poor visibility scenarios.
- Quality of the orbits and clocks has to be taken into account
- Convergence period needs special treatment to add additional margins to compensate for the strong initial correlations between different parameters.

As it is one of the preliminary attempts to define these indicators, preliminary results of integrity/reliability algorithm were presented in [Lainez and Romay, 2013]. It showed that it is possible to cover all the situations without any integrity or reliability failures observed while using reliable reference data. Protection Levels of the order of 50 cm for horizontal and 100 cm for vertical component. In urban scenarios, protection levels below 10 m/85% availability can be obtained, but it should be taken into account that in [Lainez and Romay 2013] urban scenarios were not the target.

The *magicPPP* reliability algorithm was defined for open-sky scenarios. It was tested in urban environments also, for checking its reaction capability when convergence was lost, but it has never been fine tuned for high demanding environments.

## REAL DATA ANALYSIS

This section describes the performed analysis of carrier phase data which were gathered during data collection campaign in vehicle scenarios, both in motorway and urban scenarios, collected by the especially designed data collection platform mounted on a car. All the data utilized for the analysis purpose were collected between April 11$^{th}$ 2014 and July 4$^{th}$ 2014 in the surroundings of London and the London downtown. These measurement scenarios were divided into two groups: motorway, containing data gathered mainly on the motorway between Reading and London, and urban, containing data collected in suburban and urban areas of London.

Motorway scenarios resume the characteristic of an "open-sky" environment in the major part of their trajectories, anyway there are some zones where vehicle was passing through objects that could attenuate GNSS signals or partially block them. It is the case for example of some country roads full of trees at both sides of the lane and taking into account the period of the year (spring) where vegetation is rich and it can shadow the lines of sight. In some other, very rare cases, the receiver also experienced a momentary loss of tracked signals because the vehicle was passing below a bridge or viaduct.

In urban scenarios, the major part of the trajectories were taken at the City of London, in highly urbanized area with urban canyons obstructing the LoS, and with increased traffic resulting in lower velocity and traffic jams. Some parts of the scenarios classified as urban were leading through suburban area.

### Pseudorange and Doppler analysis

Thanks to the availability of true trajectory of the vehicle collecting the data, it was possible to calculate the statistics of true errors of pseudorange and Doppler measurements. However, errors of these observables are not crucial ones for techniques of high precision, it is interesting to present their error budgets specific for motorway and urban environments

The trajectory provided by the truth solution generation was combined with the corresponding precise satellite ephemerides available from IGS in order to determine the best estimates of the true geometric range between the satellite and the receiver at each sample epoch. These reference ranges were compared against the measured ranges determined by the SRX-10 receiver to compute measurements errors for analysis.

In Figure 1 and Figure 2 we can see a common relation between the PR error and C/N0 for both analysed constellations. In motorway, as C/N0 decreases, the PR error increases; until around 35 dBHz the error increases linearly, but below 35-30 dBHz the PR error starts increasing exponentially. In urban scenarios, for higher percentiles the increase is exponential below 40dBHz and for lower percentiles around 35 dBHz.
What was observed for urban scenarios was also the relation between PR error and elevation for higher percentiles. The statistics are only maintained for elevations above 65º. The reason for this behavior could be the NLOS and high multipath in urban environment affect more to lower elevations. Especially when the vehicle is stopped for a traffic jam or just for any other reason multipath error grows. And in this case of urban scenarios, multipath from nearest reflective buildings can affect very much the measurements and PVT computation.

| Error types | motorway | | urban | |
|---|---|---|---|---|
| | GPS | Glonass | GPS | Glonass |
| Satellite clock error [meters] | 0.9 | 2.0 | 0.9 | 2.0 |
| Ephemeris error [meters] | 0.9 | 0.7 | 0.9 | 0.7 |
| Ionosphere error [meters] | 7.0 | 7.0 | 7.0 | 7.0 |
| Receiver/Tropo/Envi-ronment error [meters] | 2.1 | 2.6 | 3.2 | 5.8 |
| Total UERE [meters] | 7.7 | 7.8 | 7.8 | 9.3 |

**Table 1 Pseudorange error budget, 1σ values, Stereo FE**

In **Table 1** the total Budget of pseudorange error, increased values of receiver/tropospheric/environment error can be observed for urban environments for both GPS and Glonass constellations. Despite that the error is limited and allows good performances in urban navigation.

Doppler measurements are not affected by the ionosphere or the troposphere, so only the errors in the velocity of the satellite, the drift of the satellite clock and the receiver noise along with the environment effects contribute to the Doppler error. In motorway scenarios the Doppler error is below 10cm/s and slightly increases for low C/N0 and low elevations. In urban scenarios the Doppler error increases being around 10cm/s at 1σ (~10% more than in motorway), but the increase is higher for low C/N0 values and low elevations at high percentiles, which means that the tails of the Doppler error distribution in urban are heavier than in motorway scenarios. The summary of Doppler error can be seen in Table 2.

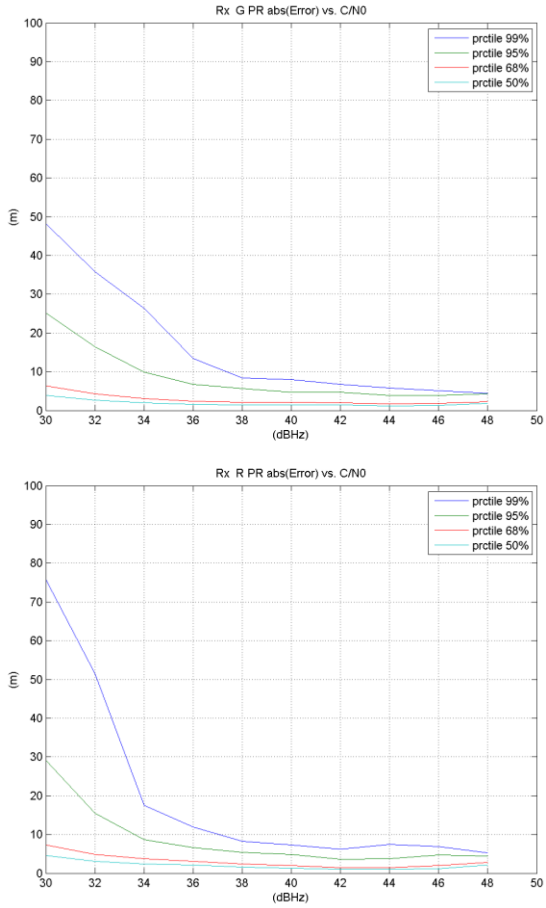
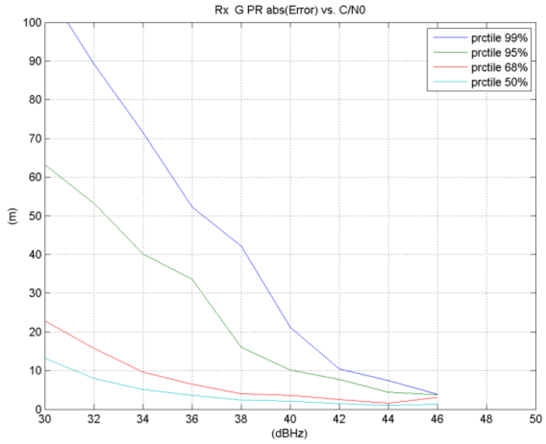



**Figure 1 Receiver PR error vs C/N0 for GPS (up) and Glonass (down), motorway**

| Error types | motorway | | urban | |
|---|---|---|---|---|
| | GPS | Glonass | GPS | Glonass |
| Satellite clock drift error [meters/sec] | 0.001 | 0.001 | 0.001 | 0.001 |
| Ephemeris velocity error [meters/sec] | 0.006 | 0.006 | 0.006 | 0.006 |
| Receiver error [meters/sec] | 0.090 | 0.085 | 0.100 | 0.090 |
| Total UERE [meters/sec] | 0.090 | 0.085 | 0.100 | 0.090 |

**Table 2 Total Doppler error budget, 1σ, Stereo FE**



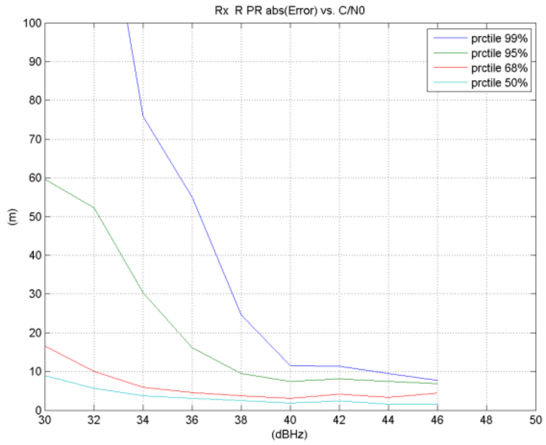




**Figure 2 Receiver PR error vs C/N0 for GPS (up) and Glonass (down), urban scenarios**

**Phase analysis**

The next part of the analysis was dedicated to the analysis of the behavior of carrier phase measurements. The Stereo front end and SRX-10 receiver combination were RINEX 3.0 files providing four types of observables: code pseudorange (PR) measurements, L1 carrier phase measurements, Doppler measurements and C/N0 of the signal for two satellite constellations – GPS and GLONASS. The phase measurements are the crucial observables utilized in RTK and PPP techniques, and to observe their behavior in constrained urban environments was an important issue to characterize potential integrity threats while using high precision navigation techniques. The main focus of the analysis was put on the observation availability, number of visible satellites, periods of continuous carrier phase observation, losses of lock of the tracked phase, presence and length of observation gaps and cycle slip detection. The analysis was performed for two satellite constellations – GPS and Glonass – together, without separating the specific results for a single constellation.

The first analyzed value was the number of satellites with tracked L1 carrier phase observables. The satellite was characterized as phase locked when the observable was present in the file and was different than 0. The measurement equal to zero indicated loss of lock of the phase, therefore these values could not be considered as providing any information.

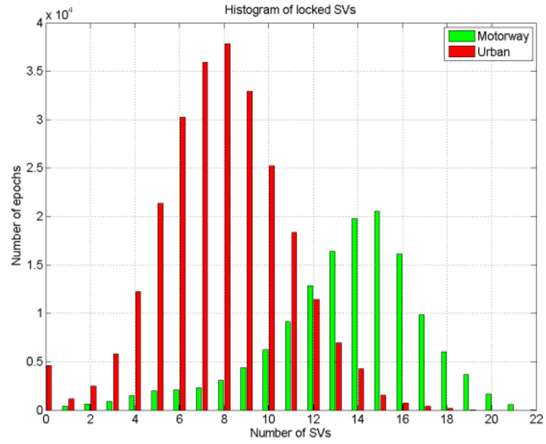



**Figure 3 Histograms of phase-locked satellites**

In Figure 3 the histograms of the phase-locked satellites are presented. A significant difference can be observed between two types of environments: urban and motorway. The motorway scenarios have more epochs with high availability of satellite signal, with the histogram centered at 15 satellite vehicles. The average number of phase locked satellites for this type of scenarios was 13.4, with mode of 15 and median of 14 locked satellites. In urban scenarios, because of the obstructed lines of sight (LoS), this value was significantly lower: 7.9 satellites as an average mode and median values of 8 locked satellites.

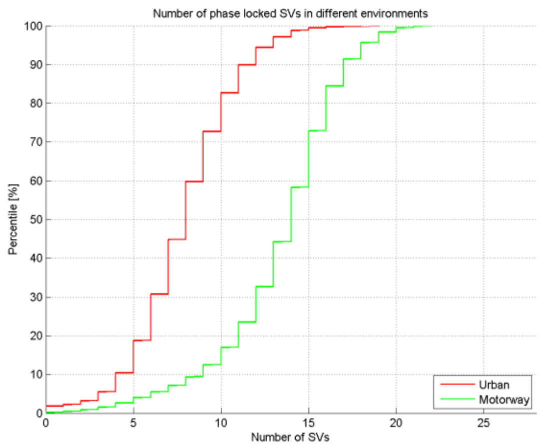



**Figure 4 Cumulative distribution function of the number of visible satellites**

This can be also confirmed in Figure 4 presenting a cumulative distribution function of number of satellites for all measurement epochs. For most of the time of observation the difference between both types of environments in the number of phase locked measurements was around five, indicating a big difference in availability in measurements between those two types of scenarios.

The next step in the analysis was to calculate statistics for the length of continuous observation periods and gaps between them. The observation periods or 'arcs' and 'gaps' were calculated as consecutive periods of the tracked/not tracked satellite at carrier-phase level counted from the first lock of SV until the end of the last arc. In the RINEX file outputs of SRX-10, the satellite is counted as tracked when it appears on a list of tracked satellites in a specific epoch. The statistics were calculated showing the number and length of arcs and gaps. They are presented in Table 3.

We can see there that the average length of observation arc in urban is only 4 seconds longer than gap, and the most frequent arc lasts for 1 second, while the most frequent gap is 3 second long. This can cause possible problems in terms of availability of tracked signal in urban environments.

| | |
|---|---|
| Number of scenarios | 37 |
| Number of epochs [sec] | 253829 (≈70,5 h) |
| Number of gaps | 51398 |
| Average gap [sec] | 34,1 |
| Mode gap [sec] | 3 |
| Median gap [sec] | 11 |
| Number of arcs | 52253 |
| Average arc [sec] | 38,3 |
| Mode arc [sec] | 1 |
| Median arc [sec] | 7 |

**Table 3 Statistics for arcs and gaps in urban environments**

These discrepancies can be also observed on cumulative distribution function graphics of arcs and gaps presented on Figure 5. 50% of arcs in urban are around 7 seconds long, while for gaps this percentile is higher and reaches around 11 seconds. The accumulated value of 80% of arcs reaches up to 35 seconds, in urban this number of observations is again higher and around 38 seconds, and the difference increases with higher percentiles.

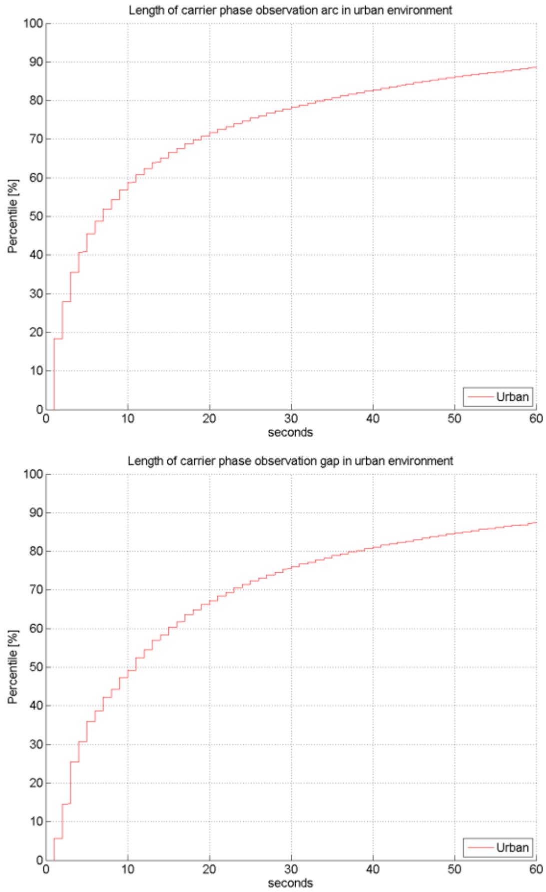



**Figure 5 CDFs of arcs and gaps in urban environment**

**RTK analysis**

For RTK solution, as the reference data were collected by NERC British Isles continuous GNSS Facility, the choice for available reference station was very limited. Therefore, as a reference station was chosen a station in Teddington near London (acronym: TEDD). The 1 Hz reference data were used. The big drawback of this solution was the average baseline length of RTK solution, which in average was around 17 km. In total 5 urban scenarios were analyzed with this method.

| | |
|---|---|
| Fixed solution | 315 (1,7%) |
| Float solution | 16821 (92,2%) |
| Single solution | 1112 (6,1%) |
| All epochs | 18248 |
| Average baseline length [m] | 16710 |

**Table 4 RTK urban solution summary**

In Table 4 the general summary of the solution is presented. The main reason of so many float solutions (above 90% for both environments) can be explained by the baseline length combined with no information about real ionospheric and tropospheric situation. After the comparison with the true trajectory, most of the errors were much beyond expected values for carrier-phase solution. The proper solution to this problem would be to apply virtual reference station (VRS) and reduce the baseline length. The average horizontal position error was equal to 196 meters, which after discarding the errors higher than 6 km lowered to the level of 21 m.

The values that react to integrity threats are the phase residuals calculated in the solution. The analysis of the residuals was performed only for satellites having valid flags in the solution, and then the average value of an absolute value of residual was calculated for a specific epoch.

| | RTK in urban |
|---|---|
| Mean residual average from epoch [m] | 4688,09 |
| Median residual average from epoch [m] | 0,12 |
| Mode residual average from epoch [m] | 0,0001 |

**Table 5 Urban residuals' statistics**

| Percentile average residual [m] | RTK in urban |
|---|---|
| 68% | 0,39 |
| 95% | 11956,07 |
| 99% | 95673,78 |

**Table 6 Urban residuals' percentile values**

In Table 5 and Table 6, the statistical values of residuals are present. From the mode and median values, as well as of those from higher percentiles, we can see that the distribution is strongly distorted by a small number of very high values, and for higher percentiles.

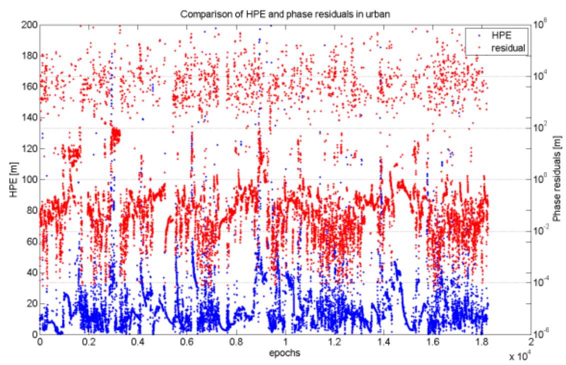



**Figure 6 Comparison of HPE (blue, linear scale) and residuals (red, logarythmic scale), motorway (up) and urban (down)**

In Figure 6, the comparison between horizontal position error and residuals values is presented. Even though the scale is different, the relation between can be noticed. The values of residuals 'follow' the values of HPE and therefore could be useful in integrity algorithms for detecting integrity threats and computing protection levels.

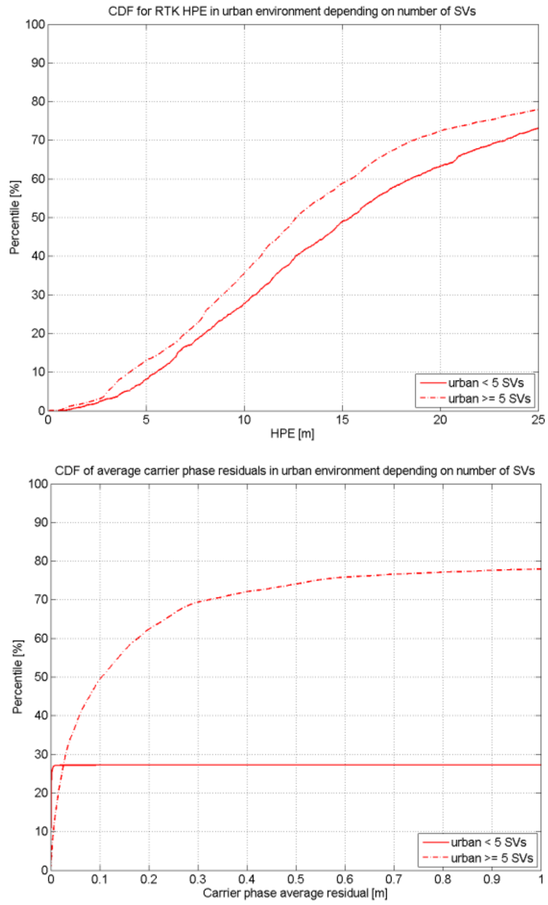



**Figure 7 CDFs for HPE and residuals depending on number of satellites**

In Figure 7 the cumulative distribution functions of HPE and residuals values are presented. We can see that for the moments with minimum of 5 satellites used in the solution, the HPE improves of about 2 meters, starting at 50% percentile and growing. For residuals, epochs with less than 5 satellites visible seem to be providing very erroneous information. Therefore, in designing integrity algorithm, the information about number of satellites visible should also be taken into account.

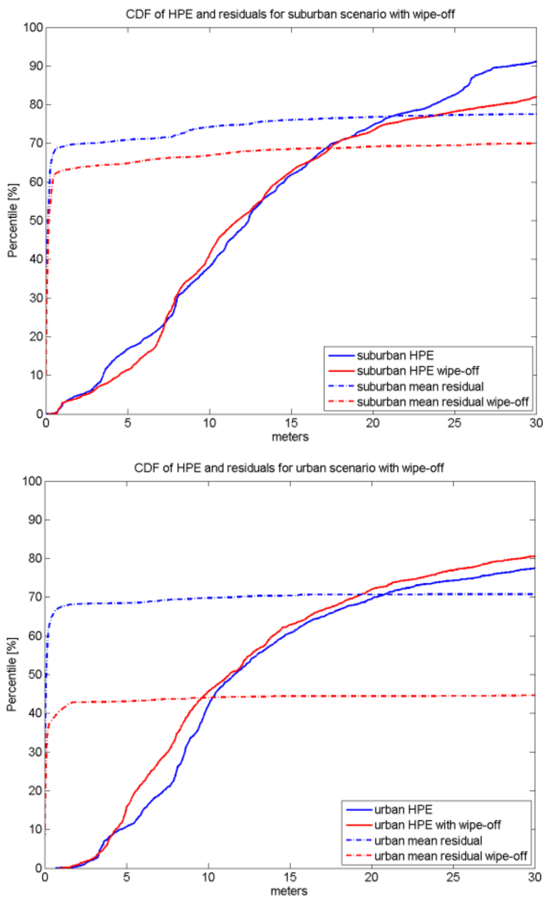



**Figure 8 CDFs of HPE and residuals from RTK solution with and without wipe-off, suburban (up) and urban (down)**

Finally in Figure 8 there are presented CDFs of HPE and residuals from RTK solutions utilizing also data wipe-off for two available scenarios. In these graphics, we can observe that the data wipe-off didn't induce the big and significant improvement of the solution. What is more, for residuals in typical urban environment, the results seem to be worse.

**PPP analysis**

Analysis of chosen motorway scenarios was performed to assess the PPP technique in the aspect of providing precision, availability and integrity.

Data used for the processing are different from the previously processed data, as on the market there are not widely available tools allowing for performing PPP with single frequency measurements only. Therefore, to perform tests with PPP method, the two frequency Novatel SPAN receiver data were used. The tools used for processing the PPP solution were:

- magicPPP developed in GMV, and
- RTKLIB PPP tool (rnx2rtkp.exe tool).

Products that are used for processing are as following:

- Precise satellite clock files in *.clk format, generated by magicGNSS ODTS tool,
- Precise satellite orbits in *.sp3 format, generated by magicGNSS ODTS,
- Broadcast navigation data for GPS and GLONASS constellations in brdc RINEX files.

The reason of choosing magicGNSS ODTS data instead of IGS products was because RTKLIB PPP tool doesn't accept using two separately generated *.sp3 files (e.g. for GPS and GLONASS). In order to use precise orbits for both systems, they had to be generated in the same process of orbit and clock estimation, and it is the functionality of magicGNSS ODTS tool.

The ODTS was performed for periods of three days, with the day of interest as the middle one. For calculating orbits and clocks, data from 57 to 60 stations were used, with 30 second data sampling rate and 10 degrees elevation mask.

Files necessary for processing the observation sessions are as following:

- Earth rotation parameters in *.erp format, obtained from IGS website,
- Ocean tide harmonic data in *.blq format, implemented in magicPPP software,
- SINEX file with the initial position of the receiver to avoid long convergence time (only for magicPPP solution),
- ANTEX file with satellite antennae phase centre variation (PCV) data,
- DCB data files for P1C1 in CODE format.

Motorway Novatel SPAN data were used for processing. Later on, the results were analysed with MATLAB scripts and prepared as input data for Position Error Computation and Position Error Statistics tools of Offline Analysis Unit (OAU) platform, part of the IGNSSRX prototype unit.

To analyse the PPP results, two RTKLIB PPP tool outputs were used: the files containing the results with position data and standard deviation values for each calculated epochs, as well as the residuals file, containing the values of pseudorange and phase residuals for each satellite tracked at given epoch, together with validity flags for each observation.

RTKLIB software doesn't have any protection level algorithm, so an algorithm has been developed for calculating protection levels with the outputs provided by the RTKLIB PPP. This integrity algorithm uses similar outputs from the PPP process as the ones used by magicPPP software, but they are not the same because the same output information is not available in both PPPs. The algorithm was refined to follow the behaviour of the position errors, using the covariance and phase residual values. In sections below, the results of analyses are presented. What was noticed was that the algorithm has the tendency of 'overreacting' with higher values of errors, providing very high protection levels for them.

| Tool | Obs period length | Valid obs | Integrity period availability | Horizontal integrity availability | Vertical integrity availability | Horizontal failures | Vertical failures |
|---|---|---|---|---|---|---|---|
| magicPPP | 22113 | 17421 | 78.78% | 100.00% | 99.99% | 0 | 1 |
| RTKLIB PPP | 22147 | 17965 | 81.12% | 99.48% | 99.34% | 93 | 119 |

**Table 7 Comparison of integrity availability for analyzed motorway scenarios magicPPP**

The input SPAN data showed a big number of cycle slips, half cycle slips and outages, which are crucial for PPP algorithm functioning, causing the necessity of re-estimation of ambiguity. Therefore, epochs with values of standard deviation of position higher than 10 m were discarded and treated as not available for navigation neither for integrity purposes. This also reduced the 'overreacting' the protection level algorithm.

The magicPPP analysis was performed based on the same data as the RTKLIB PPP analysis. The data was processed by the tool and then passed through MATLAB scripts to adjust them to the OAU Position Error Computation and Position Error Statistic tools.

The magicPPP reliability algorithm was defined for open-sky scenarios. It was tested in urban environments also, for checking its reaction capability when convergence was lost, but it has never been fine tuned for high demanding environments.

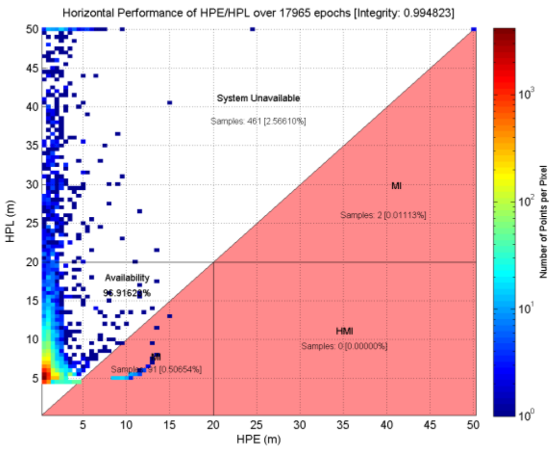



**Figure 9 Stanford diagram for horizontal performance – RTKLIB PPP**

In Stanford diagram for RTKLIB PPP in Figure 9 we can observe that more than 99% of the observations were providing integrity for the scenario horizontally. Thanks to rejecting epochs with faulty observables (outliers), the values of mean position errors reached horizontally 0.73 m. Standard deviation and RMS values were estimated as 1.86 m and 2.00 horizontally.

In the Stanford diagram for magicPPP horizontal solution in Figure 10 we can see that the horizontal integrity is accomplished for all the epochs.Mean position error for horizontal component was 0.69 m. Standard deviation and RMS, horizontally, were 0.77 and 1.03 m.

The tested motorway scenarios made the receiver to pass under a fair amount of tree canopy during important parts of the route (data collection took place in spring) and also under several bridges along the highway. While the pseudorange measurements are not severely affected by these issues, there is a considerable impact on the phase measurements and, consequently, on the ambiguity resolution, which is a process that requires time to converge and the phase cycle slips and outages are continuously hindering its convergence. Therefore, the tested motorway scenarios cannot be considered as an "open sky" environment from the PPP point of view.

Table 7 shows that both tools have a similar level of observation rejection, but with lower rejection by RTKLIB PPP, as it seems to be slightly less prone to cycle slips. Levels of integrity availability were comparable, satisfying the 95% threshold, but the integrity risk provided by the RTKLIB PPP integrity algorithm is around 5.5e-3 while the one provided by *magicPPP* is around 5.7e-5. Being the target integrity risk 1e-4, the RTKLIB PPP integrity algorithm fails in accomplishing it in more than one order of magnitude, while *magicPPP* successfully satisfies it.

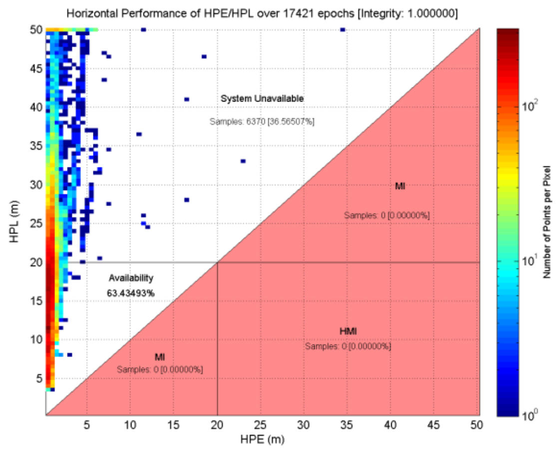



**Figure 10 Stanford diagram for horizontal performance – Comparison with multipath flags**

With respect to the motorway PLs generated by both tools, they cannot be compared as the ones generated by *magicPPP* accomplish an integrity risk two orders of magnitude lower than the one satisfied by the RTKLIB PPP PLs.

Nevertheless, scenarios analysed were very challenging for this technique, with a big number of elements obstructing the sky view, which caused cycle slips. The elimination of epochs with standard deviation of position estimation higher than 10 m was crucial in the process of assessment of both tools. Without it, the results were very noisy and showing lower performance than expected from such high precision, and also highly demanding technique, with the level of accuracy as from single frequency GNSS receiver. Therefore, taking into account the integrity analysis and from the point of view of accuracy of solution in both types of environments, the better performing tool would be *magicPPP*. However it is important to be recalled that neither the PPP positioning nor the PPP reliability algorithms have been designed for non-open-sky environments. The results presented here are the outcome of using the mentioned techniques in highly degraded scenarios. Most of the time the PPP positioning algorithms are not even converged and target centimetre-level performances are thus not reached.

Potential future improvements for adapting the current PPP techniques to more challenging environments include: multi-constellation, multi-frequency, high-sensitivity receivers, single frequency PPP with ionospheric parameters estimation, as an alternative to double-frequency PPP or as a backup in case the second frequency is lost, and more rigorous PPP associated PLs computation, among others. These improvements are very preliminary, and are still in its initial definition/design/implementation phases.

## CONCLUSIONS

The main goal of this paper was to provide an overview of the carrier-phase analysis, the main observable utilized in the precise positioning techniques such as RTK and PPP, in terms of measurements availability and continuity of observables, that was performed in the IGNSSRX project.

In these terms, carrier-phase observables in urban environments show their scarce distribution. The lengths of average observation arcs and gaps are similar. For pseudorange observables, the relation between quality of measurement and C/N0 values was noticed, as well as the influence of satellite elevation on the quality of the observable values.

In RTK analysis, however showing results much below expected accuracies for this type of method, the performed analysis of availability of satellites and measurements and possible relation between their behavior and the values of horizontal position errors can be potentially useful in designing integrity algorithms and calculation of protection levels. It was also confirmed in PPP solutions performed, however only for motorway scenarios, that very preliminary protection level algorithm based on average values of residuals, after discarding epochs with faulty measurements can provide satisfactory results. The future in designing the algorithm should focus on the behavior in the presence of high errors and to limit the tendencies of ‘overreaction’ of the algorithm. For RTK, the tests with virtual reference station could allow for better performances and more realistic distribution of errors, allowing for better understanding the behavior of errors and residuals in constrained environments. Also, applying the data wipe-off to the RTK solution has to still be investigated to understand the possible advantages for this method.

All the aspects above will help to define and propose improvements for carrier phase processing in the algorithms of high precision navigation with integrity.

## ACKNOWLEDGEMENTS

This work was financially supported by the European Commission under the IGNSSRX project (ENTR/129/PP/ENT/SP2/11/6602), as well as by EU FP7 Marie Curie Initial Training Network MULTI-POS (Multi-technology Positioning Professionals) under grant nr. 316528.
The services of the Natural Environment Research Council (NERC) British Isles continuous GNSS Facility (BIGF), www.bigf.ac.uk, in providing archived GNSS data to this study, are gratefully acknowledged.

## REFERENCES

B. Hofmann-Wellenhof, H. Lichtenegger, E. Wasle “GNSS-Global Navigation Satellite Systems. GPS GLONASS, Galileo, and more”, 2008 Springer-Verlag Wien, Vienna

E. Domínguez et al. “Characterization of Integrity Threats in Terrestrial Applications Using Real Signal Captures”, ION GNSS+ 2014.

E. Domínguez et al., Multi-Antenna Techniques for NLOS and Spoofing Detection Using Vehicular Real Signal Captures in Urban and Road Environments, ION GNSS+ 2015, Tampa, FL, USA.

D. Egea-Roca et al., Signal-level Integrity and Metrics Based on the Application of Quickest Detection Theory to Multipath Detection, ION GNSS+ 2015, Tampa, FL, USA.

D. Egea-Roca et al., Signal-level Integrity and Metrics Based on the Application of Quickest Detection Theory to Interference Detection, ION GNSS+ 2015, Tampa, FL, USA.

M. Hernández-Pajares et al. “Wide area real time kinematics with Galileo and GPS signals”, ION GNSS 2004

M.D. Laínez Samper, M.M. Romay Merino, “In-The-Field Trials for Real-Time Precise Positioning and Integrity in Advanced Applications”, ION 2013

D. Kim, R.B. Langley, "GPS Ambiguity Resolution and Validation: Methodologies, Trends and Issues", paper presented at the 7th GNSS Workshop – International Symposium on GPS/GNSS, Seoul, Korea, November 30 – December 2

Lehner A., Steingass A. "A Novel Channel Model for Land Mobile Satellite Navigation", ION GNSS 18th International Technical Meeting of the Satellite Division, 2005, Long Beach

Steingass A., Lehner A., "Land Mobile Channel Model", 2009. http://www.kn-s.dlr.de/satnav/