Vehicular and Pedestrian GNSS Integrity Algorithms and Results for Urban and Road environments developed after an Extensive Real Data Collection Campaign

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BIOGRAPHY

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.

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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.

M. Pattinson is a Principal Navigation Engineer at Nottingham Scientific Ltd, United Kingdom. He received a PhD from University of Nottingham in 2002. Michael has over fifteen years GNSS experience in PVT algorithm and software development, including integrity related algorithms and sensor fusion, and is currently technical lead of the Safety and Integrity Team at NSL.

M. Hutchinson is a Senior Navigation Engineer at Nottingham Scientific Ltd, United Kingdom. He received a MSc in Satellite Positioning Technology from University of Nottingham in 2006. Michael has nine years GNSS experience in PVT algorithm and software development, with a focus on high integrity applications in the rail, road and aviation domains. Michael is currently business lead of the Safety and Integrity Team at NSL.

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.

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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. Before, he was responsible of the receivers R&D activities, time at which he launched the IGNSSRX project. He is an ICAI engineer, has a PhD in Electrical Engineering by Aalborg University and a MBA by London Business School.

ABSTRACT

Integrity in the domain of Global Navigation Satellite Systems (GNSS) has been understood as the ability of detecting and alerting of incorrect user positions, providing therefore a certain level of reliability or trust in the estimated user location. This concept of integrity was imported from the "safety-critical" aviation services, thus requiring an extremely high level of reliability, and it has been one of the drivers of satellite navigation systems in the past decades.

As the use of GNSS has also expanded to mass market users, terrestrial user communities have also shown interest in applications requiring reliable positions. These terrestrial "liability-critical" applications (i.e. initially referred to applications that require a certain level of trust for economical or legal reasons, and later extended to terrestrial applications that require a level of trust for whatever purpose) require a high level of reliability, but somehow lower than in aviation. However, most of these users are located in populated areas and aviation environmental assumptions and algorithms are not fully applicable to them because of local environmental characteristics, which include buildings, trees, etc., increasing the multipath and the Non-Line-of-Sight (NLOS) signals, and dominating the GNSS measurement errors. Also threats like radio frequency (RF) interference and spoofing can deny the positioning service or lead to misleading positions. These local effects, which cannot be corrected by the ground or satellite segments, are very important in urban environments and degrade the signals leading to potentially high positioning errors and therefore may also hinder the provision of a full integrity positioning service.

At receiver level, integrity has been mainly provided through Receiver Autonomous Integrity Monitoring (RAIM) algorithms. Based on the redundancy of satellite measurements, receivers were able to detect a satellite failure and exclude a faulty satellite from the navigation solution. In addition, combination of GNSS measurements with different types of external sensors can be used to overcome the impact of local effects.

The objective of this paper is to present the results obtained in the research and development of PVT algorithms to mitigate the integrity faults in terrestrial environments (in particular urban and road) for vehicular and pedestrian users, thus improving terrestrial positioning services and enabling many terrestrial "liability-critical" applications. The tested integrity techniques include:

- GNSS based PVT integrity techniques for autonomous vehicular navigation, that is, those which do not require information from outside the GNSS receiver to operate.
- Hybrid integrity techniques for vehicular users using external sensors in combination with GNSS.
- Integrity techniques for pedestrian users.

The algorithms have been tested using the data obtained through an extensive collection campaign carried out in urban and road environments for vehicular and pedestrian users, allowing the assessment of high integrity confidence levels. Terrestrial applications are mainly interested in horizontal positions, so the integrity is provided in terms of a horizontal protection level (HPL), associated to the estimated position that should bound the horizontal position error (HPE) with a certain confidence level or target integrity risk (TIR). The results are evaluated in terms of accuracy (HPE), availability (size of HPLs) and integrity.

Two applications, Road User Charging (RUC) and E-112, were selected among others for being the most significant in terms of required GNSS integrity. For each application, a set of possible service performance metrics was elaborated and then it was traced, making assumptions, to examples of the navigation and integrity performance metrics that could be required by the application. These sets of navigation and integrity performance metrics were used in the comparison with the results obtained when processing the collected real data.

Summarizing, this paper presents the results of vehicular and pedestrian integrity techniques in urban and road environments using an extensive real data set, which allows the assessment of high confident levels, and provides a preliminary insight into the use of these integrity

techniques for Road User Charging (RUC) and E-112 applications.

INTRODUCTION

The paper presents the results obtained within the frame of the Integrity GNSS Receiver (IGNSSRX) project which was a European Commission funded project developed between 2012 and 2015 by a consortium including GMV, NSL, TRL and UAB. The project had three main objectives, the first two being already presented in [1] and the third one being the focus of this paper:

a) The development of two platforms (vehicular and pedestrian) to capture and store GNSS radio frequency signal samples (GPS L1 & Galileo E1 bands and the GLONASS L1 band) and low-, medium- and high-end sensors representative in terrestrial applications. It also includes a truth reference trajectory system allowing error computation to assess performances.
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.

As mentioned, this paper presents part of the results achieved within the third objective, while the other outcomes are described in [2], [3], [4] and [5].

The paper starts with a brief description of the vehicular and pedestrian capture platforms and the performed data collection campaign. Then it focuses, firstly, on describing the different types of integrity techniques, including the use of external sensors; secondly, on the trade-off performed between the different techniques based on the results obtained using real data; and, finally, on the selected algorithms for the prototype receiver and the results obtained with the whole set of collected real data. At last, an assessment is made between the obtained navigation and integrity performances and the ones that would be required by the two applications abovementioned (RUC and E-112).

DATA COLLECTION PLATFORMS

The IGNSSRX Data Acquisition and Storage Unit (DASU) is completely described in [1]. Two DASU platforms were developed:

- Vehicular DASU:
  - Two RF Front-Ends (FE): a high resolution 8-bit FE (STEREO [7]) and a three-antenna 1-bit FE system (TRITON [8]), working both in the GPS L1 & Galileo E1 and GLONASS L1 bands:
    - Recording raw data capability from medium and low cost COTS INS sensors, such as SBG IG500E (medium cost), u-blox EVK-6R (low cost) and car odometer
  - Truth reference equipment using a high accuracy and availability reference system based on high geodetic-grade GPS&GLONASS dual-frequency receiver, tactical-grade IMU and wheel probe:
    - NOVATEL GPS&GLONASS L1/L2 with SPAN-CPT and wheel sensor: error of post-processed solution is 1 cm RMS with SV visibility and 29 cm after 60 s of SV outage.
  - Common CSAC atomic clock synchronizing the platform with the truth reference equipment.

- Pedestrian DASU:
  - RF Front-End: a high resolution FE (STEREO [7]) in the GPS L1 & Galileo E1 and GLONASS L1 bands.
  - Recording capability of GSM and Wi-Fi measurements to hybridise with GNSS and mobile phone platform.
  - Reference equipment using a GPS&GLONASS L1/L2 geodetic receiver plus route trace.
  - Common CSAC atomic clock synchronizing the platform with the truth reference equipment.

Additionally, an Offline Analysis Unit (OAU) was developed, based on the SRX software receiver [6], in order to process and analyse the RF data recorded by the DASU FEs (STEREO [7] and TRITON [8]) and generate GNSS measurements (code, carrier phase and Doppler). The OAU also incorporates tools in order to characterize and identify the threats at signal and measurement levels (such as multipath and interference events), and evaluate the positioning performance.

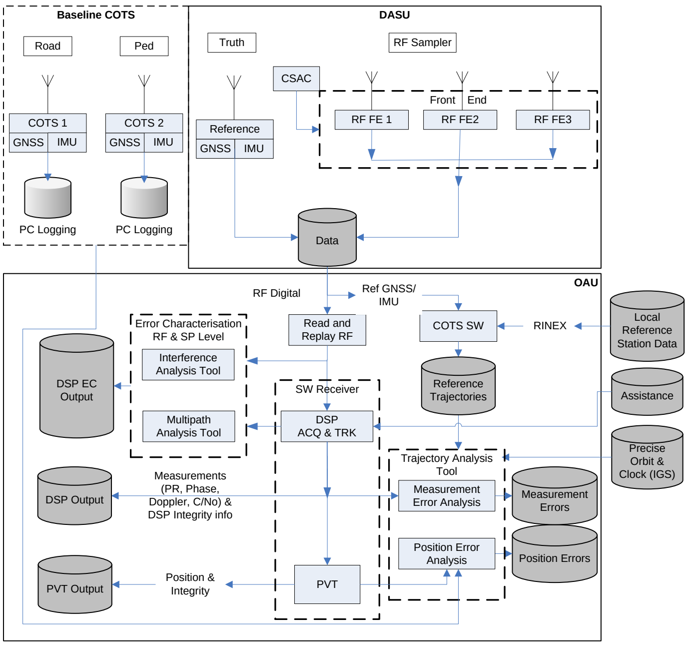

Figure 1 DASU and OAU Overview

DATA COLLECTION CAMPAIGN

The IGNSSRX data collection campaign is completely described in [1]. Both DASU platforms were used to perform an extensive data collection campaign covering representative road and pedestrian user environments:

- Vehicular campaign: 110 hours of usable data covering motorway and urban areas in London (with tunnels and urban canyons).

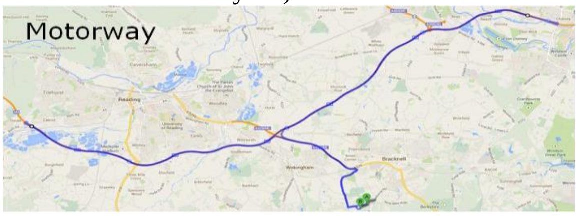

Figure 2- Vehicle Data Collection: London Motorway route

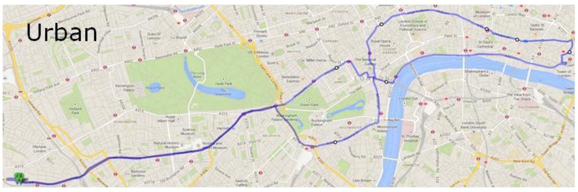

Figure 3- Vehicle Data Collection: London Urban route

- Pedestrian campaign: more than 13 hours of usable data through different routes around city areas in Leeds and Nottingham, in rural/suburban and urban environments, the last one including urban canyons, covered arcades and shopping areas (collected indoor data is not taken into account in this paper).

RESEARCH FOR INTEGRITY TECHNIQUES

Algorithms proposal

With the aim of identifying those integrity techniques that could be potentially interesting to satisfy the integrity requirements of the IGNSSRX project, an initial extensive survey of the available literature was carried out. These requirements were oriented not just to perform fault detection and/or exclusion (FDE), but to produce protection levels (PL) at some confidence level. That is, these protection levels shall satisfy a target integrity risk while maximizing their availability (i.e. minimizing the PL size).

Three different types of algorithms were tuned and tested:

- GNSS-only
- Hybrid GNSS
- Pedestrian

The following list of candidates based on GNSS-only algorithms was considered for the vehicular case (two snapshot and two filtered):

- MHSS: based on least squares navigation (LSQ), the protection level is calculated as the value that overbounds all the partial PL obtained for the different fault modes considered [9], [10]

- IBPL: based on LSQ navigation, the protection level of this GMV integrity algorithm is based on the isotropy concept, calculated as described in [11] and [12].

- KFMI: based on Kalman Filter navigation, and although it uses primarily FDE, also implements a protection level based on state covariance terms under some specific hypothesis [13]

- KIPL: based on Kalman Filter navigation, it combines an FDE with a protection level calculation relying on the isotropy concept extended to filtered solutions (see [14], [15] and [16]). KIPL is the navigation and integrity (PVT+I) solution of the SRX GMV software receiver product [6].

Additionally, a hybrid GNSS/INS navigation and integrity algorithm was considered:

- GNSSDR: based on Kalman Filter navigation, integrate GNSS measurements (pseudo-range and Doppler) together with data from external heading (gyro) and odometer in a tight coupling configuration. The integrity algorithm relies on similar assumptions and hypothesis as KFMI [17], [18]

In the case of pedestrian navigation, a hybrid algorithm that combines GNSS, Wi-Fi and GSM measurements was used.

The considered algorithms present different advantages and drawbacks. On one side, the proposed snapshot algorithms (MHSS and IBPL) provide a straightforward and justifiable way of integrity computation (PL), but since they are LSQ solutions, there exist a high lack of accuracy, especially when navigating in urban environments or harsh conditions, which also affects the availability of the integrity solution provided. On the other side, the filtered solutions (KFMI, KIPL and GNSSDR) provide a much more precise navigation in terms of accuracy, but the computation of a protection level is not so easy, and may rely on some experimental hypothesis, as is the case of KFMI and GNSSDR.
Nonetheless, in the particular case of KIPL, the isotropy concept has been mathematically extended to fit into filtered solutions through means of Bayesian methods, overcoming this main limitation regarding integrity computation, as shown in [14] and [15].
Additionally, KFMI and GNSSDR require tuning of the filter parameters in order to optimally operate under different sky conditions (e.g. motorway, urban), both from the point of view of accuracy and integrity, while KIPL

works in a single configuration regardless of the environment without penalizing the final performance.
Finally, the selection of the final candidate algorithms to be tested in the IGNSSRX prototype has been performed by selecting one of the GNSS-only PVT+I algorithms proposed after a trade-off evaluating their performance. Moreover, GNSSDR and hybrid pedestrian algorithms (which are the only hybrid candidate solutions proposed for vehicular and pedestrian respectively) are also included in the final analysis, which will process all the data gathered during the extensive campaign carried out (more than 110 hours with two different front-ends in parallel, STEREO [7] and TRITON [8], covering urban canyon and motorway/open sky areas) with the set of selected algorithms, and check the compliance of the experimental results with respect to some example metrics for the evaluated applications (RUC, E-112).

Selection of the GNSS-only candidate solution

The GNSS-only algorithms were improved and tuned using a subset of the total data gathered in the campaign and the obtained results were used to select the best GNSS-only candidate. This subset comprises two motorway scenarios (~15000 epochs) and two urban scenarios (~30000 epochs), recorded with the TRITON front-end.
The size of the aforementioned subset is considered to be enough to extract relevant information concerning accuracy and integrity availability and deduce some conclusions.
Taking into account that the target integrity risk (TIR) considered in the IGNSSRX project is TIR=1e-4, it may seem that the integrity requirement cannot be properly tested. In order to overcome this limitation, we will focus for this research stage in a TIR=1e-3, for which the number of total samples is high enough (more than 10 times the inverse of the TIR), although special attention shall also be paid to TIR=1e-4. In fact, all the horizontal protection level (HPL) values represented in the following tables are computed to guarantee integrity with an experimental integrity risk lower than 1e-4.
Notice that, at this research stage, the TIR will be tested regardless of the environment (motorway or urban), obtaining a unique experimental integrity risk value for the global data set. The reason for this is twofold: on one hand, we consider every type of scenario, since the target integrity risk shall be satisfied regardless the type of environment. On the other hand, increasing the number of samples available for the analysis implies a more reliable estimation of the experimental integrity risk.
Finally, it is worth to remark that the procedure described above involves the implicit assumption that the integrity solution provided by the algorithms herein presented can be configured for different TIRs without loss of integrity.
The metrics that will be considered in the research process relates mainly to accuracy, measured in terms of horizontal position error (HPE), integrity availability, measured in terms of horizontal protection level (HPL), and compliance of the integrity risk at the selected TIR.

The following tables summarize the results obtained with the algorithms proposed, with representative percentiles of the cumulative distribution (CDF) under analysis. Table 1 and Table 2 relate to the HPE CDF in motorway and urban, respectively (MHSS and IBPL snapshot positioning is based on LS so they both provide the same HPE performances, the difference is on the computed HPL). On the other hand, Table 4 and Table 5, show analogous results for the HPL CDF, while Table 3 represents for each integrity algorithm the number of epochs when a protection level is provided, in terms of percentage with respect to the total number of epochs. A “-” in a table means that no HPE/HPL value is available for the evaluated percentile (higher than 1e4).

Percentile [%]	MHSS [m]	IBPL [m]	KFMI [m]	KIPL [m]
50	3.03	3.03	2.42	2.51
80	5.07	5.07	3.73	3.44
90	7.74	7.74	4.58	3.91
95	12.45	12.45	5.68	4.40
99	26.90	26.90	8.08	8.48

Table 1 HPE performance for the proposed navigation algorithms (Motorway)

Percentile [%]	MHSS [m]	IBPL [m]	KFMI [m]	KIPL [m]
50	12.36	12.36	5.78	5.36
80	28.41	28.41	13.77	12.12
90	43.18	43.18	21.98	17.91
95	62.20	62.20	28.79	25.04
99	244.42	244.42	-	49.79

Table 2 HPE performance for the proposed navigation algorithms (Urban)

Environment	MHSS [%]	IBPL [%]	KFMI [%]	KIPL [%]
Motorway	99.92	99.92	97.68	99.80
Urban	95.96	95.96	93.64	95.54

Table 3 Integrity Availability (% of total epochs) for the proposed integrity algorithms

Percentile [%]	MHSS [m]	IBPL [m]	KFMI [m]	KIPL [m]
50	42.31	12.96	17.01	14.93
80	55.81	26.48	18.11	23.54
90	66.87	43.56	19.21	32.11
95	79.88	71.86	21.02	35.22
99	112.13	168.09	-	68.22

Table 4 HPL (TIR=1E-4) performance for the proposed integrity algorithms (Motorway)

Percentile [%]	MHSS [m]	IBPL [m]	KFMI [m]	KIPL [m]
50	113.75	117.22	63.27	41.03
80	215.32	276.31	69.14	56.12
90	369.32	486.75	73.49	65.02
95	930.84	924.66	81.21	83.43
99	-	-	-	-

Table 5 HPL (TIR=1E-4) performance for the proposed integrity algorithms (Urban)

Concerning the compliance of the TIR, Table 6 shows the measured integrity performance for all the algorithms under evaluation. The values in the table are normalized to the TIR for the sake of clarity and better interpretation of the results, in which we denote as normalized integrity risks.

Notice in the aforementioned table that a measured IR/TIR equal to zero does not mean at all that the integrity algorithm would never incur into integrity failures, but simply that no failures have been detected for the data set used. A good approach to interpret a zero result is to think that the integrity protection provided is equal or less than the inverse of the amount of samples used for the analysis. Finally, notice that, because of how these values are calculated, the compliance of the TIR will be depending on how close they are to 1. A value higher than 1 means that the TIR is not strictly satisfied, while a value closer to 0 rather than 1 means that the integrity algorithm is behaving conservatively and a higher integrity performance (than the expected target) is being provided.

Algorithm	Normalized Integrity Risk (Measured IR/TIR)	
	TIR=1E-3	TIR=1E-4
MHSS	0	0.20
IBPL	1.11	1.21
KFMI	0.16	0
KIPL	0	0

Table 6 Normalized Integrity Risk (Measured IR/TIR) for the proposed algorithms (Global)

In the light of the results presented in the experimentation section, the algorithm selected to be part of the prototype is KIPL. This is so for several reasons:

- Highest accuracy performance in terms of HPE, both in motorway and urban scenarios
- Higher integrity availability (HPL) than other algorithms proposed
- Compliance of the target integrity risks under analysis (with margin, conservative approach)
- The performance of the algorithm is not conditioned to the tuning of parameters, but a single configuration is used for all kinds of scenario (e.g. motorway, interurban, urban)
- Low computational load

Summarizing, three algorithms shall be tested in the IGNSSRX final prototype:

- KIPL as GNSS-only PVT+I solution
- GNSSDR as GNSS/INS PVT+I solution
- Hybrid GNSS/Wi-Fi/GSM pedestrian algorithm

PVT+I ANALYSIS IN IGNSSRX PROTOTYPE

Data Campaign

As detailed in [1], a very extensive data campaign was carried out with the purpose of testing the performance of the PVT+I algorithms, gathering vehicular data in motorway and urban areas, and pedestrian data in rural/suburban and urban environments.

Table 7 contains the number of total processable epochs used for the analysis with each front-end.

Notice that, in the particular case of vehicular analysis, it shall be expected to have the same number of epochs recorded with each front-end. Nevertheless, they are not the same, due to the fact that the FEs are not switched on or off simultaneously, and differences between recorded samples tends to grow as the number of journeys increase. It is also worth to remind that pedestrian data has only been gathered with the STEREO FE. Also, as different antennas are used for each vehicular FEs (all placed on top of the car roof), the noise and the impact of multipath will be different between them, thus making the datasets independent from the noise and multipath point of view (which in some way doubles the amount of data used to test the algorithms). This fact, together with the HW differences between the FEs (although the samples collected by the FEs are processed in the same way by the SRX software receiver), leads to differences in the results obtained when using the same algorithm with each FE (similar performances but not exactly the same).

Analysis		Front-End	
	Environment	STEREO	TRITON
Vehicular	Motorway	148059	146180
	Urban	275159	274182
Pedestrian	Suburban	28345	-
	Urban	19391	-

Table 7 Total number of total processable epochs recorded in the data campaign with each FE

For the sake of clarity, in the present article we will split the analysis into two: first, we will show representative results for the vehicular analysis, and some conclusions will be highlighted; second, a similar procedure will be applied for the pedestrian case. At the same time, each analysis is performed for each type of environment independently: motorway and urban for vehicular data, and suburban and urban analysis for pedestrian data. Due to the relevance of the topic, the evaluation of the compliance of the target integrity risk will be carried out at the end of each section (vehicular, pedestrian), once we have presented all the experimental results concerning the involved metrics.

Additionally, some validation results concerning the performance of the two front-ends available will be shown (vehicular data), which will lead us to the conclusion that the performance achieved by each one of the algorithms herein tested (KIPL, GNSSDR) is quantitatively similar regardless of the front-end used.

Vehicular Analysis

As we can observe, the effort dedicated to process the recorded samples has been huge. Around 450000 epochs for each front-end have been recorded, trying to cover with enough variety typical harsh events like tunnels, urban canyons, NLOS or multipath. This guarantees that the results herein presented, both from the point of view of

accuracy and (especially) integrity, are representative enough of the real performance. Special attention has been paid in the recording of samples in urban areas, having twice the number of epochs as in motorway.
The HPE analysis herein described will be performed taking into account all the epochs (including also those with no integrity solution). The underlying reason is to ensure that the comparison between different navigation algorithms in terms of accuracy is properly performed. Besides, it allows us to provide the worst case point of view, since outlier/outage epochs (such as tunnel events), which may be discarded in the set of integrity epochs due to the lack of GNSS data, are accounted for.
On the other hand, the integrity availability (HPL, computed to provide TIR=1e-4) performance is provided showing only epochs when the integrity solution is available. Moreover, the HPE performance under these conditions (only epochs with integrity) can be implicitly observed in Stanford diagrams, although we can advance that they are very similar to the results including the overall dataset. This fact indicates the robustness of the algorithms herein proposed.
Stanford diagrams are used for clarity purposes, the alarm limit and the distinction between MI and HMI cannot be directly translated from the aeronautic to the liability-critical domain where each application will have its own constraints.
Finally, it is worth to remind that there exist four possible combinations that shall be evaluated: KIPL and GNSSDR with STEREO and with TRITON data.

Algorithms performance under motorway conditions

The number of epochs during which the HPL solution is available in motorway environment for each algorithm is shown in Table 8. Notice that the number of total epochs represented do not coincide with the results of Table 7, since in this case we only account for epochs when it has been considered that the raw data recorded by FEs is valid (e.g. losses of samples were detected in vehicular DASU during initialization, generating transient periods at the beginning of the recording that have been discarded), and reference truth solution is available.

Front-End	Total Epochs [s]	KIPL	GNSSDR
		Integrity Availability	Integrity Availability
STEREO	140036	99.58%	99.79%
TRITON	142950	99.86%	99.85%

Table 8 Percentage of epochs with computed integrity solution (Motorway)

Table 9 summarizes the accuracy results for motorway, showing representative percentiles of the HPE cumulative distribution for each front-end and algorithm. Analogously, Table 10 summarizes the integrity availability results, highlighting representative percentiles of the HPL cumulative distribution.

Percentile [%]	STEREO		TRITON	
	KIPL [m]	GNSSDR [m]	KIPL [m]	GNSSDR [m]
50	2.02	1.90	2.00	2.10
80	3.41	3.42	3.56	3.80
90	4.41	4.80	4.79	5.65
95	5.81	6.82	6.78	7.75
99	9.64	14.25	12.09	16.82

Table 9 HPE performance at representative percentiles (Motorway)

Percentile [%]	STEREO		TRITON	
	KIPL [m]	GNSSDR [m]	KIPL [m]	GNSSDR [m]
50	13.19	14.78	13.51	13.89
80	22.84	22.41	24.00	24.17
90	28.40	36.75	29.02	51.56
95	32.33	74.62	32.77	85.51
99	46.20	97.82	48.77	116.34

Table 10 HPL (TIR=1E-4) performance at representative percentiles (Motorway)

Complementary, the following figures represent the Stanford diagrams for all the possible combinations between FE and algorithms: Figure 4 and Figure 5 represent the Stanford diagram for KIPL and GNSSDR using the STEREO FE at TIR=1e-4, while Figure 6 and Figure 7 show analogous results using the TRITON FE.
From the results, it is worth to note that the HPE and HPL availability performances provided by KIPL are better than the ones from the hybrid algorithm despite including external information from the odometer and heading. The reason is that, while the GNSSDR implements a standard hybrid Kalman Filter navigation, as described in the available literature, the KIPL filter follows a more refined approach, as a result of research efforts (see [14] and [15]). Therefore, due to the nature of the hybrid algorithm and with additional improvements, the GNSSDR would be expected to overcome the results of the KIPL.
Therefore, KIPL results will be used in following steps when evaluating the applicability of GNSS techniques for Road User Charging.

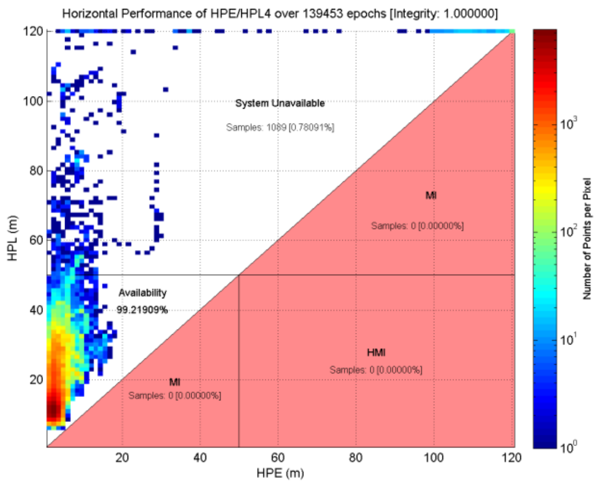

Figure 4 Stanford diagram (TIR=1E-4) - STEREO KIPL (Motorway)

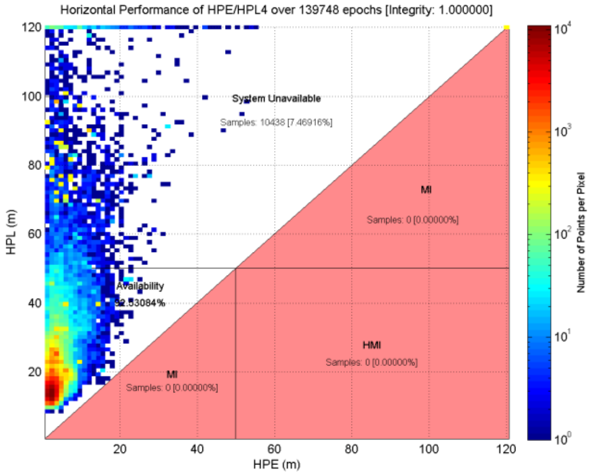

Figure 5 Stanford diagram (TIR=1E-4) - STEREO GNSSDR (Motorway)

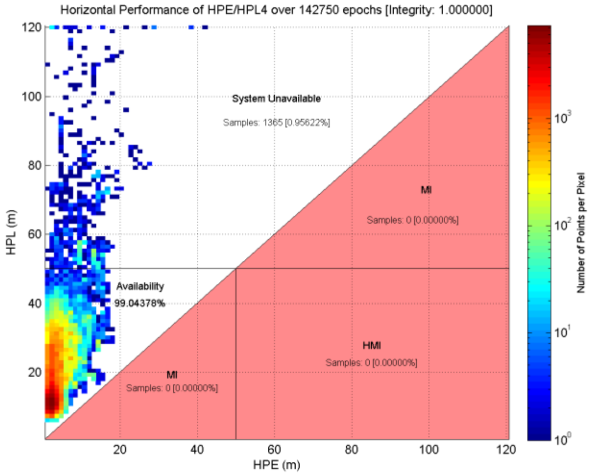

Figure 6 Stanford diagram (TIR=1E-4) - TRITON KIPL (Motorway)

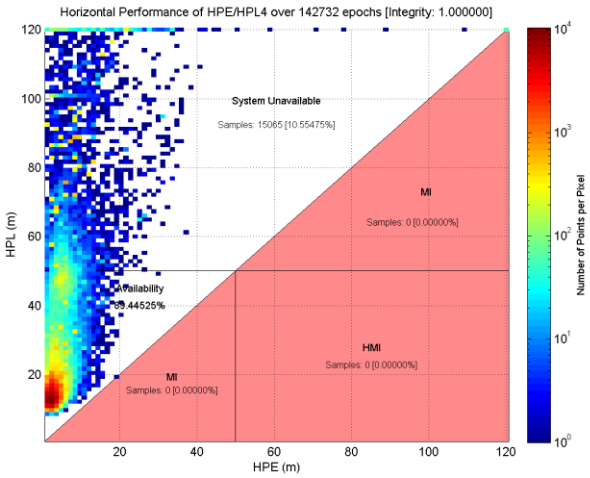

Figure 7 Stanford diagram (TIR=1E-4) - TRITON GNSSDR (Motorway)

Algorithms performance under urban conditions

The number of epochs during which this HPL solution is available in motorway environment for each algorithm is shown in Table 11. The number of total epochs shown do not coincide with the results in Table 7 for the same reason as in the motorway case.

Front-End	Total Epochs [s]	KIPL	GNSSDR
		Integrity Availability	Integrity Availability
STEREO	252860	95.06%	99.82%
TRITON	271907	96.54%	99.89%

Table 11 Percentage of epochs with computed integrity solution (Urban)

Table 12 summarizes the accuracy results for urban environment, showing representative percentiles of the HPE cumulative distribution for each front-end and algorithm. Analogously, Table 13 summarizes the integrity availability results, highlighting representative percentiles of the HPL cumulative distribution.

Percentile [%]	STEREO		TRITON	
	KIPL [m]	GNSSDR [m]	KIPL [m]	GNSSDR [m]
50	4.69	5.79	4.87	6.57
80	10.66	13.57	10.76	14.70
90	16.63	20.20	16.20	21.27
95	23.34	27.27	22.21	28.26
99	86.46	52.94	81.82	53.00

Table 12 HPE performance at representative percentiles (Urban)

Percentile [%]	STEREO		TRITON	
	KIPL [m]	GNSSDR [m]	KIPL [m]	GNSSDR [m]
50	41.47	64.93	41.80	73.64
80	56.32	170.81	54.64	187.74
90	70.08	269.66	64.42	278.91
95	89.08	387.24	77.59	376.00
99	191.45	837.10	143.69	646.95

Table 13 HPL (TIR=1E-4) performance at representative percentiles (Urban)

Complementarily, the following figures represent the Stanford diagrams for all the possible combinations between front-ends and algorithms: Figure 8 and Figure 9 represent the Stanford diagram for KIPL and GNSSDR using the STEREO FE at TIR=1e-4, while Figure 10 and Figure 11 show analogous results for the TRITON FE.
From these figures, it is remarkable the fact that, even for urban environments, most of the pairs (HPE, HPL) are still concentrated in the semiplane HPL > HPE, being HPE, HPL > 0, with a probability higher than the TIR.

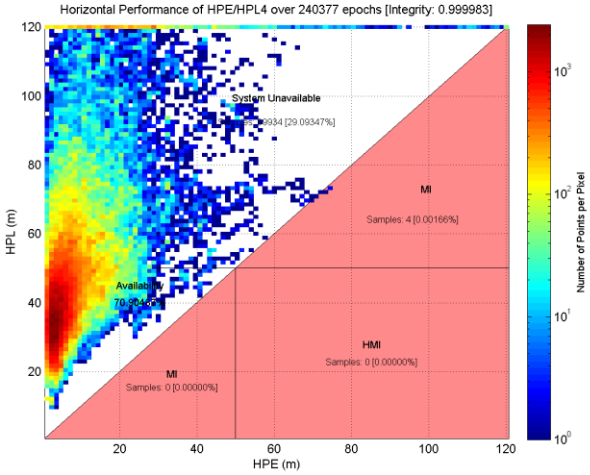

Figure 8 Stanford diagram (TIR=1E-4) - STEREO KIPL (Urban)

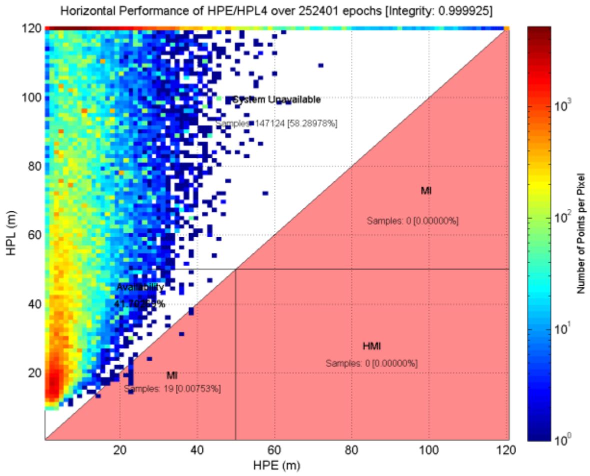

Figure 9 Stanford diagram (TIR=1E-4) - STEREO GNSSDR (Urban)

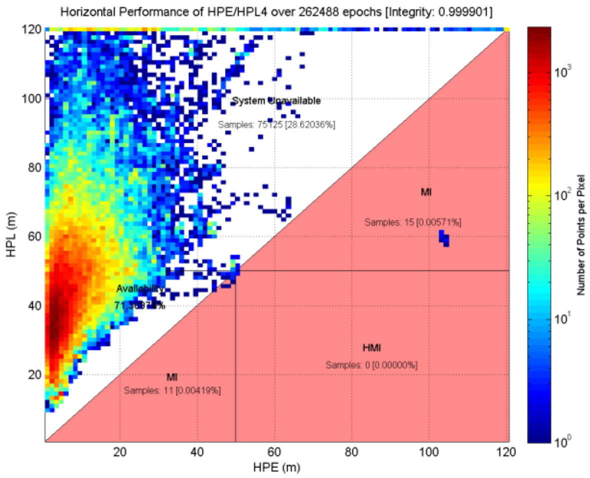

Figure 10 Stanford diagram (TIR=1E-4) - TRITON KIPL (Urban)

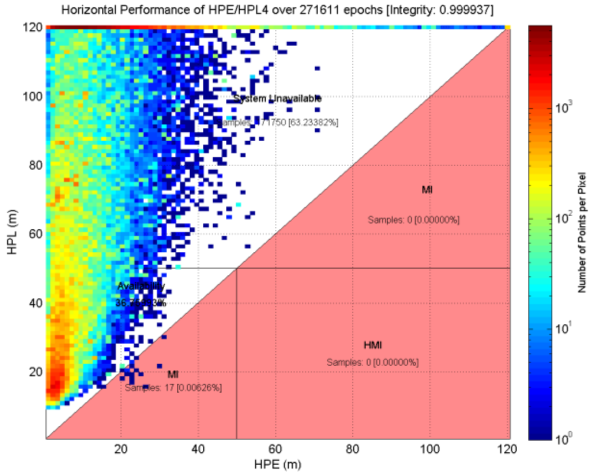

Figure 11 Stanford diagram (TIR=1E-4) - TRITON GNSSDR (Urban)

Similarly to the motorway case, it can be observed that KIPL performances are better than GNSSDR ones except for HPE high percentiles where the usefulness of the dead-reckoning implementation is noticeable. As explained in the motorway case, the different approach followed within the KIPL improves the performances with respect to a standard hybrid Kalman Filter.
Like in the motorway case, the KIPL algorithm will be used when evaluating Road User Charging metrics in urban environments.

Compliance of the Target Integrity Risk

In contrast to the integrity analysis performed in the research stage, where both motorway and urban data were put together in order to compute the experimental integrity risk, here we will compute it separately for each environment, taking advantage of the high number of samples available (more than 1e5 for each type of scenario and front-end). Therefore, the size of the set is, as planned, high enough to provide reliability in the computation of integrity risks up to TIR=1e-4, which is selected to be the target integrity risk in the IGNSSRX prototype platform.
Moreover, notice that this integrity analysis is much more stringent than the research analysis for autonomous GNSS techniques, since it guarantees that the integrity requirements are satisfied regardless of the environment, instead of being satisfied only in global terms. Table 14 includes the number of epochs used in each case for the integrity failures analysis.

Front-End	Motorway		Urban	
	KIPL	GNSSDR	KIPL	GNSSDR
STEREO	139453	139748	240377	252401
TRITON	142750	142732	262488	271611

Table 14 Number of epochs with integrity solution available used to compute IR

The measured integrity performances are represented in Table 15 and Table 16, for motorway and urban environments respectively. The values in the tables are

normalized to the TIR for the sake of clarity and better interpretation of the results, in which we denote as normalized integrity risks.
Notice in the aforementioned tables that a measured IR/TIR equal to 0 does not mean at all that the integrity algorithm never incurs in integrity failures, but simply that no failures have been detected for the data set used. A good approach to interpret these results is to think that the integrity risk provided is, at least, 10 times better than expected (i.e. IR < TIR/10). In fact, the integrity risk would be equal or less than to the inverse of the samples used for the analysis (i.e. ~1e-5).
Finally, notice that, because of how these values are calculated, the compliance of the TIR will be depending on how close they are to 1. A value higher than 1 means that the TIR is not strictly satisfied, while a value closer to 0 rather than 1 means that the integrity algorithm is behaving conservative and a higher integrity performance (with respect to the expected target) is being provided.

Front-End	Algorithm	TIR = 1E-3	TIR = 1E-4
STEREO	KIPL	0	0
	GNSSDR	0	0
TRITON	KIPL	0.05	0
	GNSSDR	0.01	0

Table 15 Normalized Integrity Risk (Measured IR/TIR) for the proposed algorithms (Motorway)

Front-End	Algorithm	TIR = 1E-3	TIR = 1E-4
STEREO	KIPL	0.77	0.17
	GNSSDR	0.10	0.75
TRITON	KIPL	0.82	0.99
	GNSSDR	0.23	0.63

Table 16 Normalized Integrity Risk (Measured IR/TIR) for the proposed algorithms (Urban)

From the previous tables we can extract some conclusions concerning the compliance of the target integrity risk. First, that both algorithms (KIPL and GNSSDR) satisfy experimentally the integrity requirement at TIR=1e-3 and TIR=1e-4 both for motorway and urban environments using all the collected data. Second, that the computed HPL values provide a measured integrity risk much more stringent than required in all cases, which is traduced in normalized integrity risk values closer to 0 rather than 1. An immediate derivation of this is that the HPL values, both in KIPL and GNSSDR algorithms, could be relaxed without penalizing the integrity requirement.

As a summary:

- SRX integrity algorithm (KIPL) provides horizontal protection levels that satisfy the target integrity risks selected for the application (in case of RUC, in the order of TIR=1e-3 and TIR=1e-4).

- Hybrid GNSSDR algorithm provides horizontal protection levels that satisfy the target integrity risks selected for the application (in case of RUC, in the order of TIR=1e-3 and TIR=1e-4).

- With the equipment and the extensive data used in the analysis, the integrity objective is satisfied by both algorithms regardless of the environment with an experimental integrity risk more stringent than required.

Performance comparison between STEREO and TRITON

Due to the huge effort that has been made not only to record, but also to fully process the data both from the STEREO and TRITON FEs, we have a data set of around 450000 epochs for each FE, being its size high enough to consider the results representative of the true performance of the involved devices.
In a first step, the evaluation of STEREO and TRITON FEs shall be carried out without taking into consideration the algorithm being used at the PVT+I level. In particular, what is primarily important is the analysis of the measurements generated by SRX, especially in terms of number of satellites in view and CN0, taking advantage that the recorded data correspond to common scenarios. With this aim, only epochs when the number of measurements is strictly higher than zero are considered (avoiding tunnels and outages periods).
Similarly to previous analysis, we show separated analysis for motorway and urban scenarios.
Figure 12 and Figure 13 represent the cumulative distribution functions for the number of available GPS/GLONASS satellites and the associated CN0, respectively, under motorway conditions. On the other hand, Figure 14 and Figure 15 show analogous results for urban environments.
In the light of these figures, we can conclude that the performance of both front-ends is very similar, both from the point of view of measurements available and CN0, although the STEREO FE seems to provide a slightly higher signal to noise ratio. Therefore, from the point of view of the navigation and integrity solution, one should not expect a priori very uneven results regardless of the front-end being used.
In order to prove the previous hypothesis, we have represented in the following figures the HPE and HPL results with the two front-ends and one of the algorithms (KIPL). Figure 16 and Figure 17 represent the HPE and HPL distribution for motorway scenarios, while Figure 18 and Figure 19 show analogous results for urban data.
As it can be clearly observed, both the HPE and HPL performance is, just as expected, quite independent of the front-end used for the analysis.
The consequences of this are twofold: on one hand, it is proven that two independent front-ends working in parallel provide very similar information, which in some sense validates the hardware deployed in the DASU platform. On the other hand, the fact that the algorithm achieves similar performance in both analysis (satisfying in all cases the integrity requirement with similar HPE and HPL metrics) gives a measure of the robustness of the PVT+I algorithms, and how they successfully overcome their responsibility for integrity computation.

Because of the reasons exposed above, the performance analysis of one of the FE (STEREO) is considered enough to evaluate in the following sections the applicability of the algorithms (KIPL) to RUC applications.

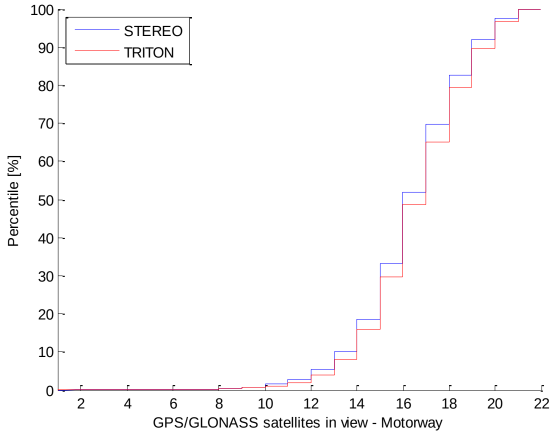

Figure 12 Number of GPS/GLONASS satellites in view CDF (Motorway)

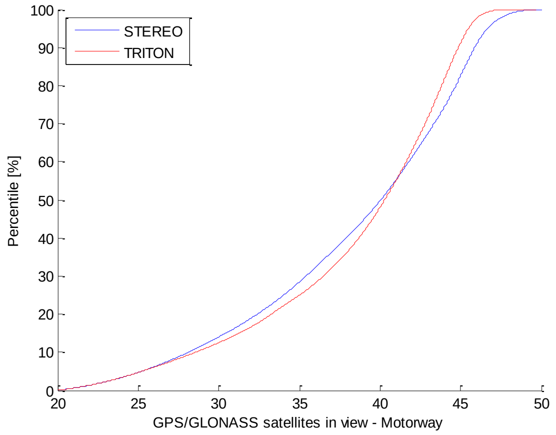

Figure 13 CN0 distribution of GPS/GLONASS observations (Motorway)

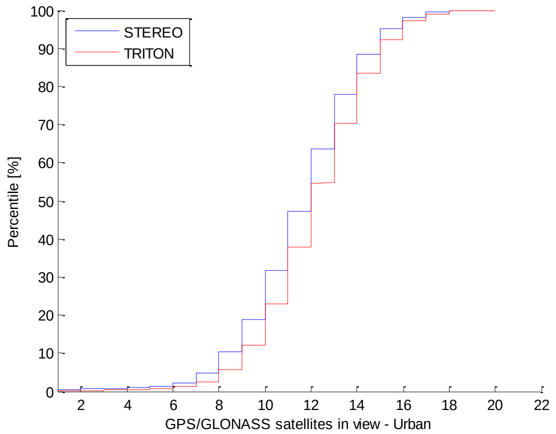

Figure 14 Number of GPS/GLONASS satellites in view CDF (Urban)

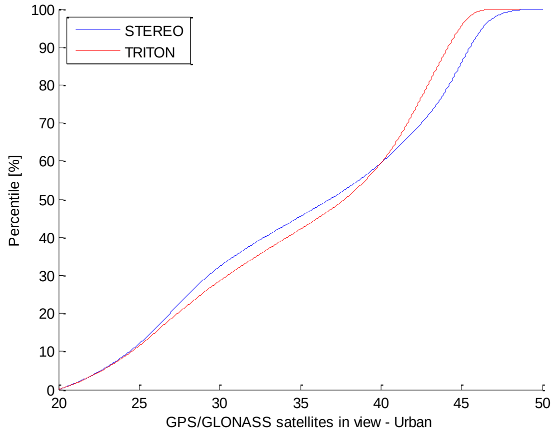

Figure 15 CN0 distribution of GPS/GLONASS observations (Urban)

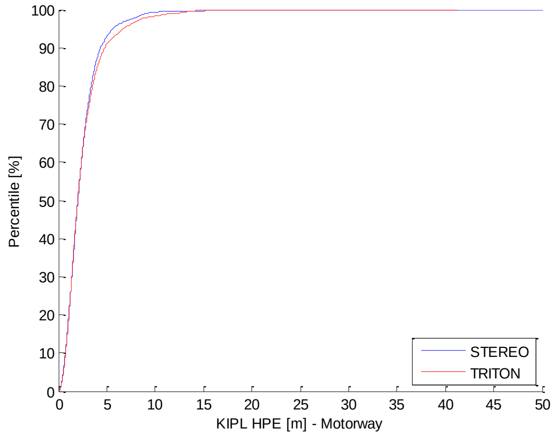

Figure 16 HPE distribution for KIPL with STEREO and TRITON FE (Motorway)

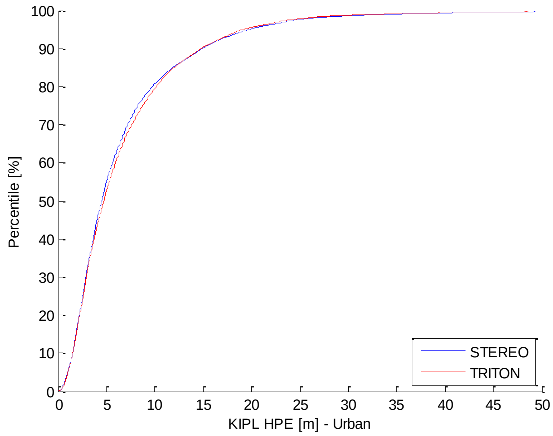

Figure 17 HPE distribution for KIPL with STEREO and TRITON FE (Urban)

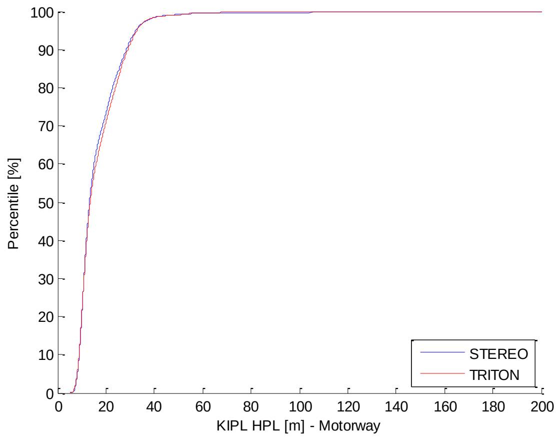

Figure 18 HPL distribution for KIPL with STEREO and TRITON FE (Motorway)

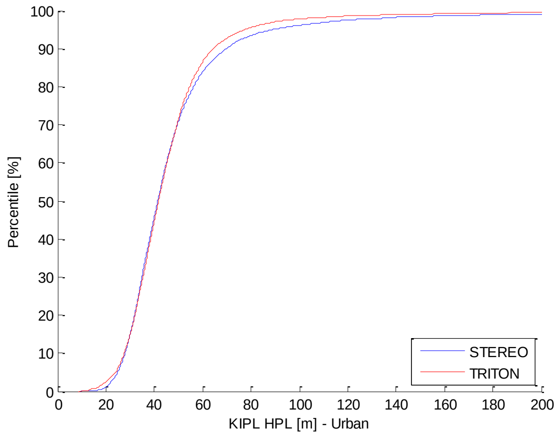

Figure 19 HPL distribution for KIPL with STEREO and TRITON FE (Urban)

Pedestrian Analysis

In the case of pedestrian data, not as many data as in the vehicular case was recorded, but enough to test TIR=1e-3, which is the value defined in the scope of the IGNSSRX project for pedestrian applications.

In particular, the pedestrian analysis will focus into two main environments: suburban and urban areas.

Similarly to vehicular data analysis, the metrics to evaluate are accuracy (HPE), integrity availability (HPL) and TIR compliance. Due to the limitations of movements of pedestrian users, the rate at which an integrity solution is provided is relaxed to 1/6Hz, i.e. each 6 seconds, instead of every second.

Algorithm performance in suburban areas

The number of epochs in which the HPL solution is available for suburban environment is represented in Table 17.

Front-End	Total Epochs [s]	Total Epochs [1/6Hz]	Hybrid Pedestrian Integrity Availability
STEREO	28256	4705	99.17%

Table 17 Percentage of epochs with computed integrity solution (Suburban)

Since we are only testing one algorithm in the pedestrian analysis using a single front-end, the evaluation is much simpler than the vehicular case. In order to simplify the information, HPE and HPL results will be put together as in Table 18, where relevant percentiles for suburban case are represented.

Percentile [%]	Hybrid Pedestrian + STEREO	
	HPE [m]	**HPL [m]**
50	4.66	17.66
80	10.31	45.41
90	14.98	73.50
95	18.92	93.41
99	33.74	264.37

Table 18 HPE and HPL performances at representative percentiles (Suburban)

Complementary, the Stanford diagram (at TIR=1e-3) associated to the previous HPE/HPL values is represented in Figure 20.

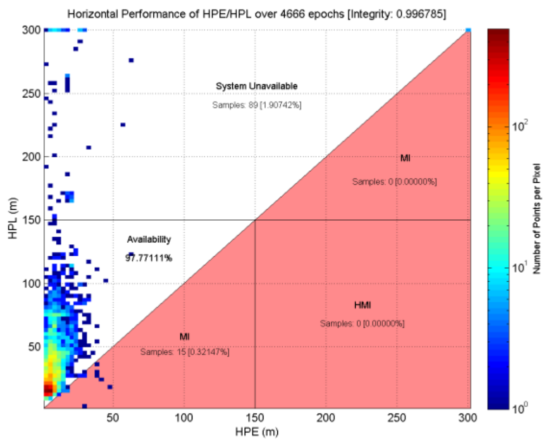

Figure 20 Stanford diagram (TIR=1E-3) - STEREO Pedestrian (Suburban)

Algorithm performance in urban areas

The number of epochs when the HPL solution is available for urban environment is represented in Table 19.

Front-End	Total Epochs [s]	Total Epochs [1/6Hz]	Hybrid Pedestrian Integrity Availability
STEREO	19391	3226	81.56%

Table 19 Percentage of epochs with computed integrity solution (Urban)

Table 20 summarizes the results obtained for HPE and HPL in urban environments for the hybrid pedestrian algorithm.

Percentile [%]	Hybrid Pedestrian + STEREO	
	HPE [m]	HPL [m]
50	17.54	49.00
80	34.13	73.50
90	48.20	95.55
95	63.32	117.60
99	94.33	154.35

Table 20 HPE and HPL performances at representative percentiles (Urban)

Complementary, and analogously to the suburban case, the Stanford diagram associated to the previous results is represented in Figure 21.

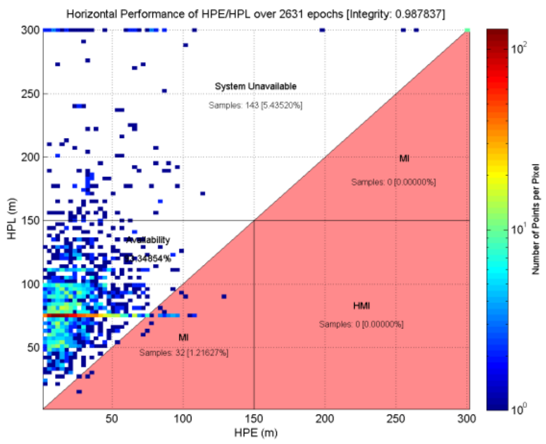

Figure 21 Stanford diagram (TIR=1E-3) - STEREO Pedestrian (Urban)

USE IN LIABILITY-CRITICAL APPLICATIONS

One of the main purposes of the IGNSSRX project was to identify PVT+I algorithms capable of providing good enough navigation and integrity performances to be used in liability critical applications. In particular, two were selected as the more suitable for this purpose: Road User Charging (RUC) for the vehicular case and E-112 [19] for pedestrian users, for being the most significant in terms of required GNSS integrity.

For each application, a set of service requirements was elaborated and then, by making some assumptions, it was traced to a priori example bounds of the navigation and integrity performance metrics that could be required by the application.

The purpose of this section is to compare the performance of the techniques described throughout this paper with these example metrics and check whether they are suitable for the requirements of the application. As usual, the metrics involved refer to HPE and HPL.

The analysis will be split into two different parts: first, we will evaluate whether the algorithms proposed satisfy the accuracy requirements of the application (RUC for vehicular, E-112 for pedestrian); second, we will perform the analogous analysis corresponding to the integrity availability requirements. For the sake of clarity, and since this section has only illustrative purposes, we will consider only one algorithm per configuration (KIPL or pedestrian hybrid) with one front-end (STEREO).

Accuracy Requirements of the applications

First of all, we need to define the metrics with which we want to compare the performance of our algorithms. Table 21 represents the 95-percentile values of the vehicular HPE example distributions for several types of road segments and urban zones in RUC. An “Urban Zone” is understood as a several km radius circle covering most part of the city and an “Urban Small Zone” as a one km radius circle covering a small part of the city. As the radius decreases the required navigation performances would need to become more stringent in order to satisfy the overcharging and undercharging RUC requirements.

The HPE 95-percentiles are interpreted as Rayleigh (that represents the distribution of the norm of a 2-dimensional Gaussian). This implicitly assumes that East and North error components distribute as Gaussian, which is not generally true (and sometimes quite optimistic), although it is useful to check whether the computed distribution overbounds the experimental HPE.

Similarly, Table 22 shows metrics proposed for pedestrian E-112 application, also distributed as Rayleigh. It should be taken into account that these metrics are not official mandatory requirements for E-112, since such requirements are not yet well-defined.

It is also worth to remark that the example percentiles defined of HPE for pedestrian relate mainly to the needs of the application (e.g. recommend a local business close to a user’s position), while vehicular example values take into account the limitations of GNSS systems, allowing more relaxed bounds for urban areas.

Highway Segment [m]	Highway Lane Segment [m]	Urban Zone [m]	Urban Small Zone [m]
5.20	0.54	93.00	18.60

Table 21 RUC example performance for positioning error (HPE at 95-percentile)

Urban [m]	Suburban [m]	Rural [m]
25	75	125

Table 22 E-112 example performance for positioning error (HPE at 95-percentile)

Notice that in both applications, and with the information provided, it is very easy to interpolate any percentile we require.

Table 23 shows representative percentiles of the HPE distribution for KIPL in vehicular motorway environments (obtained from Table 9), in comparison with the example performances from Table 21. We can observe how the results are in line with the example values proposed for RUC applications in highway segments (although they are sometimes slightly higher), especially in low and medium percentiles. Highway lane segment example is not included because the demanded accuracy is within error ranges only achievable by algorithms such as PPP/RTK, which is not the case.

Table 24 shows representative percentiles of the HPE distribution for KIPL in vehicular urban environments (obtained from Table 12), in comparison with the RUC example performances from Table 21. We notice that the results satisfy comfortably the RUC example value for urban zone, and are very close to the values specified for urban small zone, although some problems arise with the distribution at high percentiles, due to the lack of availability in the navigation solution. This can be easily explained because of the existence of tunnels and signal outages in deep urban environment. In principle, the GNSSDR hybrid algorithm should overcome this lack of signal, since it can be compensated by the availability of heading and odometer data. Nevertheless, as stated in previous sections, KIPL was selected for the comparison since it achieved the best global performance.

On the other hand, Table 25 compares analogous results for the pedestrian hybrid algorithm (already shown in Table 18 and Table 20) with the example performance in Table 22. Due to the aforementioned dependence of the metrics with respect to the application needs, instead of the GNSS capabilities in terms of the environment, it is observed how the suburban example is widely overcome by the algorithm, while in the urban case we are below the proposed example performance.

Percentile [%]	Example Performances	STEREO KIPL
	Highway Segment [m]	HPE [m]
50	**2.50**	2.02
80	**3.81**	3.41
90	**4.56**	4.41
95	**5.20**	5.81
99	**6.45**	9.64

Table 23 RUC example and HPE performance (Motorway)

Percentile [%]	Example Performances		STEREO KIPL
	Urban Zone [m]	Urban Small Zone [m]	HPE [m]
50	**44.74**	**8.95**	4.69
80	**68.18**	**13.64**	10.66
90	**81.55**	**16.31**	16.63
95	**93.01**	**18.60**	23.34
99	**115.3**	**23.06**	86.46

Table 24 RUC example and HPE performance (Urban)

Percentile [%]	Example Performances		Pedestrian - HPE [m]	
	Suburban	Urban	Suburban	Urban
50	**36.06**	**12.02**	4.66	17.54
80	**54.95**	**18.32**	10.31	34.13
90	**65.77**	**21.92**	14.98	48.20
95	**75.00**	**25.00**	18.92	63.32
99	**93.03**	**31.01**	33.74	94.33

Table 25 E-112 example and HPE performance (Pedestrian)

Integrity Availability Requirements of the applications

Analogously to the accuracy requirements, we need to define the availability metrics with which compare the experimental results. Table 26 represents the 95-percentile of the HPL example distribution (Rayleigh) for RUC applications. Besides, Table 27 shows examples of the horizontal alarm limits (AL) derived from the E-112 application needs.

Highway lane segment is removed from the analysis, because of similar reasons to the exposed before. On the other hand, recall that the proposed alarm limit values are very hard to achieve, as they represent half the 67% accuracy level for E-911 [20] (the alarm limit derived is calculated as 3 times the 67% accuracy required in the CGALIES report, giving a 99% confidence level, being the alarm limit correlated with the accuracy needs).

Highway Segment [m]	Highway Lane Segment [m]	Urban Zone [m]	Urban Small Zone [m]
27.30	2.82	490.0	98.00

Table 26 RUC example performance for positioning error (HPL at 95-percentile – TIR=1E-4)

Urban [m]	Suburban [m]	Rural [m]
30	90	150

Table 27 E-112 example of Alarm Limit

Table 28 shows representative percentiles of the KIPL HPL distribution for vehicular motorway environment already shown in Table 10 comparing them with the RUC example performances from Table 26. Additionally, Table 29 shows the analogous comparison for vehicular urban environment using Table 13 results and Table 26 example performances. In motorway scenarios, we observe that the HPL values are close to the proposed example performances, although they have poorer availability, especially at high percentiles.

In the urban case, we notice how the proposed availability performances defined for urban zones are comfortably satisfied. In the case of small zones in urban we observe that the example performance is generally satisfied, although the margins are tighter.

Table 30 compares the percentiles of the HPL distribution obtained with the pedestrian algorithm (already shown in Table 18 and Table 20) with the alarm limit examples from Table 27. As we can see, the fact that the alarm limits are related more to the needs of the application than to the GNSS system capabilities, is translated into a huge availability margin for the suburban case (with exception of high percentiles) and almost no availability in urban scenarios, since the AL are more stringent and, on the contrary, the HPL values obtained in these conditions are much higher than in suburban/rural.

Percentile [%]	Example Performances	HPL [m]
	Highway Segment [m]	STEREO KIPL
50	**13.13**	13.19
80	**20.01**	22.84
90	**23.94**	28.40
95	**27.30**	32.33

Percentile [%]	Example Performances	HPL [m]
	Highway Segment [m]	STEREO KIPL
99	**33.85**	46.20

Table 28 RUC example and HPL performance (Motorway)

Percentile [%]	Example Performances		HPL [m]
	Urban Zone [m]	Urban Small Zone [m]	STEREO KIPL
50	**235.7**	**47.16**	41.47
80	**359.2**	**71.85**	56.32
90	**429.6**	**85.95**	70.08
95	**490.0**	**98.03**	89.08
99	**607.6**	**121.5**	191.45

Table 29 RUC example and HPL performance (Urban)

Percentile [%]	Example (Alarm Limit)		Pedestrian - HPL [m]	
	Suburban	Urban	Suburban	Urban
50	**90m**	**30m**	17.66	73.50
80			45.41	95.55
90			73.50	117.60
95			93.41	154.35
99			264.37	454.61

Table 30 E-112 application alarm limit and HPL performance (Pedestrian)

CONCLUSIONS

A complete data collection platform with different Front-Ends, INS sensors and a dedicated equipment to obtain the truth reference trajectory (needed to assess the positioning errors) was used to carry out an extensive real data collection campaign (more than 100 hours) in road and urban environments (urban routes include tunnels and street canyons).

This paper has provided an overview of the leading edge integrity algorithms for vehicular and pedestrian users and the high amount of real data collected in urban and road environments has been used to test these integrity algorithms assessing their performances (vehicular: 1.5e5 epochs in road and 3e5 epochs in urban; pedestrian: 2.5e4 in sub-urban and 2e4 in urban). This high amount of real data has allowed assessing integrity risks (IR) as stringent as 1e-4.

The obtained results have shown that the integrity algorithms succeed in providing horizontal protection levels (HPL) able to bound at each epoch the horizontal positioning errors (HPE) with integrity risks (IR) as stringent as 1e-4, thus achieving the integrity goal in road and urban environments. Moreover, the tested integrity algorithms show outstanding HPE and HPL performances in road an urban environments.

The availability of an application or service depends on its requirements and it is accomplished depending on the size of the HPLs provided by the integrity algorithm, so the obtained performances have been compared against examples of the navigation and integrity performance metrics that could be required by the Road User Charging (RUC) and E-112 applications, providing a clear link to what can be achieved with the current technology.

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