Preliminary field trials and simulations results on performance of hybrid positioning based on GNSS and 5G signals

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BIOGRAPHIES

Francisco José Mata received his M.Sc. in Mechanical Engineering and Transportation in 2015 at Universidad Carlos III de Madrid (UC3M). He also holds a M.Sc. in Industrial Engineering and a B.Eng. He has been involved in kinematic and dynamic analysis since 2013, moment when he became R&D member in the School of Mechanical Engineering at the University of Birmingham (UoB) in UK. In here, he was developing self-resonating kinematic-based energy harvesting system at Fusion Innovations Ltd. Afterwards, he became part of the UC3M's staff, and started its research on vehicle dynamics. Later on, he joined the R&D department of Euroconsult Nuevas Tecnologías (ECG) in the systems integration and sensors hybridization area. In here, he developed the U.S. Nevada's Department of Transportation (NDOT) Road Mapping System, integrating very high grade sensors such as Applanix POS-LV, Velodyne LiDAR, Allied Vision GT cameras, among others. From here on, he focused on multi-sensor hybridization (GNSS, IMU, DMI, LIDAR, 3D Vision, S-LWIR vision, etc.) to estimate a vehicle's trajectory in GNSS denied/harsh environments for different user grades. His developments were used to assess more than 20km of London Underground tunnels (UK), 6km of Shinkansen's tunnels (Japan), the 17km of Hallandsås tunnels (Sweden), among others. He joined GMV's team in 2018 to work in the advance user equipment area and GNSS/sensor hybridization area. He has been involved in several projects, being the most relevant POSITRINO and GINTO5G (EGEP 107).

Florin-Catalin Grec holds a MSc (2015) in Geomatics from the Polytechnic University of Milano and BSc (2013) in Geodesy from the Polytechnic University of Timisoara. After graduating he spent another year at Politechnic University of Milano as a research fellow and teaching assistant doing further work on the use of mass-market GNSS in landslides monitoring and GNSS antenna calibration. During 2014 he has been a visiting research at Leica Geosystems AG where he made important contributions to Leica´s products for GNSS CORS networks and Network RTK positioning techniques. He is currently working as GNSS Evolutions Strategy Engineer in the Directorate of Navigation at ESA where he contributes to R&D efforts on hybrid positioning based on GNSS and telecommunication signals broadcast by 5G networks. He also contributes to 3GPP RAN1 and RAN2 working groups where he is playing a central role in the standardization of GNSS features in mobile wireless standards since 2017.

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Miguel Azaola has a Master of Science in Mathematics from the University Complutense of Madrid and a Ph.D. in geometry and topology from the University of Cantabria (at Santander, Spain). He has worked at GMV since 2001 as an engineer in several GNSS projects related to both the ground and user segments. Since 2005 he has been involved in user segment R&D activities at engineering and management levels.

Fernando Blázquez holds a MSc. in Chemical Engineering by the UPM (Universidad Politécnica de Madrid). He joined GMV in 2018, working on GNSS systems activities. He has been involved in projects for the European Commission, the European GNSS Agency and the European Space Agency, in which his work mainly focuses on the performance assessment of different GNSS technologies and support to standardization activities.

Alejandro Fernández holds both Masters Degrees in Telecommunications and Electronics Engineering from the University of Granada. In 2018 he started working for GMV within the GNSS Business Unit in close collaboration with the Time and Frequency Group. His previous work experience is focused in the development of synchronization techniques between embedded real-time kernels designed for Low Power Wide Area Networks.

Enrique Domínguez-Tijero 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, integrity algorithms, localization systems for autonomous driving vehicles and 5G positioning.

Gema Cueto-Felgueroso is a project manager of GMV within GNSS User Segment Division in the GNSS Business Unit. She holds an MSc in Industrial Engineering from the Polytechnic University of Madrid and she joined GMV in 2012. She has been involved in several projects for various European institutions (GSA, EC and ESA) such as ECAPPS, EGUS, MSIL2, MULCOBA, ASQF or PROSBAS and she has a solid background in the SBAS and Galileo concepts and its application and standardization for different market segments, mainly aviation and maritime domains. She has also experience in the development of GNSS performance analysis tools (Teresa, magicGEMINI, eclayr). She is well known to ESA, GSA and EC due to her recent involvement as project manager of SEASOLAS (EC project), GINTO5G (ESA EGEP ID 107) or GMV activities in GSALOT3TRANS-SC3 (GSA project), just to name a few.

Prof. Gonzalo Seco-Granados received the Ph.D. degree in Telecommunications Engineering from the Universitat Politecnica de Catalunya, in 2000, and the MBA degree from IESE Business School, in 2002. Until 2005, he was with the European Space Agency, involved in the design of the Galileo System. Since 2006, he has been with the Universitat Autonoma de Barcelona, where he is a Professor. He is also affiliated with the Institute of Space Studies of Catalonia. In 2015 and 2019, he was a Fulbright Visiting Scholar with the University of California, Irvine. He is the Chair of the Spanish Chapter of the IEEE Aerospace and Electronic Systems Society. His research interests include the design of signals and reception techniques for satellite and terrestrial localization systems, multi-antenna receivers, and positioning with 5G technologies.

Dr. José A. del Peral-Rosado received the Ph.D. degree on Telecommunications Engineering from Universitat Autonoma de Barcelona (UAB) in 2014. From 2014 to 2019, he was a Postdoctoral Researcher at the Department of Telecommunications and Systems Engineering at UAB, where he largely contributed to the work presented in this paper. He was also a Visiting Researcher at the European Space Research and Technology Centre (ESTEC) of the European Space Agency (ESA) in the period 2014-2016. Since late 2019, he is with Airbus Defence and Space, Germany. His research interests are in satellite and terrestrial localization and navigation.

Emanuel Staudinger received a M.Sc. in Embedded Systems Design from the University of Applied Sciences of Hagenberg, Austria, in 2010, when he joined the Institute of Communications and Navigation of the German Aerospace Center (DLR), Munich, Germany as Research Staff Member. He received a Ph.D. with distinction from the Institute of Electrodynamics and Microelectronics of the University of Bremen, Germany, in 2015. His current research interests include system design for cooperative positioning, experimental platform design based on SDRs, and experimental validation for swarm navigation.

Christian Gentner received the Dipl. Ing. (BA) degree in electrical engineering, focusing on the main topic of communication technology, from the University of Applied Science RavensburgWeingarten, in 2006, and the M.Sc. and Dr. Ing. (Ph.D.) degrees in electrical engineering from the University of Ulm, in 2009 and 2018, respectively. During his BA study, he received practical experience at Rohde & Schwarz in Munich. Since 2009, he has been working at the Institute of Communications and Navigation, German Aerospace Center (DLR). His current research focuses on multipath assisted positioning and indoor positioning.

Maximilian Kasparek received his master's degree in Computer Science from the Friedrich-Alexander Universität Erlangen-Nürnberg. He works as a project manager and researcher at the Fraunhofer Institute for Integrated Circuits in Nürnberg. His current research is focused on industrial applications for mobile radio communication and positioning. He previously worked on precise and energy-efficient radio-based positioning systems for sports analytics, miniaturized satellites and environmental surveys.

Christian Backert received his degree in Electrical Science as Diplom Ingenieur from the Friedrich-Alexander Universität Erlangen-Nürnberg. He works as chief project manager at the Fraunhofer Institute for Integrated Circuits in Nürnberg. His current activities are focused on industrial applications for mobile radio communication and positioning. He previously worked on precise positioning systems for sports analytics and in the field of high speed video imaging.

David is a Chartered Electronics Engineer (CEng) and Member of the IET with a background in Signal Processing, Software Engineering and Wireless Communications with many years of experience in the field of Positioning, Navigation and Timing which has become a specialisation of his. He is a member of the RIN (Royal Institute of Navigation) and co-champion of the Location Special Interest Group at Cambridge Wireless. He has also co-founded several companies and has a track record building technology strategies and IPR, with many patents and publications to his name. He is presently working for u-blox in the technology research group with a focus on hybrid solutions combining GNSS with terrestrial ranging and other signals

Elena Serna Santiago received the B.Sc. degree in Telecommunication Systems Engineering from Polytechnic University of Madrid, Spain, in 2015, and the Master of Engineering degree in Telecommunication Systems from Polytechnic University of Madrid, Spain, in 2017. She worked with the Department of Electronics and Communications Engineering of Tampere University of Technology (TUT) to develop her Master's Thesis about Passive positioning approaches in the future positioning systems, in 2017 during her exchange year, with a journal paper published in Inside GNSS. She joined Telefonica I+D in 2016 as Research Engineer in Global CTIO Radio Innovation Unit to actively participate in European and internal projects focused on researching 5G radio access techniques and new radio solutions. In the recent years, she has also work as project manager in very strategic projects for Telefonica. Her current research interests include mmWaves, cellular networks, wireless location techniques, satellite communications, signal processing, and radar systems.

Lionel Ries is the Head of the Radio Navigation Systems and Technology Section in the Directorate of Technology, Engineering and Quality at ESA/ESTEC, which supports the Galileo and EGNOS programs, space missions requiring a GNSS receiver on board and performs the associated R&D at system and positioning technologies levels. In the past, he was head of the Location/Navigation Signal Department in CNES, the French Space Agency, leading R&D activities on signal design and processing, receivers and payloads regarding location, and navigation systems including GNSS (Galileo, GNSS space receivers), search & rescue by satellite.

Roberto Prieto-Cerdeira is the GNSS R&D Principal Engineer in the Directorate of Navigation of the European Space Agency, where he is responsible for space and ground technology R&D for the evolution of the European GNSS Systems, Galileo and EGNOS. He also coordinates the ESA 5G GNSS Task Force and the scientific research activities for GNSS. In the past, he was responsible of Radiowave Propagation activities for Galileo, EGNOS and Satellite Mobile Communications at ESA where he actively contributed and chaired working groups at ITU-R, URSI and international SBAS-Ionospheric WG.

ABSTRACT

From 1G to 4G, different advances on network-based localization have been developed and included. The 3rd-Generation Partnership Project (3GPP) has being working on these standards defining localization features, such as the Positioning Reference Signals (PRS) and the Long-Term Evolution (LTE) Positioning Protocol (LPP). However, network-based localization has been always considered an optional feature for cellular networks due to its low accuracy, and its methods have been focused mainly on assistance data for GNSS and cell ID enhancement.
Now, a new perspective came up in the latest releases of 4G LTE and 5G due to the introduction of high-accuracy positioning services. 3GPP is moving towards including localization for a new range of markets, which has been translated in specific 3GPP activities, aiming at providing high accuracy GNSS for LTE and 5G technologies and designing Radio Access Technology (RAT)-dependent technologies to meet more stringent targets than in previous generations. For high-accuracy positioning, for instance to

support autonomous driving or industrial automation, the integration of GNSS (augmented with precise or differential corrections), terrestrial (RAT-dependent) technologies and complementary sensors is expected to play a key role on 5G localization.

The goal of GINTO5G project is to support the design of PNT solutions in the context of 5G applications by carrying out extensive experiments and simulation campaigns, as well as theoretical assessment of possible disruptive techniques. For downlink TDoA using 5G SRS signal, the field trials of one campaign shows that sub-meter accuracy can be achieved with 100 MHz bandwidth in the 3.7 GHz band. At the same time the evaluation shows a significant discrepancy between achieved TOA accuracy, and the overall positioning performance, especially for the outdoor tests. Based on CEP95 and SEP95 values, it can be stated that a 2D accuracy of sub 3 meter can be achieved an outdoor area where transmitting points have been deployed and optimized for positioning purpose. Similar performance could be seen in the results of the tests carried out in indoor spaces; what is more, half of all measured indoor positions even show a significantly lower error (sub 1 meter for 2D, and sub 3 meters for 3D). Another set of outdoor trials, conducted this time on a set of transmitting points deployed more randomly, revealed a mean 2D positioning error ranging from sub metre to several hundreds of metres.

INTRODUCTION

5G is the newest mobile communications technology expected to connect the world and is focused on three main applications: enhanced mobile broadband (eMBB), massive Machine Type Communication (mMTC), and Ultra Reliable Low Latency Communication (URLLC). The 5G New Radio (NR) is a new radio access technology (RAT) developed by 3GPP for the 5th (fifth generation) mobile networks. The NR wireless standard is expected to generate a revolution in the market by combining different wireless technologies such as millimeter waves, small cells, massive Multi Input Multiple Output (MIMO) among others. Two different frequency ranges are available for the 5G technology and the different ranges have been designated FR1 - frequency range 1 (recently extended from bands below 6 GHz to bands below 7.125 GHz) and FR2 - frequency range 2 (bands between 24.25 – 52.6 GHz). The 5G NR supports signal bandwidths up to 100 MHz for carrier frequencies below 7.125 GHz, and up to 400 MHz for frequencies in the FR2. More precisely, 50, 100, 200, 400 MHz in bandwidth. Wideband signals present a superior robustness against multipath, the main source of error in urban and indoor settings, due to the short pulses transmitted over a wide signals. This feature is very interesting for attempting high precision ranging. The opportunity here is to understand what bandwidth works best for ranging in different environments and applications.

Massive MIMO – which is an extension of MIMO – expands beyond the legacy systems by adding a much higher number of antennas on the base station. This has become an important technology because the latest 3GPP specifications support beamforming and higher frequencies allow massive yet compact MIMO antennas. The use of massive MIMO and mmWave systems are attracting interest from the localization community. The “massive” number of antennas helps focus energy in certain direction which can lead to better ranging when put in the context of positioning services. Large scale antenna system offers high angular resolution too and therefore enable precise measurements of the angle of arrival (A0A) and the angle of departure (AoD).

Downlink-based positioning is supported by providing an optimised reference signal called the Positioning Reference Signal (PRS). Compared with 4G, the PRS has a more regular structure and a much larger bandwidth, which allows for a more precise correlation and time of arrival (ToA) estimation. Uplink-based positioning is based on Release 15 Sounding Reference Signals (SRSs) with Release 16 extensions. Based on the received SRSs, the base stations can measure and report (to the location server) the arrival time, the received power and the angle of arrival from which the position of the user can be estimated. The opportunity here is to select signal power and - both on downlink and uplink – to improve range estimation.

ESA has taken the initiative in 2016 to strongly contribute in 3GPP and other standardization bodies to assess the 5G positioning user needs and possible technological solutions, including the role of GNSS and hybrid solutions [1]. This initiative has strongly contributed to the identification of 5G use cases and performance targets and grouping them in positioning service levels as part of the 5G_HYPOS 3GPP Study Item [2]. It has also supported the adoption of dissemination of high-accuracy positioning corrections (RTK, PPP and in the future PPP-RTK) for multi-constellation GNSS as part of the LPP protocol [3-5].

One of the outputs of the project is The Positioning Performance and Coverage Tool (PoPeCoT), a simulator configured based on the overall assessment and error models obtained and derived from the field campaigns carried out in the frame of the project. The

PoPeCoT simulator is able to perform both trajectory and coverage simulations for the relevant figures of merit, so a set of scenarios covering the different use cases and environments has been defined and the simulator has been employed to compute, for each scenario, navigation errors (based on the knowledge of the true position/trajectory), derive the performance figures and display them on the 2D map.

In the following chapters the paper will provide a brief summary of the use cases, field scenarios, platform and experimental tests along with the conclusions extracted from them, and then will focus on describing the PoPeCoT simulation platform and on showing the relevant outcomes of the simulation test cases, covering the different use cases and positioning technologies (GNSS, 5G and Hybrid).

USE CASES

Autonomous Driving

Automated driving is an old dream: already back in the 1960s, some enthusiasts conducted some first experiments with self-driving cars. In addition to offering broader access to mobility, it can also help to reduce the number of driving-related accidents and crashes. When doing so, the safety of automated driving vehicles is one of the most important factors. Items like positioning accuracy, reliability, resilience against threats, and availability are discussed against requirements collected from various standards or directly reported by industry. According to automotive industry, lane - level 3-D positioning accuracy **of 1 m (3-sigma)** is needed, especially for high-level of automations, and this can be achieved by multi-frequency multi-constellation GNSS in combination with advanced sensors and Vehicle-to-Everything (V2X) technology.

Table 1. Positioning requirements for Automotive use cases

Positioning Level	Accuracy [m]	Applications	Technology Enablers
Which Road	<2-5	Turn-by-turn navigation; geofencing	GNSS + Mapping
Which Lane	<1m	V2X;ADAS	Accurate absolute positioning, HD maps, relative positioning
Where in Lane	<0.5 highways <0.3 city roads	Lane departure warning; autonomous driving	High accuracy absolute positioning, advanced image processing, V2X

Industrial IoT

Today, there is a surging demand for precise real time localization and this can be seen across many disruptive applications: connected and automated driving, unmanned aerial vehicles, Industry IoT (IIOT) and other. The IIOT was a major vertical focus area for the current 3GPP set of specifications (Release 16) and will continue to be so for Release 17 where positioning for IIOT has been identified as a main objective.

In manufacturing plants, supervisors and applications need to receive information regarding the positions of specific staff to react to business situations. Positioning therefore is increasingly considered as a utility, with a high level of expectation from all parties involved in an operation. In the context of Industry 4.0, very accurate indoor positioning can be used to track assets and workforce, navigation, real-time monitoring, location-based events, and data collection of geo-referenced positioning data.

Regardless of all benefits brought by interoperable multi-GNSS constellations and betterment of GNSS user technology, this technology has intrinsic limitations in indoor locations where the signals may not be always available. Therefore, 5G would be well positioned to fill this gap and meet industry´s needs representing an advantage with respect to ad-hoc proprietary solutions, that cannot benefit from the economy of scale and increase interoperability of a global standard as 5G.

According to 3GPP TR 22.804, several different application areas can be distinguished. These areas can be briefly characterised as follows: factory automation, process automation, human-machine interfaces, logistics and warehousing, monitoring and warehousing. The 5G service requirements specified in 3GPP TS 22.261 include High Accuracy Positioning requirements, which are characterized by ambitious system requirements for positioning accuracy in many verticals. In the context of Industry 4.0, very accurate indoor positioning can be used to locate and track assets and workforce, navigation, real-time monitoring, location-based events, and data collection of geo-referenced positioning data. The requirements demand a performance that yield a position accuracy below 1m, and in some cases even below 0.5m (e.g., inbound logistics for manufacturing).

FIELD CAMPAIGNS

High Accuracy GNSS

There are different assessment purposes depending on the use cases, hence the field scenarios are different for each one. This project is focused on two different use cases, the one oriented to High Accuracy devices (for land vehicles and unmanned aerial vehicles) and the one oriented to Internet of things and its energy consumption. In all the use cases the tests were carried out several times to avoid singularities.

The scenarios defined for high accuracy devices installed in land vehicles are placed in Munich (Germany) in four different locations comprising open sky areas, suburban areas, urban areas and transitions. Those areas and the trajectory defined are presented in the following figures.

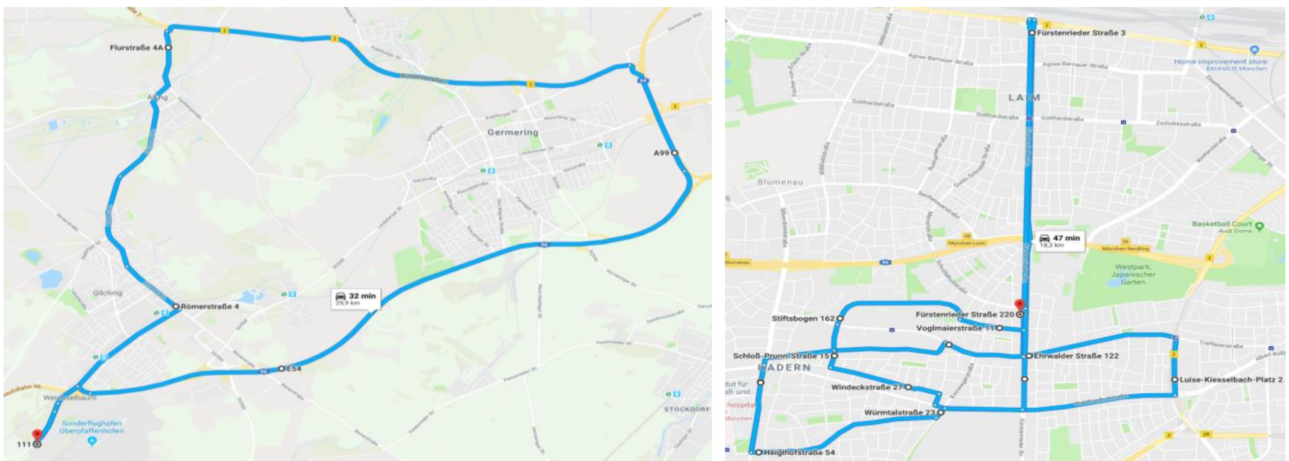

Figure 1: Open sky trajectory (left) and suburban trajectory (right) for high accuracy land vehicles

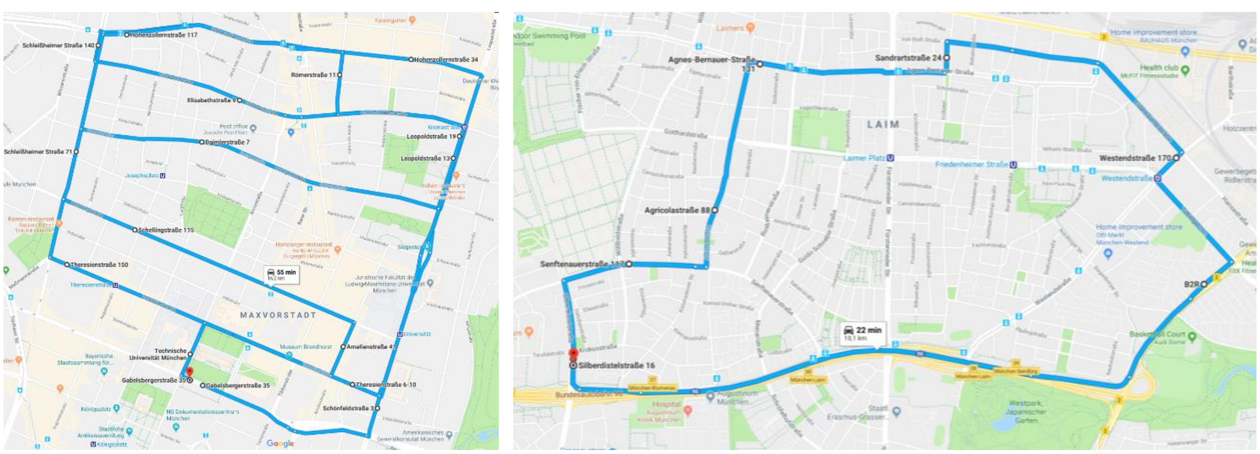

Figure 2: Urban trajectory (left) and transitions trajectory (right) for high accuracy land vehicles

Hybrid GNSS – 5G FR1

The scenario defined for the experimental campaign in Hybrid GNSS with 5G FR1 is placed in Nuremberg. The tests have been conducted at the L.I.N.K. Test and evaluation Center's indoor and outdoor areas (Fraunhofer IIS).

Figure 3 shows the four areas, characterized by different propagation conditions, in which GNSS and 5G signals have been recorded. The indoor area (light green), as well as the loading zone (darker green), will be covered by 5G NR positioning sequence transmitters. The street area (yellow) and the driveway (red) have no specific 5G NR coverage. As a matter of fact, the street area ended up being discarded from the analysis.

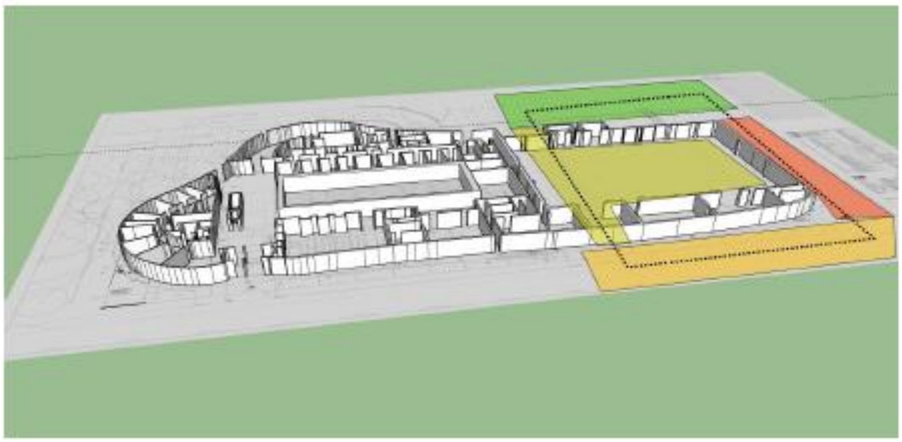

Figure 3: Fraunhofer IIS´s L.I.N.K Test and Evaluation Centre

EXPERIMENTAL PLATFORMS

High Accuracy GNSS

The experimental platform was defined after a deep analysis of the different state-of-art devices and sensors in the market to cover all the use cases and scenarios defined. Three different platforms were defined for the three scenarios defined previously in the paper.

The experimental platform defined for high accuracy devices installed in land vehicles comprises two cars, one as a Rover and the second as a Base. The most relevant devices and technologies installed and used in each car are depicted in Figure 4 and Figure 5 where he schematic view of the devices installed in each car is shown. The NovAtel SPAN-SE has a well-known reputation and proven accuracy and reliability. It provides a tight-coupling hibridization between GNSS and IMU, resulting in a very precise solution. This receiver is installed in the rover vehicle and combined with an iMAR-FSAS IMU (High-grade) and is used as a ground truth receiver. In addition to the GNSS equipment, Ettus USRP X310 with GPSDO and TwinRX have been used as LTE acquisition equipment. The X310 is a software defined radio capable of streaming I/Q samples from an installed RF front-end over a 10 Gbit network interface. To coherently sample two channels (we use two antennas) we use the TwinRX front-end. The X310 includes a GPS-L1 disciplined clock (GPSD) from which an internal and external 10 MHz reference and PPS is generated. The 10 MHz reference is fed into a Septentrio PolaRX receiver for clock-observation.

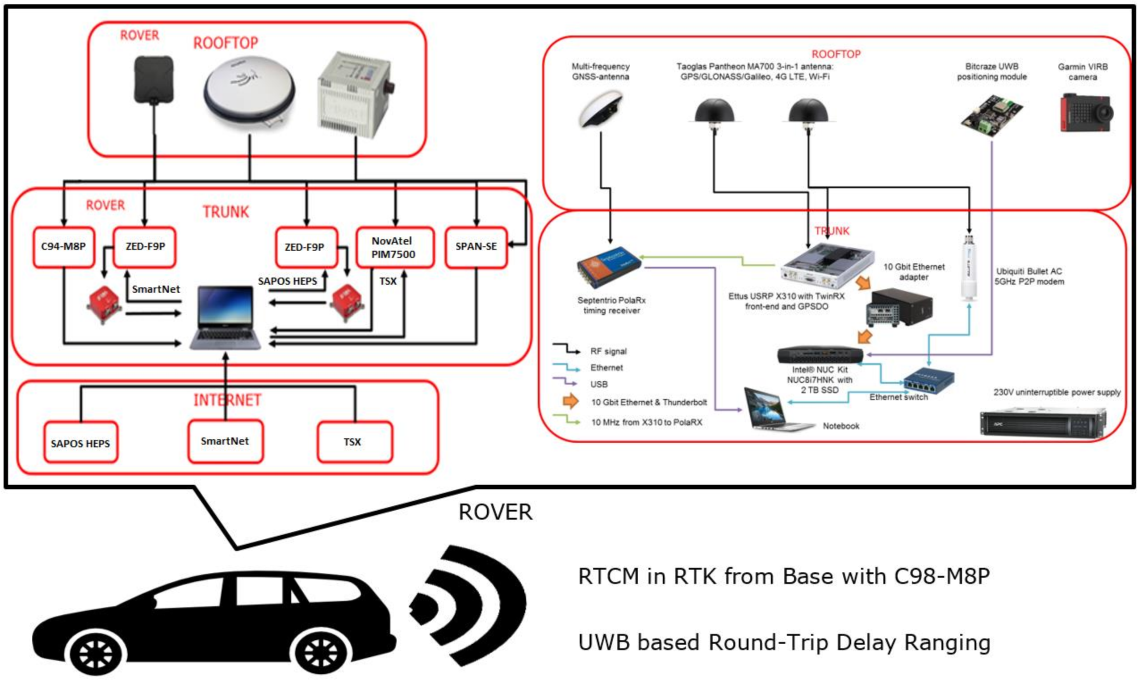

Figure 4: Schematic view of the devices installed in the rover vehicle

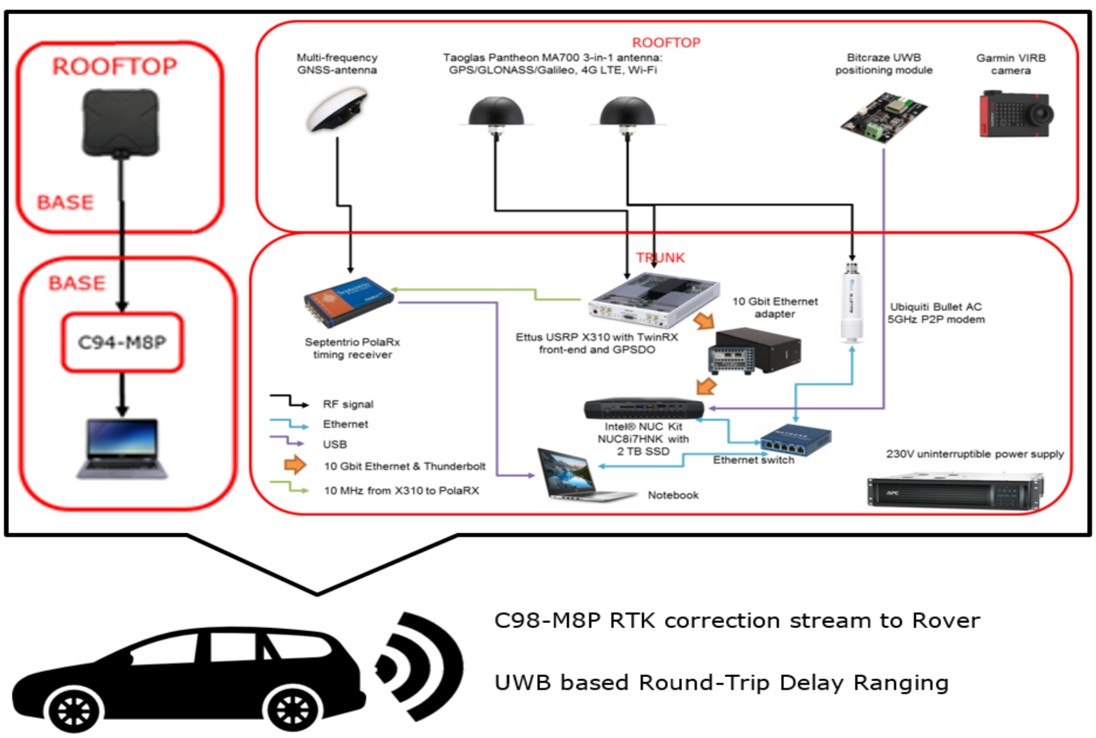

Figure 5: Schematic view of the devices installed in the base vehicle

Hybrid GNSS – 5G FR1

The platform consists of eleven TRPs (Tx/Rx Points), distributed at the L.I.N.K. industrial campus environment, to emulate the 5G infrastructure. Each TRP consists of a USRP, transmitting positioning signals, and is connected to a centralized signal processing cluster. A common 10MHz/1PPS signal is used for the synchronization of the USRPs.
A mobile receiver is used to emulate the tracked user equipment. It consists of a single USRP, two GNSS receivers and a control PC that also records the received radio signals.

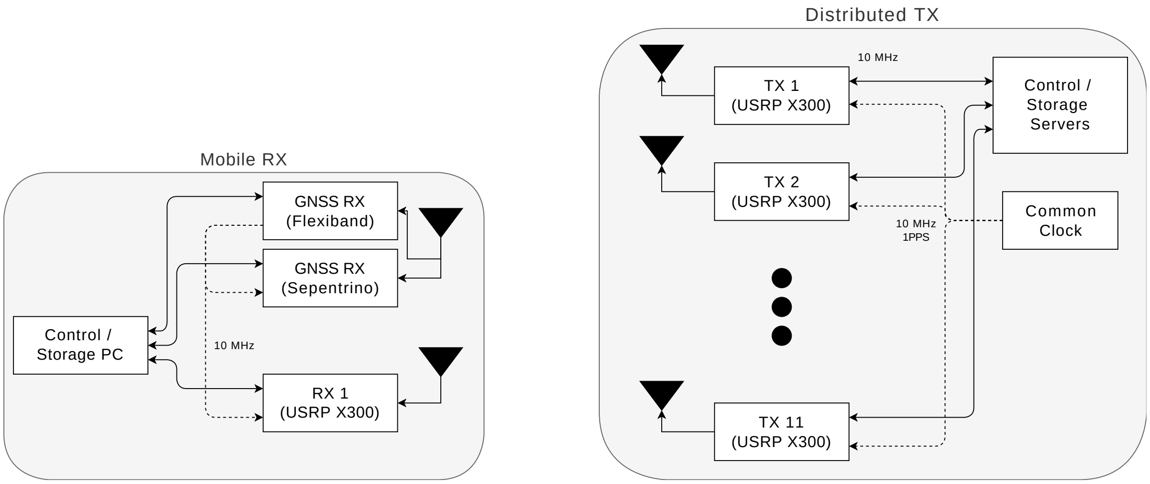

Figure 6: Hybrid GNSS - 5G FR1 experimentation platform.

The hybrid positioning is performed based on GNSS pseudo-ranges and 5G downlink time-of-arrival (ToA) measurements. For GNSS, the GPS L1-band and the Galileo E1-band are used. For 5G FR1, positioning signals are periodically transmitted at a center frequency of 3.75 GHz and 100 MHz bandwidth by each TRP. In deviation from the standard, no Positioning Reference Sequences (PRS), but Sounding Reference Sequences (SRS), fully specified for 100 MHz NR bandwidth with 3GPP Release 15, have been used for the downlink transmission and ToA measurement.

RESULTS AND ASSESSMENT

High-Accuracy GNSS

For the high accuracy automotive case, The National Highway Safety Administration (NHTSA) has, as part of its Federal Motor Vehicle Safety Standards in Vehicle to Vehicle (V2V) Communications, determined that position must be reported to an accuracy of 1.5 meters (1σ or 68%) as this is tentatively believed to provide lane-level information for safety applications. Based on this information and additional parameters selected, the next tables present the results for a selection of receivers (mid-end or MM2 and high-end or PRO1) as following:

Table 2: Automotive assessment success criteria

	SUCCESS CRITERIA			
Horizontal Error	**FAIL**	**P50%**	**P68%**	**P95%**
Availability	**FAIL**	**75%**	**95%**	**99%**
Convergence time	**FAIL**	**180 sec**	**150 sec**	**15 sec**
Loss of lock	**FAIL**	**6%**	**3%**	**1%**

Table 3: Automotive result. MM stands for mass-market GNSS receivers, and PRO stands for professional GNSS receivers

	DEVICE	OPEN	SUBURBAN	URBAN	TRANSITIONS
Which Road: Horizontal accuracy < 5m (turn-by-turn navigation)	**MM2 + N-RTK**				
	MM2 + N-RTK + IMU				
	PRO1				
Which Lane: Horizontal accuracy < 1.5m (ADAS – assisted driving)	**MM2 + N-RTK**				
	MM2 + N-RTK + IMU				
	PRO1				
Horizontal accuracy < 1m (ADAS – assisted driving)	**MM2 + N-RTK**				
	MM2 + N-RTK + IMU				
	PRO1				
Where in lane: Horizontal accuracy < 0.3…0.5m (autonomous driving)	**MM2 + N-RTK**				
	MM2 + N-RTK + IMU				
	PRO1				
Availability above [%]	**MM2 + N-RTK**				
	MM2 + N-RTK + IMU				
	PRO1				
Convergence time less than [s]	**MM2 + N-RTK**				
	MM2 + N-RTK + IMU				
	PRO1	-	-	-	-

Hybrid positioning based on GNSS and 5G

The assessment of the hybrid positioning approach evaluates the raw 5G FR1 positioning as well as the combined GNSS – 5G FR1 positioning performance. For the raw 5G FR1 measurements, Table 4 shows diverse results, indicating achievable sub-meter accuracy as well as high error measurements. Thorough investigation reveals that this heterogeneity is not monocausal but results from a set of influencing factors.

Table 4: Positioning accuracy 5G FR1 downlink measurements. All metrics are expressed in meters.

Test	Iteration	Mean 2D	Mean 3D	CEP50	CEP95	SEP50	SEP95
Loading Zone	1	1.27	4.21	1.01	1.97	3.27	8.76
	2	40.84	55.94	1.15	2.84	4.52	8.42
	3	1.38	3.93	0.97	2.60	3.12	9.85
Indoor Area	1	63.30	181.94	0.67	1.56	1.55	3.70
	2	247.55	640.69	1.14	5.40	2.25	6.99
	3	0.62	1.38	0.50	1.44	1.29	2.88
Driveway	1	482.62	513.48	4.08	1162.08	10.87	1261.91
	2	563.90	604.59	216.24	1287.12	216.32	1288.01
Loading Zone → Indoor	1	1661.23	1807.81	1.93	30.08	4.14	33.33
	2	1956.07	2105.47	1.28	30.77	4.90	32.46

For the loading zone and the indoor area, where at least 5 TRPs with good line-of-sight conditions are available, the CEP indicates that in general sub-meter 2D accuracy can be achieved. As can be seen in Figure 7, even a varying amount of all measurements has an accuracy of 1 meter or better. However, even the three takes for the indoor area show a significant range of variation, with a CEP50 ranging from 0.5 to 1.14 meters and a CEP95 from 1.44 to 5.40 meters. These differences for the three indoor area iterations, also illustrated in Figure 8, can be led back to the impact of the positioning area: While measurements at the center of the indoor area result in low error, significantly increased error is introduced by measurements at the edges of the positioning area (c.f. Figure, Figure 10). While this effect is in parts introduced by narrow multipath due to wall reflections, it can also be accounted to the distribution of the indoor TRPs and the resulting dilution of precision (Figure).

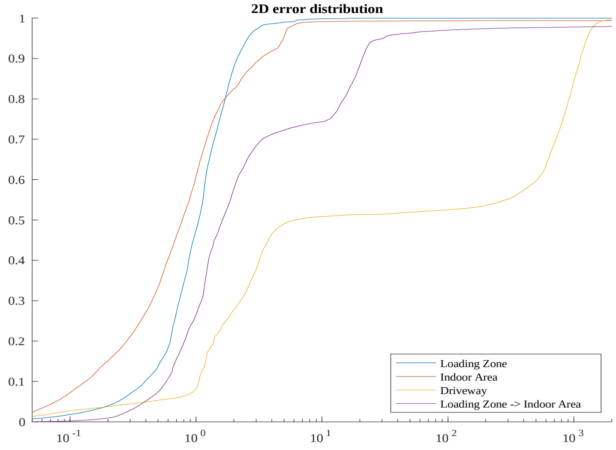

Figure 7: 2D error CDFs for all four areas (iterations combined).

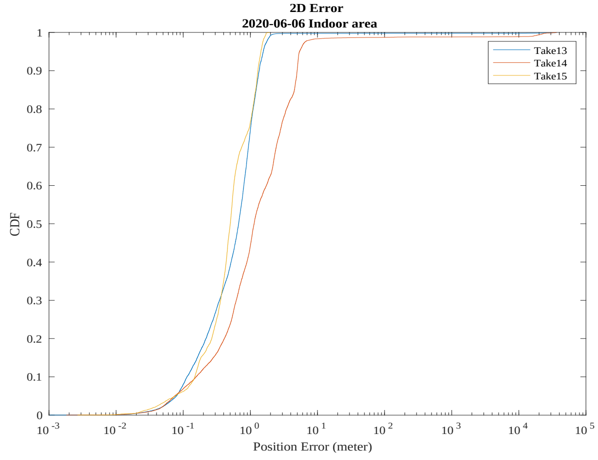

Figure 8: 2D error CDF for the three indoor area iterations.

For 3D accuracy (SEP50 and SEP95 in Table 4) a lower performance compared to 2D positioning is not uncommon, due to the limited capability to distribute TRPs vertically around the positioning area for terrestrial beacon systems. Yet the divergence shows a significant potential for optimization, as reflected by the vertical dilution of precision.

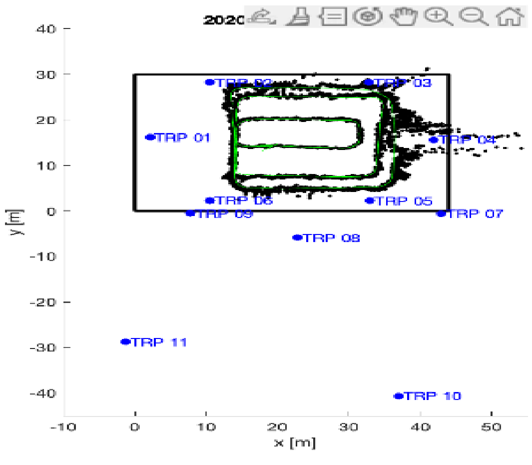

Figure 9: Indoor area trajectory Take14.

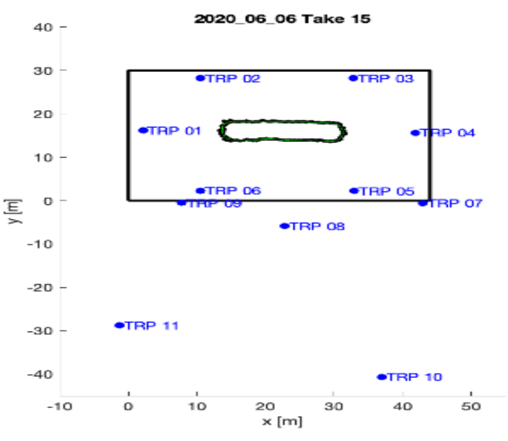

Figure 10: Indoor area trajectory Take15.

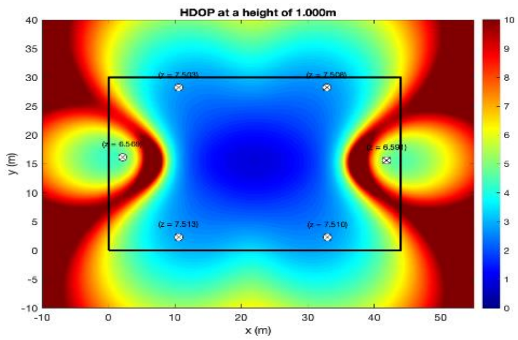

Figure 11: Horizontal dilution of precision for the indoor area.

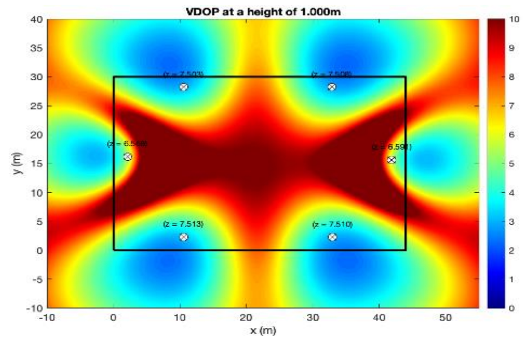

Figure 12: Vertical dilution of precision for the indoor area.

While indoor area and loading zone show reduced positioning accuracy due to multipath and antenna distribution, the driveway and the transition from the loading zone to the indoor area also suffer from non-line-of-sight (NLOS) measurements. In combination with only five TRPs available at the outdoor area, these NLOS measurements can effectively render positioning impossible, even if only a single TRP's line-of-sight and narrow multipath are shadowed. Accordingly, high error measurements, e.g. comprising up to 50% for the driveway, should be considered as reduced positioning availability, resulting from an inappropriate TRP deployment.

For the hybrid positioning approach, FR1 TOAs are combined with GPS (L1-band) and Galileo (E1-band) pseudo ranges for positioning. The resulting accuracy for GNSS-only and hybrid positioning, given in Table 5, thereby shows no significant improvement when 5G FR1 TOAs are incorporated. While this seems surprising considering the lower ranging error of the 5G FR1 platform, it also has to be considered that GNSS pseudo-range can easily be overweighed, since up to 15 satellites but only 5 FR TRPs are used for the outdoor position calculation.

Table 5: Positioning accuracy for GNSS and hybrid positioning approach. All metrics are expressed in meters

Test	Approach	Mean 2D	Mean 3D	CEP50	CEP95	SEP50	SEP95
Loading zone	GNSS	2.09	12.96	1.75	4.50	12.99	22.57
	Hybrid	1.95	13.48	1.81	3.59	13.40	21.63
Driveway + Transition	GNSS	13.10	24.76	12.82	28.74	22.79	46.49
	Hybrid	13.52	23.63	10.36	31.64	22.66	44.95
Loading Zone → Indoor	GNSS	5.35	17.63	4.66	11.77	18.44	20.54
	Hybrid	5.90	18.47	4.87	13.53	18.27	33.85

As can be seen in Figure , the actual impact of incorporating the FR1 TOAs varies over the measurements, so that a positive as well as a negative impact on the positioning accuracy can be observed. Early evaluation thereby shows that the hybrid approach has the potential for optimizations, resulting in an overall increased accuracy for combined FR1 and GNSS.

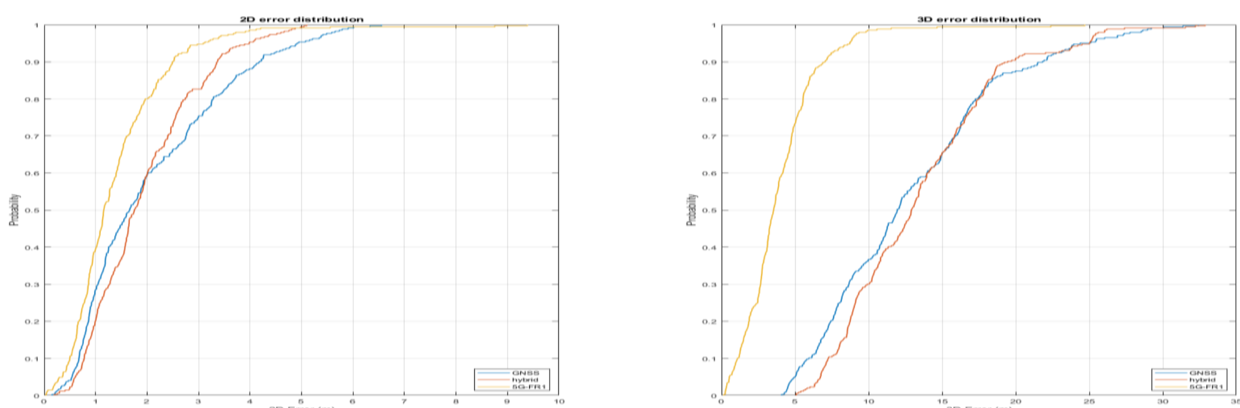

Figure 13: 2D and 3D error CDF for 5G FR1, GNSS and Hybrid position at the loading zone area.

SIMULATIONS CAMPAIGN

The PoPeCoT simulator is based on three main modules, one for GNSS simulation, one for 3GPP simulations, and a one for the Navigation Service Volume Simulator in charge of hybridising technologies and computing the final navigation solution and performances. The main goal of the PoPeCoT is to anticipate the performances (mainly in terms of positioning and energy consumption) that can be obtained in different environments using different combinations of GNSS and 3GPP technologies.

The type of environment defines not only the GNSS reception conditions but also the 3GPP network density and channel model. Besides, a number of GNSS enhancements such as the use of differential services (RTK, NRTK, PPP, PPP-RTK) or various grades of inertial technologies (as well as different GNSS receiver grades) will be among the possible PoPeCoT configuration options.
The GNSS simulation module will use 3D maps to simulate the environment. A COTS SW tool named Polaris is used to simulate the constellations and to precisely determine the LoS geometry for a grid of users or for a user trajectory taking into account the local environment, which is determined based on a 3D map.

The strong point of PoPeCoT is the capability of including the assessment results of the experimental campaign to extrapolate the results to different scenarios with a wide variety of technologies, receiver grades, IMUs and also the power consumption for IoT devices. As a summary, PoPeCoT is capable of providing the following outputs:

- Outputs from GNSS module:
  - On a per-epoch and per user basis:
    - GNSS Position, velocity and attitude errors
    - GNSS Geometry matrix (including LoS unit vectors)
    - Pseudorange and Doppler measurement errors (per LoS)
    - IMU errors (filled with zeros if not applicable)
    - GNSS energy consumption (IoT)
  - On a per-user basis:
    - Relevant FoMs (accuracy and DoP of the GNSS-only PVT solution, average GNSS energy per fix…)

- Outputs from 3GPP module (all outputs from the GNSS module will be available as inputs if needed):
  - On a per-epoch and per user basis:
    - 3GPP PVT errors
    - OTDoA measurement errors
    - RMSE of OTDoA measurement errors
    - 3GPP non-line-of-sight (NLoS) flag per link
    - 3GPP geometry matrix
    - 3GPP energy consumption
  - On a per-user basis:
    - Relevant FoMs (accuracy and DoP of the 3GPP-only PVT solution, average 3GPP energy per fix…)

- Outputs from Hybridization module (all outputs from the GNSS and 3GPP modules will be available as inputs):
  - On a per-epoch and per user basis:
    - Position, velocity and attitude errors
  - On a per-user basis:
    - Relevant FoMs (accuracy and DoP of the hybrid PVT solution, average total energy per fix…)
  - Performance maps (FoMs represented on the input map)

With the GNSS results extracted from the experimental campaign introduced in PoPeCoT, the tool is capable of simulating new scenarios and extrapolate the results attending to the characteristics of each scenario. One of the scenarios tested is Madrid. Two simulations were carried out with the same high-end GNSS receiver but with different IMU grades. As expected, the errors are higher with the lower grade IMU. This is shown in the next figure:

- Simulation 1: Automotive + High-end (RTK) + Mid-grade (IMU) with GPS+GLO+GAL
- Simulation 2: Automotive + High-end (RTK) + High-grade(IMU) with GPS+GLO+GAL

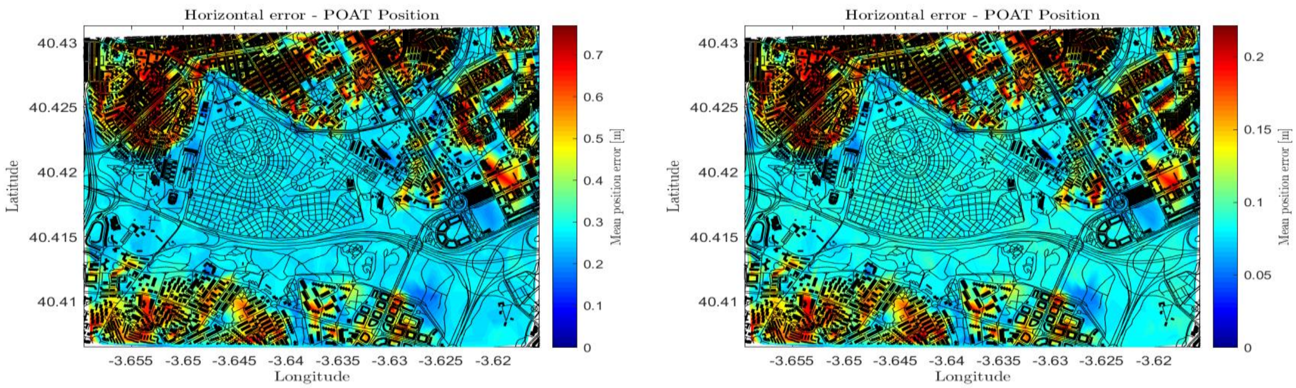

Figure 14: Tokyo results for simulation 1 (left) and simulation 2 (right)

In the same way, different IoT scenarios were tested to check position errors and power consumption. One of them are from the whole city of Tres Cantos (Madrid). In the next figure are presented the power consumption results where a reduction of energy used by the system can be identified when using GPS+GAL instead of only GPS due to the higher number of satellites, which means less re-acquisition times.

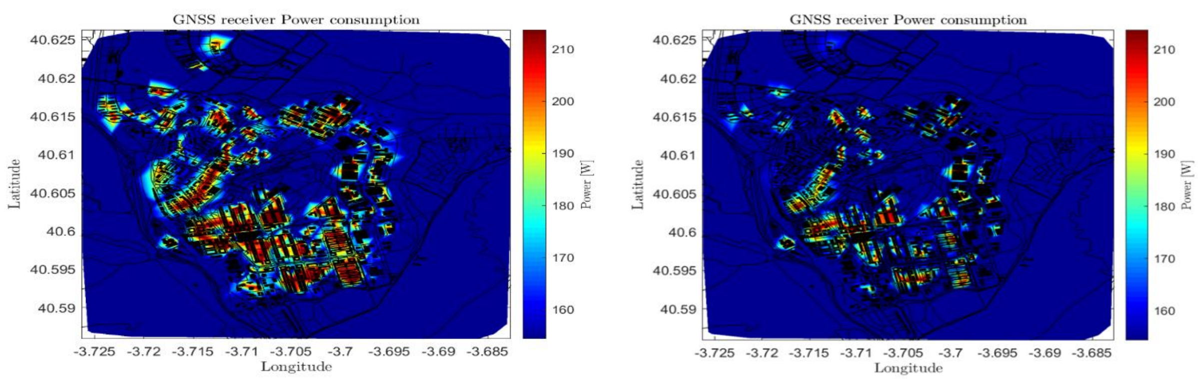

Figure 15: Tres Cantos results for IoT simulation. Power consumption with GPS (left) and GPS+GAL (right)

There are no definitive results for the hybrid position error of 5G+GNSS since the GINTO5G project is still in progress. However a preliminary result of how the tool is expected to behave is presented in the next figures. In here, a typical cellular antennas deployment in a city is defined and combined with the GNSS results. These results highlight the importance of antenna deployment strategies that on a normal public network are not optimized for positioning services. For the deployment of Enhanced positioning Service Areas, the deployment of transmitting points could be optimized to ensure LOS conditions to enough antennas.

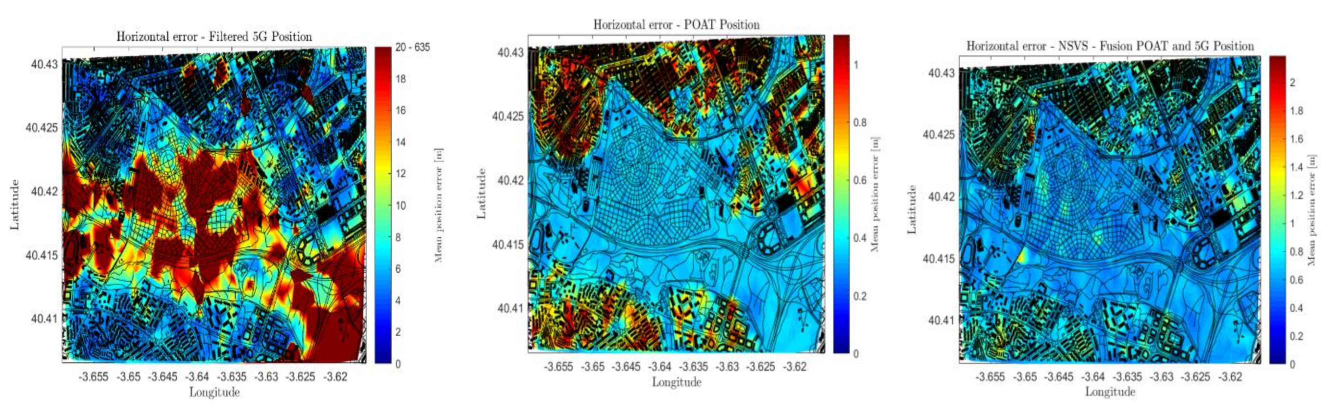

Figure 16: Madrid position error map for 5G (left), GNSS (center) and hybrid (right).

CONCLUSIONS

Preliminary results of all takes with high-accuracy GNSS solutions, augmented by IMU technologies, show very good performance in all type of environments, including urban area typical to European cities. Regarding 5G, the overall positioning performance can be considered as very heterogeneous, with mean 2D errors ranging from sub meter accuracy to multiple 100 meters for other measurements. Based on CEP95 and SEP95 values, it can be stated that a 2D accuracy of sub 3 meter, and a 3D accuracy of sub 10 meter has been measured for the Indoor Area tests, whereas half of all measured positions even show a significantly lower error (sub 1 meter for 2D, and sub 3 meters for 3D). Regarding outdoor spaces, for practical application of 5G NR TDoA, solutions for a dynamic optimization of TOA sets and the cancelation of NLOS influence will be required.

The PoPeCot simulator gives insights into how the state-of-art GNSS, 5G, and IMU behave in different environments without testing them in the field. This could also help the new 3GPP standardization phases, providing a wide knowledge base of how the today's equipment behaves.

Once the project is closed the 5G and GNSS hybridization results will be definitive and will show (as the preliminary results show) how 5G and GNSS can be used to extract the benefit of each one and empower the positioning accuracy and any area.

Next step in this project is to validate PoPeCot simulator based on the results obtained during the two field campaigns introduced in the beginning of this paper.

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