First Field Trial Results of Hybrid Positioning with Dedicated 5G Terrestrial and UAV-Based Non-Terrestrial Networks

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ABSTRACT

This work presents field results of a dedicated fifth generation (5G) network with ground and aerial base stations (BSs) deployed at Airbus premises for positioning purposes. This field campaign is part of a first-of-a-kind testbed for hybrid Global Navigation Satellite Systems (GNSS), 5G new radio (NR) and sensor positioning, called Hybrid Overlay Positioning with 5G and GNSS (HOP-5G) testbed. The dedicated 5G network exploits the standard positioning reference signal (PRS) to support positioning capabilities within the 5G NR downlink transmissions. The goal of this dedicated 5G network is to enhance the accuracy and reliability of hybrid positioning services based on the fusion of GNSS, 5G NR and sensors. This hybridization is especially relevant in the case of a service interruption by any of those technologies, being GNSS the most reliable but not exempt of vulnerabilities. To the best of authors' knowledge, this paper presents the first field results of a 5G network with mixed setup of BSs deployed on ground and at unmanned aerial vehicle (UAV) payloads dedicated for positioning purposes. This field campaign is performed at a heliport within Airbus premises in Ottobrunn (Germany), as representative use case. The paper assesses the pseudorange noise of the real-time 5G NR measurements from three ground and one aerial BSs. These first field trials results achieve a pseudorange noise below 80cm in the 95% of cases, thanks to the 80-MHz PRS bandwidth, demonstrating the feasibility to deploy a dedicated 5G network of ground and flying BSs for high-accuracy positioning. Future work focuses on the assessment of sub-meter hybrid positioning accuracies.

1 INTRODUCTION

There is nowadays an increasing demand for precise and reliable navigation in a wide range of applications, such as in Urban Air Mobility (UAM) or autonomous vehicles. Current solutions are based on Global Navigation Satellite Systems (GNSS) for absolute positioning, navigation and timing (PNT), which are fused with relative positioning from multiple sensor technologies (e.g. inertial measurement units, cameras, radars and LiDAR, among others) for further accuracy and robustness. However, complementary navigation technologies are still expected to be necessary to fulfil the stringent reliability requirements. In this sense, fifth generation (5G) cellular technologies are very promising thanks to their key positioning features and standard support, as it is discussed in del Peral-Rosado (2018), including 5G new radio (NR) terrestrial and non-terrestrial networks (NTN).

5G commercial and private networks are deployed over many different use cases, i.e., from mobile broadband connectivity to Internet of Things (IoT). Still, the exploitation of 5G positioning has been mainly focused on indoor industrial use cases, such as asset tracking and industrial automation. This has been reflected on the 3rd Generation Partnership Project (3GPP) standardization, where the studies on enhanced 5G positioning has been initially focused on indoor use cases, as in 3GPP TR 38.857 (2021). As a result, a very limited attention has been paid to the dedicated deployment of ground and aerial base stations (BSs) for enhanced 5G positioning service area in outdoor applications. Indeed, aerial BSs (ABSs), unmanned aerial vehicle (UAV)-mounted BSs or flying BSs have been mainly considered for communication purposes, as in Li et al. (2019); Zeng et al. (2019), but to a limited extent for enabling enhanced positioning services, which can be especially beneficial for the increased diversity in the vertical dimension with respect to ground-fixed BSs. Thus, to prove this concept in the field, the Hybrid Overlay Positioning with 5G and GNSS (HOP-5G) testbed has been proposed as first-of-a-kind demonstrator of dedicated aerial 5G positioning networks.

The design considerations of these dedicated 5G positioning networks have been studied in del Peral-Rosado et al. (2022a), and their expected positioning capabilities in a representative scenario in del Peral-Rosado et al. (2022b). Experimental 5G positioning results have been presented in predecessor testbeds, such as in Maymo-Camps et al. (2018); Mata et al. (2020), as well as with signals of opportunity approaches in Shamaei & Kassas (2021); Abdallah & Kassas (2021). The use of ad-hoc terrestrial infrastructure for UAV UE positioning has been demonstrated for alternative PNT (A-PNT) in Herschfel et al. (2019), the concept of exploiting aerial platforms as transmitters or beacons for UE positioning is simulated for emergency situations in Kolawole & Hunukumbure (2022), and even envisaged for reliable positioning services as in Wang, Z. et al. (2022) and Rothmaier & del Peral-Rosado (2023). However, to the best of authors' knowledge, the use of dedicated flying 5G BSs for positioning has not been demonstrated yet. Preliminary ranging results of a single link between a flying 5G BS and a user equipment (UE) have been recently shown in del Peral-Rosado et al. (2023). This paper presents the first trial results of a dedicated 5G network based on multiple ground and aerial BSs deployed specifically for positioning purposes.

2 HOP-5G DEMONSTRATOR

2.1 Key Features

The main objective of the HOP-5G testbed is to demonstrate the enhanced positioning capabilities, resulting from the deployment of a dedicated 5G network over a certain area. Indeed, one of the key differentiators of this dedicated 5G network is the use of both ground and aerial BSs in order to easily adapt to a specific environment and to enable optimal propagations conditions for positioning. In contrast to 5G commercial networks deployed in dense urban areas with heavy blockages, the deployment of a 5G private network can be optimized to ensure line-of-sight (LoS) transmissions, able to fulfil stringent positioning requirements for certain purposes, e.g. urban aerial corridors in UAM operations. Furthermore, the use of flying BSs provides further flexibility and fast on-demand deployment, as well as enhanced positioning diversity in the vertical domain with respect to ground-fixed BSs.

The HOP-5G proof-of-concept is mainly based on the following key features:

- Modular architecture: The use of software-defined radio (SDR) and on-board computers (OBC) allows to use each of the testbed nodes either as BS or UE, by adapting the 5G signal numerology to the computational limits of the unit.
- Innovative technologies: The exploitation of wideband signals, cmWave and mmWave bands, including antenna arrays, is envisaged to achieve high-accuracy positioning.

- Real-time operations: The software modules are designed and implemented to operate in real-time, in order to demonstrate the positioning capabilities in representative operational conditions.
- Post-processing capabilities: Several post-processing capabilities are supported from the 5G physical layer to the hybrid positioning configurations, in order to perform prototype optimizations and comprehensive experimental assessments.

2.2 High-Level Architecture

The HOP-5G testbed is based on the following main building blocks:

- Ground-fixed 5G BSs: Deployable and temporary 5G BSs (or 5G gNBs as in the 3GPP nomenclature) are fixed on ground to provide high-performance and reliable transmissions.
- Flying 5G BSs: 5G BSs are also deployed on the payload of UAVs able to hover at certain altitude for a limited period or able to operate over longer periods after landing at certain locations, at the expense of limited computational capacities.
- User Equipment: 5G UE can be deployed on ground or in the UAV payload.
- Ground support equipment (GSE): The operations and monitoring of the testbed are performed within the GSE, which is able to remotely send commands, to collect measurement data and to visualize the real-time results.

Additional details of the architecture can be found in del Peral-Rosado et al. (2022b).

2.3 Testbed Hardware and Software Components

The testbed equipment is based on commercial off-the-shelf (COTS) components, while keeping a high-degree of flexibility and modularity thanks to the use of SDR and regular computers. The specific hardware components are adapted either to operate in frequency range 1 (FR1), i.e., below 6 GHz, or in FR2, i.e., above 24 GHz. In this paper, the testbed is only described for FR1 operations. Each node of the HOP-5G testbed shares the same high-level architecture, including both aerial and ground deployments. As it shown in Figure 1, the nodes are based on four key components:

- Platform: Tripods are used on ground BSs deployment, while the PM Raptor Carbon Hexacopter is used as UAV.
- Computer: The HOP-5G software modules are installed and executed in a regular computer with Ubuntu 20.04 operating system. When installed within the UAV payload, an Intel NUC with Thunderbolt3-to-10GbE adapter is used to fulfil the size, weight and power (SWaP) constraints. When fixed on ground, a workstation or tower computer with 10GbE adapter is preferred to support very high computational performance. In both cases, a Wi-Fi module is used to establish a remote connection with the operator.
- SDR: The USRP X300 is considered the preferred SDR to transmit and receive 5G signals. This SDR is built with an UBX-160 daughterboard to operate at FR1 between 10 MHz and 6 GHz, and with a GPS disciplined oscillator (GPSDO) to keep a tight synchronization among testbed nodes.
- GNSS receiver: The COTS GNSS receiver is the u-blox F9P for ground-fixed nodes and the u-blox F9R for moving nodes.
- Antennas: The two additional antennas of the node are a 5G monopole omnidirectional antenna and a GNSS helical antenna. An L-band splitter is used to connect the GNSS antenna output with the SDR and the GNSS receiver.

The 5G real-time operations are based on a specific upgrade of OpenAirInterface (OAI). This upgrade allows to transmit downlink 5G NR positioning reference signals (PRS) synchronized to GPSDO pulse per second (PPS), and to obtain 5G real-time ranging measurements every 10ms. The PRS bandwidth can be set to either 40MHz or 80MHz in FR1, being these values driven by the SDR sampling and the compliance to 3GPP numerology. An increased interpolation factor is also performed to enhance the resolution of the 5G real-time pseudorange or time-of-arrival (ToA) measurements. In addition, the channel impulse response (CIR) can be extracted for further post-processing. The 5G baseband signals can also be recorded for post-processing, by using a MATLAB software receiver.

The COTS GNSS receiver libraries are used to collect the raw observables and position estimates. Both 5G and GNSS measurements are disseminated within the wireless local area network (WLAN) by using a MQTT protocol. This measurement data is logged and exploited by two additional software modules. First, the 5G BS Time Offset Estimation (BSTOE) module is deployed in a UE with known location, or Positioning Reference Unit (PRU) as described in 3GPP TS 38.305 (2022), in order to estimate and to provide corrections of the time synchronization offsets between BSs, by using the known position of the BSs and the 5G time-difference of arrival (TDoA) measurements. Second, the positioning engine collects GNSS and 5G pseudoranges (with or without 5G time offset corrections) to perform the UE position estimation. Finally, the measurements and position estimates are logged and visualized in real-time.

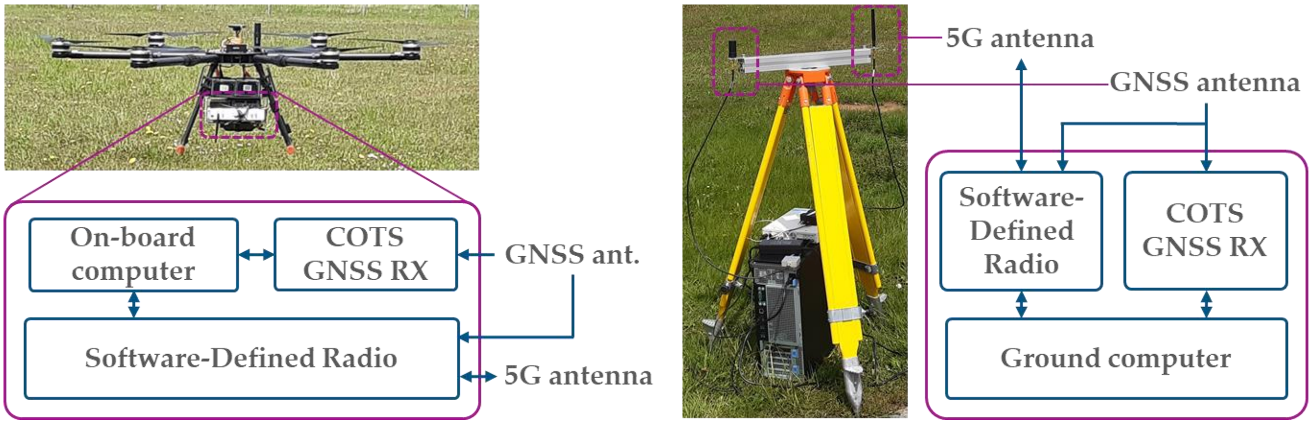

FIGURE 1 Example equipment of the HOP-5G testbed for UAV-mounted (left) and ground (right) deployments.

3 PERFORMANCE METRICS

The assessment of the HOP-5G field trial results is here focused on the UE ranging performance at static position using 5G NR PRS transmissions from ground and aerial BSs. The impact of the UAV movement on the ranging measurements is of special interest to address the suitability of the dedicated UAV-based 5G network.

Let us define the downlink UE pseudorange measurements from the flying 5G BS as:

$$\rho(n) = \|\mathbf{x}_{\mathrm{UAV}}(n) - \mathbf{x}_{\mathrm{UE}}\|^2 + c \cdot \left(\delta t_{\mathrm{UE}}(n) - \delta t_{\mathrm{UAV}}(n)\right) + \varepsilon(n), \tag{1}$$

where $\mathbf{x}_{\mathrm{UAV}}(n)$ is the three-dimensional (3D) position of the UAV, $\mathbf{x}_{\mathrm{UE}}$ is the 3D position of the static UE, $\delta t_{\mathrm{UE}}(n)$ is the receiver clock offset, $\delta t_{\mathrm{UAV}}(n)$ is the flying BS clock offset, and $\varepsilon(n)$ is the pseudorange error due to noise and multipath. As one can observe from this expression, the main sources of pseudorange variability are the slow-moving distance $d(n) = \|\mathbf{x}_{\mathrm{UAV}}(n) - \mathbf{x}_{\mathrm{UE}}\|^2$ due to UAV hovering movements, the BS and UE clock offsets, and the noise and multipath errors. Note that the pseudorange model from the flying BS in Equation (1) is also applicable to pseudoranges obtained from ground 5G BSs, by using the corresponding 3D position and BS clock offset. The preliminary assessment in del Peral-Rosado et al. (2023) considered the variability of the pseudoranges over a period of 1 second, by subtracting to the pseudorange measurements their mean computed over a period of 1 second. This pseudorange variability can be used to analyze the impact of the clock drift on the ranging precision, however this metric tends to be biased with large outliers. Thus, this paper considers another metric to evaluate the pseudorange noise based on the third-order derivative over four consecutives epochs, described in Pirazzi et al. (2017) for GNSS carrier phase noise and applied to GNSS pseudoranges in Otero-Villamide et al. (2022). Based on this method, the pseudorange noise is defined as:

$$\rho_w(n) = \frac{1}{\sqrt{20}} \cdot \left(\rho(n) - 3 \cdot \rho(n-1) + 3 \cdot \rho(n-2) - \rho(n-3)\right). \tag{2}$$

As a complementary metric, the 5G downlink PRS reference signal received power (RSRP) in 3GPP TS 38.215 (2023) is computed to further assess the results in terms of propagation conditions.

4 FIELD EXPERIMENTATION

Field experimentation of the HOP-5G testbed is performed at Airbus heliport premises in Ottobrunn (Germany). The testbed deployment is shown in Figure 2 during the drone flight operated by the pilot. The field trial results are used to assess the pseudorange noise with respect to the distance between BS and UE. This assessment is focused on the use of UE2 measurements for a UAV trajectory of 200s, which includes hovering and slow movements. As it is shown in Figure 3, the UEs are static and only gNB1 is moving from one hovering point to another.

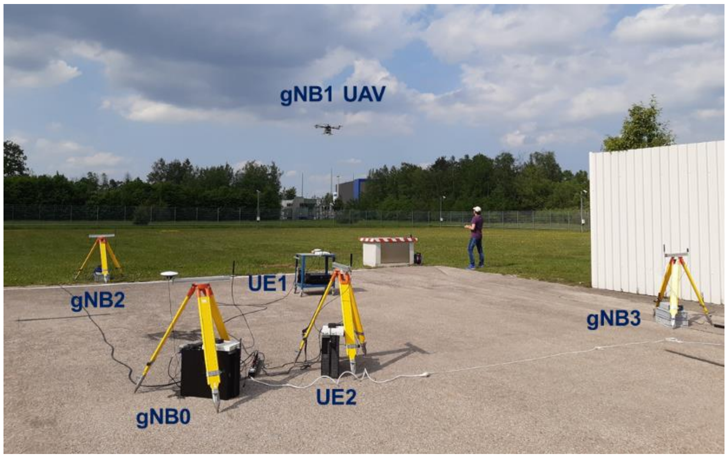

FIGURE 2 Field deployment of HOP-5G testbed based on three ground BSs (i.e., gNB0, gNB2 and gNB3), one flying BS (i.e., gNB1 UAV) and two UEs.

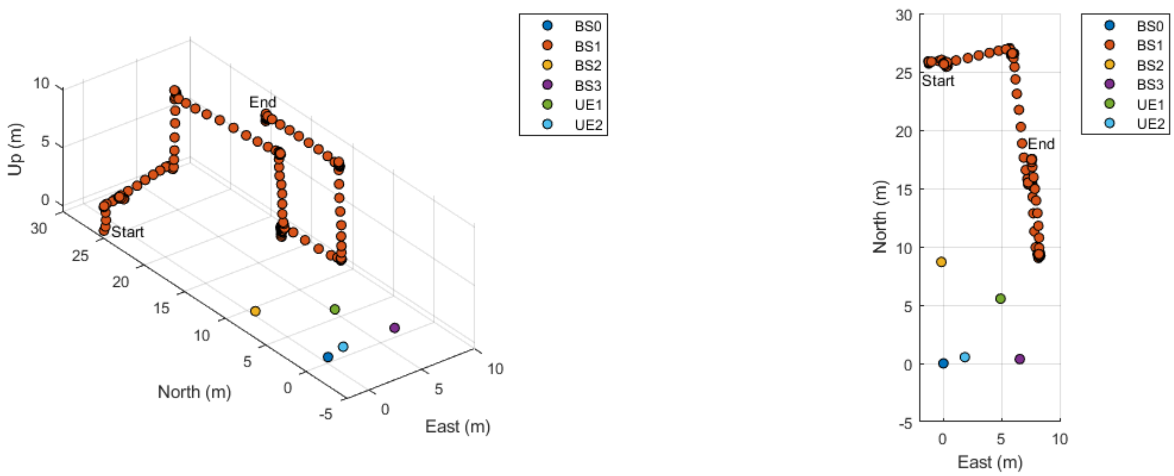

FIGURE 3 Positions of the BSs and UEs during the flight campaign in 3D (left) and 2D (right) view.

The downlink 5G PRS are transmitted over a bandwidth of approximately 80MHz at 3.75 GHz and a subcarrier spacing of 30kHz. This 80-MHz bandwidth is defined as result of the supported sampling rate of the USRP X300, which is set to 92.16MSps. Each BS transmits its PRS in a different slot allocation to fully avoid inter-cell interference. The maximum resolution of the 5G real-time ToA measurements is $\Delta_{\min} = c \cdot F_s \cdot I = 20.35$ cm, where c is the speed of light, F_s is the sampling rate of 92.16MSps, and I is the interpolation factor, which is here set to 16. In terms of the pseudorange noise, the third-order derivative method scales down the resolution to $\Delta_{\min}/\sqrt{20} = 4.55$ cm.

The distance between BS and UE, i.e., $d(n)$, is computed with a precise positioning solution of each BS and UE by using their GNSS receiver observables in post-processing. As expected, Figure 4 shows the impact of this distance on the pseudoranges and the received power. As expected, the received power decreases with the distance between BS and UE, thus increasing the pseudorange noise. Still, stable results are shown on the pseudoranges with few outliers at gNB1, which typically occur due to threshold setup and fading.

The cumulative density function (CDF) of the pseudorange noise and of the RSRP are shown in Figure 5. The real-time pseudorange noise is below 30 cm on the 99.9% of cases for a UE closer than 2 m with respect to a BS, and below 50cm on the 99.8% of cases for distances between BS and UE up to 10m. The pseudorange noise of gNB1 is higher due to the increased distance to UE2, i.e., 10 and 20m between BS and UE, resulting in 80cm on the 95% of cases. Thus, the 5G real-time ToA measurements achieve a pseudorange noise at sub-meter level. Future results will be used to assess the BS time offsets and hybrid positioning performance.

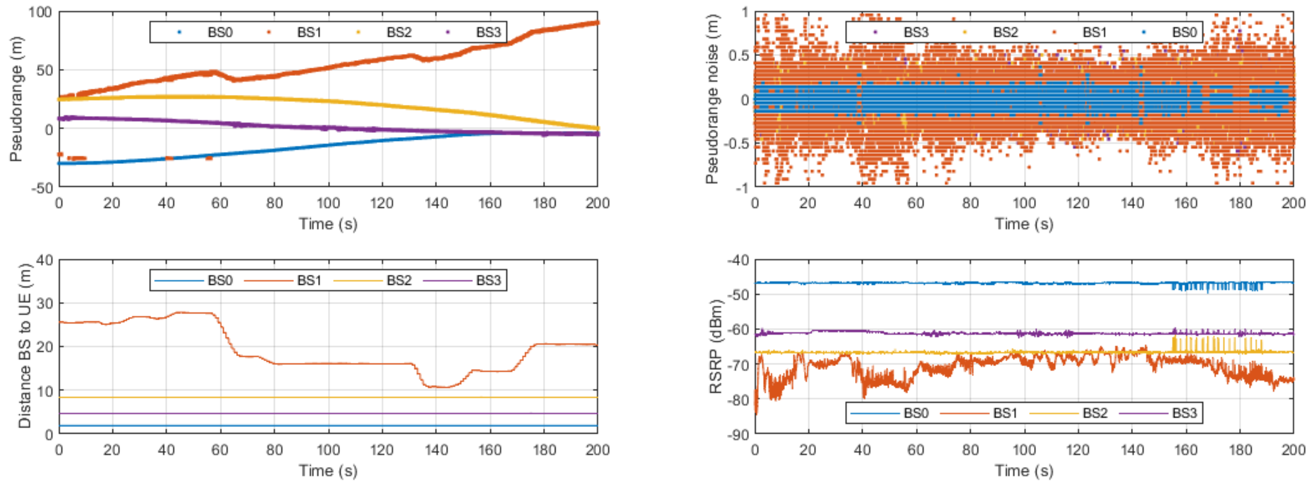

FIGURE 4 Real-time 5G NR measurements from UE2 at 80MHz during HOP-5G flight campaign, i.e., pseudorange measurements (top-left), pseudorange noise (top-right), distance between BS and UE (bottom-left) and RSRP (bottom-right).

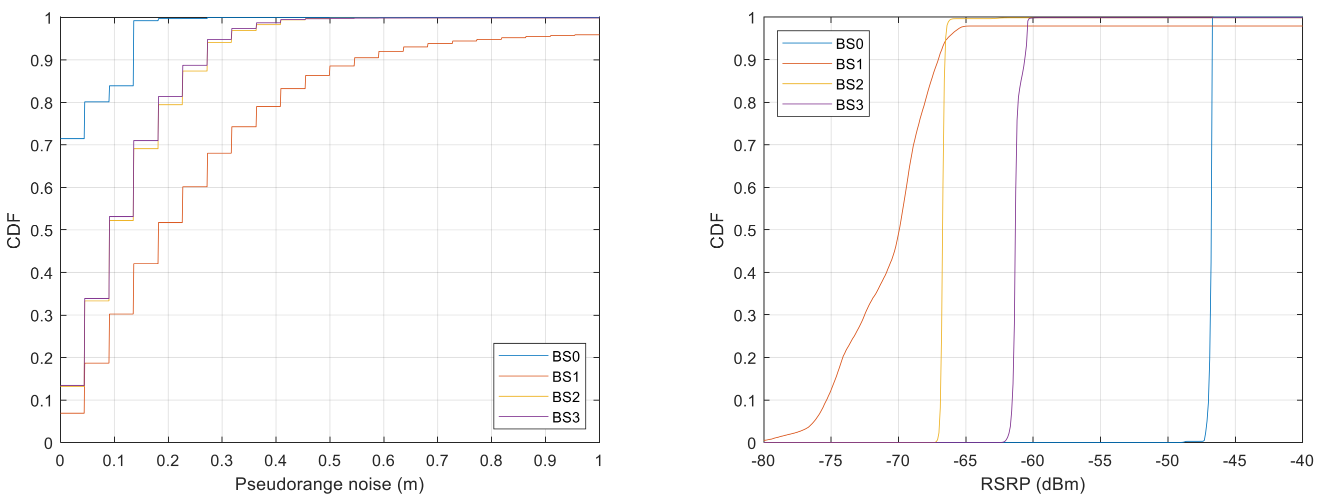

FIGURE 5 CDF of the pseudorange noise (left) and CDF of the RSRP (right) from the 5G NR real-time measurements at 80MHz during HOP-5G flight campaign.

5 CONCLUSIONS

This paper provides the first field results of a dedicated 5G network of ground and UAV-based base stations (BSs) for positioning purposes. The field trial is based on the impact of the ground and flying 5G BSs on the ranging performance of a static user equipment (UE). The BSs transmit 5G NR positioning reference signals (PRS) with a bandwidth of 80MHz at 3.75GHz. The UE is able to perform in real-time ranging measurements every 10ms. The computation of the pseudorange noise indicates that the testbed is able to achieve submeter-level ranging measurements on the 95% of cases. Furthermore, a limited impact has been observed on the ranging performance of the signal from the flying BS, thus demonstrating the opportunity for such dedicated 5G deployment concepts to enable high-accuracy positioning. Future updates of these first field results focus on the assessment of the 5G stand-alone and hybrid positioning algorithms to achieve sub-meter level accuracies.

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DISCLAIMER

The view expressed herein can in no way be taken to reflect the official opinion of the European Space Agency.

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