

A UNIFIED HYBRID TERMINAL INTEGRATING GNSS AND LEO-PNT WITH 5G AND LEO SIGNALS OF OPPORTUNITY: CONSOLIDATED SYSTEM DESIGN AND MEASURED PERFORMANCE

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BIOGRAPHIES

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, integrity algorithms, RFI detection, mitigation and localization, resilient navigation systems for autonomous driving vehicles and 5G TN/NTN positioning.

Dr. Javier Fidalgo holds a Ph.D. in Particle Physics by the UAM (Universidad Autónoma de Madrid). He joined GMV in 2012, working on GNSS activities, acting during several years as Project Manager and GNSS Consultant. He is currently Section Head of the GNSS Consultancy, Strategy, System evolutions & User Technologies Section at GMV. His main areas of expertise are GNSS Standardization, Space Based Augmentation Systems, GNSS Applications and User Equipment.

Marcelo Meneses Marín obtained a B.Sc in Aerospace Engineering from the Polytechnic University of Madrid in 2022 and a M.Sc in Mathematical Engineering from University of La Rioja in 2024. From the time he joined GMV, in 2022, he has worked implementing and testing PVT algorithms, sensor fusion schemes (including INS and 5G) and maritime navigation, in the context of projects such as ERASMO, LEGION and ISLET.

Freddy A. Pinto-Benel is a Telecommunication engineer who got his PhD in Signal Processing from the University of Alcalá in 2019. Since 2018, he has been working as a GNSS Signal Processing Engineer. During this time, he has contributed to various projects, primarily related to the second generation of Galileo (G2G), with notable involvement in the G2GTUR-WO1 and G2GTURN projects. Additionally, he has also worked on projects involving NTN/5G signals.

David García Santana obtained a Bachelor's degree in Telecommunication Technologies Engineering with a specialization in electronic systems in 2022. He received a Master's degree in Applied Electronics and Telecommunications in 2023, both from the University of Las Palmas de Gran Canaria, and a Master's degree in GNSS in 2025 from the GNSS Academy. He joined GMV in early 2025, working as a GNSS engineer in the software development of GNSS receivers.

Francisco José Mata received an M.Sc. in Industrial Engineering in 2014 and an M.Sc. in Mechanical Engineering and Transportation in 2015, both from Universidad Carlos III de Madrid (UC3M). His work focuses on Global Navigation Satellite

Systems (GNSS), including the development of PVT engines, integration with communication technologies such as 5G, and fusion with external sensors for improved navigation and timing performance. He has been involved in several projects, including HARMONY, POSITRINO, GINTO5G, ERASMO, G2GTURB, GERMINAL and LEGION.

Dr. Domenico Giustiniano is Research Professor (tenured) at IMDEA Networks Institute and leader of the Pervasive Wireless System Group. Before joining IMDEA, he was a Senior Researcher and Lecturer at ETH Zurich. He also worked for a total of four years as Post-Doctoral Researcher in industrial research labs (Disney Research Zurich and Telefonica Research Barcelona). He holds a PhD in Telecommunication Engineering from the University of Rome Tor Vergata (2008).

Dr. Giuseppe Santaromita is Post-Doc Researcher at IMDEA Networks Institute, within the Pervasive Wireless Systems Group. His research activities are focused on wireless networks. In particular on the programmable PHY layer for optimizing wireless networks performance and on the low-latency and high-accuracy Localization methods, mainly on 5G New Radio (NR) networks.

Dr. Timothy Otim is a Post-Doc researcher specializing in wireless communication at IMDEA Networks, within the Pervasive Wireless Systems Group. He earned his PhD in Positioning and Navigation Systems from Universidad de Deusto, Spain, in 2020. Prior to his current role, he held a postdoctoral position at the German Aerospace Centre (DLR) in Wessling, Germany, in 2021, where he worked on statistical models for Intelligent Transport Systems. His research interests include, positioning and navigation, 5G, mobility behavior modeling.

Francesco Pigato is a PhD Student at IMDEA Networks Institute, within the Pervasive Wireless Systems Group. He completed his Master's Degree in Telecommunication Engineering in 2024 from Politecnico di Milano, Italy, with a thesis on processing sensor data from autonomous race cars for positioning applications. His research interests include positioning and navigation, sensor fusion and signal processing techniques.

Antoni Reus-Bergas graduated with B.Sc degrees in Telecommunication Systems Engineering and Computer Engineering, as well as a M.Sc. degree in Telecommunications Engineering, from Universitat Autònoma de Barcelona. Since 2023, he has been a member of the SPCOMNAV group, involved in LEO-based satellite positioning and signal processing for communications and navigation. His current research interests lie in the fields of LEO-PNT, satellite communications, and digital signal processing.

Marc Fernández-Temprado graduated with a B.Sc. degree in Telecommunications Engineering from Universitat Politècnica de Catalunya (UPC). Since 2024, he has been part of the SPCOMNAV group at Universitat Autònoma de Barcelona, where he has been involved in the investigation of LEO-based satellite positioning techniques and SDR-based testbed development. His current research interests lie in the fields of LEO-PNT and signal processing for communication and navigation.

Qi Liu received his bachelor's degree in 2019 and his doctoral degree in 2024 from the Southeast University (SEU). Since 2025, he has been the postdoc of the SPCOMNAV group at Universitat Autònoma de Barcelona, where he has been involved in the investigation of LEO-based satellite positioning techniques. His research interests lie in the field of satellite and terrestrial positioning using LEO satellites, either for dedicated PNT or as a source of signals of opportunity (SOP).

Fran Fabra received the Ph.D. degree in Telecommunication Engineering from UPC in 2013. From 2007–2019, he worked with the Earth Observation Research Group (ICE-CSIC/IEEC), advancing GNSS-R remote sensing from theory to experimental validation. Since 2019, he has been with the Signal Processing for Communications & Navigation Group (UAB/IEEC), becoming Associate Professor in 2024, where he mainly works on GNSS and LEO-PNT data processing.

Gonzalo Seco-Granados received the Ph.D. degree in telecommunication engineering from Universitat Politècnica de Catalunya (UPC) in 2000, and the MBA degree from the IESE Business School, Spain, in 2002. From 2002 to 2005, he was member of the European Space Agency. He is currently Professor at Universitat Autònoma de Barcelona (UAB) and Head of the Signal Processing for Communications and Navigation (SPCOMNAV) research group.

José A. López-Salcedo received the Ph.D. degree in telecommunication engineering from Universitat Politècnica de Catalunya (UPC) in 2007. In 2006 he joined Universitat Autònoma de Barcelona (UAB), where he is a Professor and served as coordinator of the telecommunications engineering degree. His research interests lie in the field of signal processing for communications and navigation, with special emphasis on GNSS signal processing techniques.

ABSTRACT

Positioning, Navigation and Timing (PNT) is evolving beyond conventional Global Navigation Satellite Systems (GNSS) through the use of complementary terrestrial and space-based signals. Dedicated Low Earth Orbit PNT (LEO-PNT), 5G New Radio (NR) terrestrial network (TN) signals, 5G non-terrestrial networks (NTN) signals (evaluated through controlled emulation of LEO-like delay and Doppler conditions), and LEO Signals of Opportunity (LEO-SOP) offer complementary geometry, availability, bandwidth and resilience. Their integration within a common receiver architecture can improve navigation performance in environments where GNSS alone is insufficient.

This paper presents the consolidated design and experimental results of a Unified Navigation and Communications Hybrid Terminal developed within the GERMINAL project. The terminal integrates four distinct positioning sources: dual-frequency GNSS, GNSS-like LEO-PNT signals, 5G NR TN positioning signals and emulated 5G NTN signals compliant with 3GPP Release 17, and multiple LEO-SOP constellations including Orbcomm, Iridium, Globalstar and Starlink.

The architecture combines dedicated signal-processing chains for each technology with a common timing infrastructure and a hybrid navigation module based on Extended Kalman Filtering (EKF). The proposed design enables coherent fusion of pseudorange, carrier phase, Doppler, Time of Arrival (TOA), Time Difference of Arrival (TDOA), Frequency Difference of Arrival (FDOA), and signal-quality observables obtained from heterogeneous sources.

The paper describes the receiver architecture, signal-processing subsystems, hybrid navigation framework and validation methodology, together with subsystem and initial integrated navigation results assessing horizontal accuracy. The work demonstrates a practical implementation of Joint Communication and Navigation and the benefits of combining terrestrial and space-based signals in a unified, time-coherent PNT platform.

1 INTRODUCTION

Positioning, Navigation and Timing (PNT) systems are evolving toward multi-source architectures that complement conventional Global Navigation Satellite Systems (GNSS) with terrestrial and space-based infrastructures. Although GNSS remains the primary positioning source for most civil and professional applications, its performance may degrade under blockage, multipath, radio-frequency interference, spoofing or jamming. These limitations motivate resilient navigation solutions able to exploit independent positioning sources within a common estimation framework.

Promising complementary technologies include dedicated Low Earth Orbit PNT (LEO-PNT), 3GPP-standardized 5G NR terrestrial and non-terrestrial positioning services, and LEO Signals of Opportunity (LEO-SOP) from commercial communication constellations ([3GPP TS 38.211], [3GPP TS 38.331], [3GPP TS 38.811], [Kozhaya et al., 2025]). Their lower orbital altitude, diverse signal structures, higher received power, wider bandwidths and dense terrestrial infrastructure can improve availability, geometry and robustness in challenging environments. Rather than replacing GNSS, they enable hybrid solutions able to maintain positioning when an individual source is degraded or unavailable.

The convergence of navigation and communication technologies is fostering Joint Communication and Navigation (Joint Comm/Nav), where communication infrastructures also provide navigation observables ([Palamà et al., 2023], [Palamà et al., 2024]). This requires receivers able to process heterogeneous waveforms and consistently combine GNSS observables, 5G Time of Arrival (TOA) and Time Difference of Arrival (TDOA), NTN Doppler information and measurements from LEO-SOP.

In this context, GERMINAL addresses the design, implementation and validation of a Unified Hybrid User Terminal (UHUT) jointly processing GNSS, LEO-PNT, 5G TN, emulated 5G NTN, and LEO-SOP signals ([Domínguez et al. 2025]). The project is co-funded by the European Union through EUSPA under the Fundamental Elements programme and combines GMV expertise in GNSS and hybrid navigation, IMDEA Networks Institute expertise in 5G TN/NTN, and UAB expertise in LEO-SOP processing and positioning.

The resulting hybrid architecture is a flexible, modular platform in which each technology is processed by a dedicated acquisition, tracking and measurement-extraction chain. The generated observables—including pseudorange, carrier phase, Doppler, TOA, TDOA, FDOA and signal-quality indicators—are fused by a common tightly coupled hybrid navigation engine. A common timing infrastructure enables coherent fusion across RF front ends and supports cross-technology consistency monitoring.

Such architecture is applicable to a broad range of resilient PNT applications, including autonomous road transportation, railway systems, maritime navigation, unmanned aerial vehicles (UAVs) and advanced location-based services. By exploiting multiple independent signal sources operating in different frequency bands and originating from different infrastructures, the Hybrid Terminal aims to improve positioning accuracy, increase solution availability and continuity, and enhance robustness against satellite outages, interference and spoofing attacks.

This paper presents the GERMINAL Unified Hybrid User Terminal consolidated design and its progressive validation methodology. It first describes the supported technologies, receiver architecture, signal-processing subsystems and hybrid navigation framework. It then presents representative subsystem and initial integrated navigation results, and discusses the contribution of hybridization to positioning accuracy, navigation resilience and operational flexibility.

2 POSITIONING SIGNALS

2.1 Signal Sources Supported by the Hybrid Terminal

The Unified Hybrid User Terminal (UHUT) has been designed to exploit a heterogeneous set of positioning signals whose characteristics are complementary in terms of geometry, received power, bandwidth, availability and resilience. The signal

sources considered in the terminal can be grouped into four main families: conventional GNSS signals, dedicated LEO-PNT signals, 5G TN and NTN signals, and LEO communication signals of opportunity.

Each signal family is processed through a dedicated reception and signal-processing chain, including the corresponding antenna, radio-frequency front end and baseband processing functions. This modular approach enables each technology to operate independently while also allowing the Hybrid Navigation module to combine the resulting observables whenever they are available. In this way, the terminal can support standalone positioning, partial hybridization or full multi-source navigation depending on the operational scenario. The following subsections summarize the role of each signal family within the UHUT, the observables extracted from them, and their contribution to standalone or hybrid navigation.

2.2 GNSS and LEO-PNT Signals

GNSS and LEO-PNT signals are treated as range-based satellite navigation sources. In the current implementation, both types of signals are received through a common antenna and RF front-end architecture, while their acquisition and tracking are performed using independent processing pipelines adapted to their respective signal characteristics and dynamics.

For GNSS, the terminal is focused on the processing of GPS and Galileo Open Service signals, including GPS L1/L5 and Galileo E1/E5a/E5b ([OS SIS ICD, 2025]). Particular attention is given to Galileo E1 Quasi-Pilot processing, which is relevant for improving acquisition and tracking performance ([OS SIS ICD, 2025]). The GNSS processing chain generates the standard set of navigation observables required for PVT estimation, including code phase, carrier phase, Doppler and carrier-to-noise density ratio (C/N_0). These measurements are produced in real time and are made available to the Hybrid Navigation module.

The LEO-PNT component assumes the availability of GNSS-like spread-spectrum navigation signals transmitted from low Earth orbit. This assumption allows the terminal to reuse part of the baseband processing principles already employed for GNSS, while adapting the tracking strategy to the higher dynamics associated with LEO satellites. In particular, Doppler shifts and Doppler rates are expected to be significantly larger than in conventional MEO GNSS scenarios, requiring appropriate configuration of the acquisition search space and tracking loops.

Although the GNSS and LEO-PNT chains share part of the reception hardware, they are designed to operate independently. The LEO-PNT processing does not rely on GNSS assistance, and the two sources can therefore contribute separate measurements to the hybrid estimator. This separation is important from a resilience perspective, since it allows the terminal to preserve the benefits of LEO-PNT even when GNSS measurements are degraded or unavailable.

The GNSS receiver platform also includes capabilities for processing Galileo Open Service Navigation Message Authentication (OSNMA). However, OSNMA-specific authentication processing is outside the scope of the GERMINAL activities described in this paper and is therefore not further addressed.

2.3 LEO Signals of Opportunity

The LEO-SOP subsystem exploits radio signals transmitted by existing low Earth orbit communication constellations. These signals are not primarily designed for navigation, but they can provide useful observables because of the high dynamics, frequent satellite visibility and diversity of orbital geometries associated with LEO constellations.

In the UHUT, the LEO-SOP chain processes digitized I/Q samples from dedicated RF front ends using a record-and-process workflow. Captures are stored and later processed by constellation-specific software receivers, enabling flexible algorithm development and offline validation.

The main observables extracted from LEO-SOP signals include Doppler frequency, carrier phase, symbol timing or time-delay indicators, and signal-to-noise ratio (SNR). The availability and quality of each observable depend on the structure of the specific signal being processed and on the level of public information available for that constellation.

Four LEO communication constellations have been considered in the GERMINAL terminal: Orbcomm, Iridium NEXT, Globalstar and Starlink ([Kozhaya et al., 2025], [Peña et al., 2024]). These constellations provide a diverse set of frequency bands, access schemes and waveform structures. This diversity is useful for evaluating the potential of LEO-SOP-based positioning under different signal conditions and for assessing their contribution to the overall hybrid PNT solution.

The LEO-SOP measurements are particularly valuable as a complementary source of Doppler and timing information ([Kozhaya et al., 2025]). Even when the signal structure is only partially known, the high relative velocity of LEO satellites can generate strong Doppler signatures that may contribute to multi-epoch positioning, consistency monitoring and navigation robustness in GNSS-challenged environments.

2.4 5G TN and NTN Signals

The 5G subsystem of the UHUT addresses both terrestrial network (TN) and non-terrestrial network (NTN) configurations ([3GPP TS 38.211], [3GPP TS 38.331], [3GPP TS 38.811]). The terminal is designed to operate in 5G Frequency Range 1 (FR1), which is relevant for the targeted TN and NTN implementations considered within the project. The 5G reception chain combines suitable antenna and RF front-end hardware with a configurable software implementation of the 5G New Radio protocol stack.

For 5G TN positioning, the relevant observables are obtained from downlink reference signals, in particular Positioning Reference Signals (PRS) ([3GPP TS 38.211], [Palamà et al., 2023], [Palamà et al., 2024]). By processing the received PRS from multiple gNBs, the terminal can estimate Time of Arrival (TOA) or Time Difference of Arrival (TDOA) measurements. These measurements can then be used for multilateration and also integrated with observables from other positioning sources.

The 5G NTN component extends processing to non-terrestrial links, whose propagation differs from terrestrial cellular operation ([3GPP TS 38.811]). In the current test setup, NTN conditions are emulated using OpenAirInterface (OAI), where propagation delay and Doppler impairments representative of a LEO channel are introduced in a controlled way. The terminal signal processing accounts for larger delays, high Doppler shifts and time-varying Doppler rates caused by LEO motion, enabling evaluation of 5G NTN measurements within the hybrid navigation framework.

The 5G subsystem also preserves the communication functionality of the terminal including data transmission through the 5G TN service. This is important because GERMINAL is not limited to the processing of navigation-specific signals; it also explores the practical integration of communication and positioning capabilities. From the perspective of Joint Communication and Navigation, the 5G chain provides both a communication service and a source of navigation-relevant measurements that can be fused with GNSS, LEO-PNT and LEO-SOP observables.

3 ARCHITECTURE

3.1 High-Level Design

The Unified Hybrid User Terminal (UHUT) is a modular receiver platform where heterogeneous positioning and communication technologies are processed independently while feeding a common navigation framework. This supports operation from single-technology processing to tightly coupled hybrid navigation using all available sources.

At system level, the UHUT is organized around five functional elements. The **signal reception and processing** chains include the GNSS/LEO-PNT, LEO-SOP and 5G subsystems, each with the antennas, RF front ends, SDR components and digital processing required by its signal family. The **Hybrid Navigation** module receives the generated observables and computes standalone or hybrid PNT estimates, while supporting cross-source consistency checks. The **data storage** capability records raw I/Q captures, observables, configurations, logs and navigation outputs, which is particularly relevant for LEO-SOP offline processing and campaign analysis. **Timing and synchronization** are provided by an Oven-Controlled Crystal Oscillator (OCXO) and Ettus OctoClock distribution unit, enabling coherent multi-source fusion. Finally, a **graphical user-interface and control** layer supports configuration, execution, recording and visualization.

The resulting architecture, illustrated in FIGURE 1, provides a flexible experimental platform for evaluating the contribution of GNSS, LEO-PNT, 5G TN, 5G NTN and LEO-SOP signals to resilient PNT.

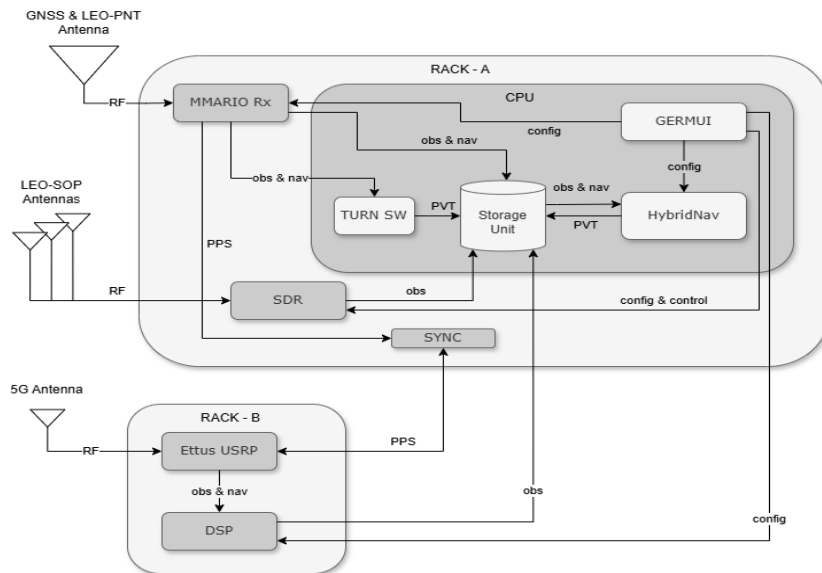


FIGURE 1 Hybrid Terminal Architecture

3.2 GNSS and LEO-PNT Subsystem

The GNSS and LEO-PNT subsystem, see its high-level design in FIGURE 2, provides the satellite-navigation component of the UHUT. It is implemented as a multi-constellation receiver focused on GPS and Galileo Open Service signals, while also supporting GNSS-like LEO-PNT waveforms. The subsystem is based on a Mercury XU1 system-on-module mounted on an ST1 carrier board and connected to a THOR front end developed by GMV. This hardware architecture provides the signal conditioning, down-conversion and digitization functions required for the subsequent baseband processing.

Although GNSS and LEO-PNT share part of the RF reception chain, the processing has been organized to preserve independent acquisition and tracking capabilities. This independence is important because the two signal families exhibit different orbital dynamics and, consequently, different Doppler and tracking requirements. The receiver can therefore process conventional MEO GNSS signals and higher-dynamic LEO-PNT signals without assuming that one source must assist the other.

The signal-processing chain begins with a Fast Acquisition Unit (FAU), which performs the initial search and detection of the incoming signals. Galileo E1C/Quasi-Pilot and GPS L1 C/A are used as primary acquisition targets because of their relevance for robust and efficient signal access ([OS SIS ICD, 2025]). Once acquisition has been achieved, dedicated tracking channels are assigned to the detected signals. These tracking channels use configurable Delay Locked Loops (DLL), Frequency Locked Loops (FLL) and Phase Locked Loops (PLL), allowing the receiver to adapt loop parameters to signal quality and expected dynamics.

The subsystem generates the observables required for navigation processing, including pseudorange, carrier phase, Doppler and carrier-to-noise-density ratio. The nominal output rate is 1 Hz, while higher rates up to 10 Hz can be configured when required by the application or by the test scenario. Continuous monitoring of C/N0 and tracking status provides quality indicators that can be used by the Hybrid Navigation module when assigning measurement weights or detecting degraded observations.

For LEO-PNT operation, the same general receiver principles are applied to GNSS-like spread-spectrum signals transmitted from low Earth orbit. However, the tracking configuration is adapted to the larger Doppler shifts and faster time variation expected from LEO platforms. This enables the terminal to evaluate how dedicated LEO-PNT signals can contribute to accuracy, availability and robustness when combined with GNSS and other positioning sources.

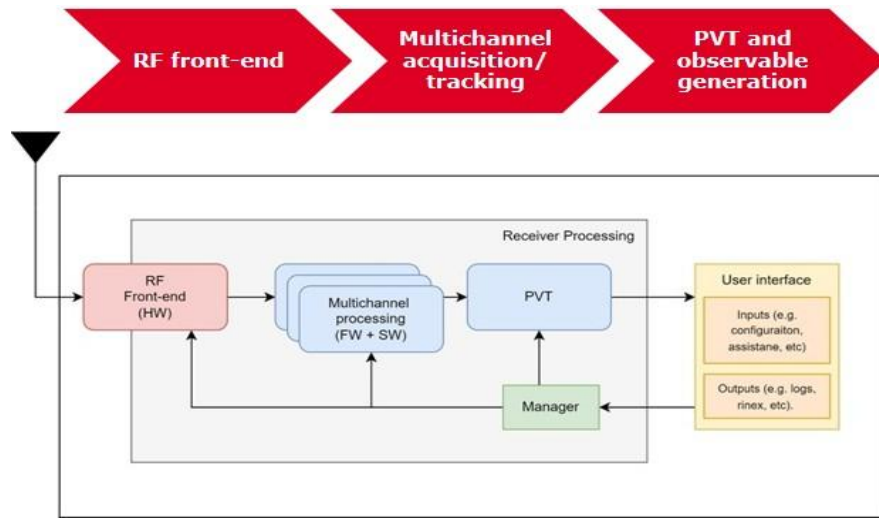


FIGURE 2 GNSS & LEO-PNT High Level Design

3.3 LEO-SOP Subsystem

The LEO-SOP subsystem has been designed to extract navigation-relevant measurements from communication signals transmitted by low Earth orbit constellations. Unlike GNSS or dedicated LEO-PNT signals, these signals are not necessarily optimized for positioning, and their structure may be only partially known. The subsystem therefore adopts a flexible software-defined approach that enables constellation-specific processing strategies. See FIGURE 3.

From a hardware perspective, the LEO-SOP chain includes a multi-constellation RF reception setup with dedicated antennas and commercial off-the-shelf bladeRF software-defined radios. Each targeted constellation is associated with a reception path adapted to its frequency band and signal characteristics. The SDRs are synchronized through the common timing infrastructure of the terminal so that the generated observables can be related to the same time reference used by the rest of the UHUT.

The LEO-SOP software includes two main functions. A recording manager uses public Two-Line Element (TLE) files to predict satellite visibility and schedule captures, which is necessary because LEO visibility windows are short. The LEO-SOP software receiver then processes the stored I/Q samples to extract Doppler frequency, carrier phase, symbol timing or delay-related

quantities, and signal-quality indicators. The resulting measurements are exported in structured files, such as JSON outputs per epoch and visible satellite, for use by the Hybrid Navigation module or offline analysis.

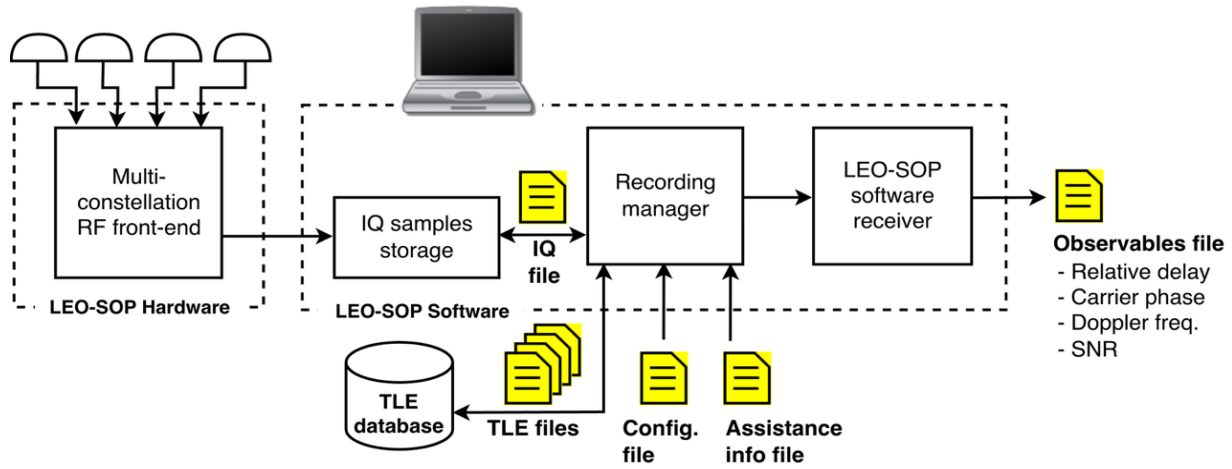


FIGURE 3 LEO-SOP Subsystem High Level Architecture

The processing strategy described in FIGURE 4 is adapted to the characteristics of each constellation. Orbcomm and Iridium follow an acquisition-and-tracking logic based on burst detection, PLL-based Doppler and phase estimation, and DLL-based timing. Orbcomm processing is adapted to its narrower VHF Doppler range and FDMA channel structure. Starlink processing focuses on narrowband beacon components located in guard-band regions, enabling channel detection and Doppler tracking, while timing tracking is not considered in the same way because the underlying modulation information is not fully available ([Kozhaya et al., 2025]). Globalstar processing follows an open-loop approach based on self-correlation to detect the CSS preamble, with Doppler estimation obtained through spectral techniques such as dirty de-chirping ([Peña et al., 2024]).

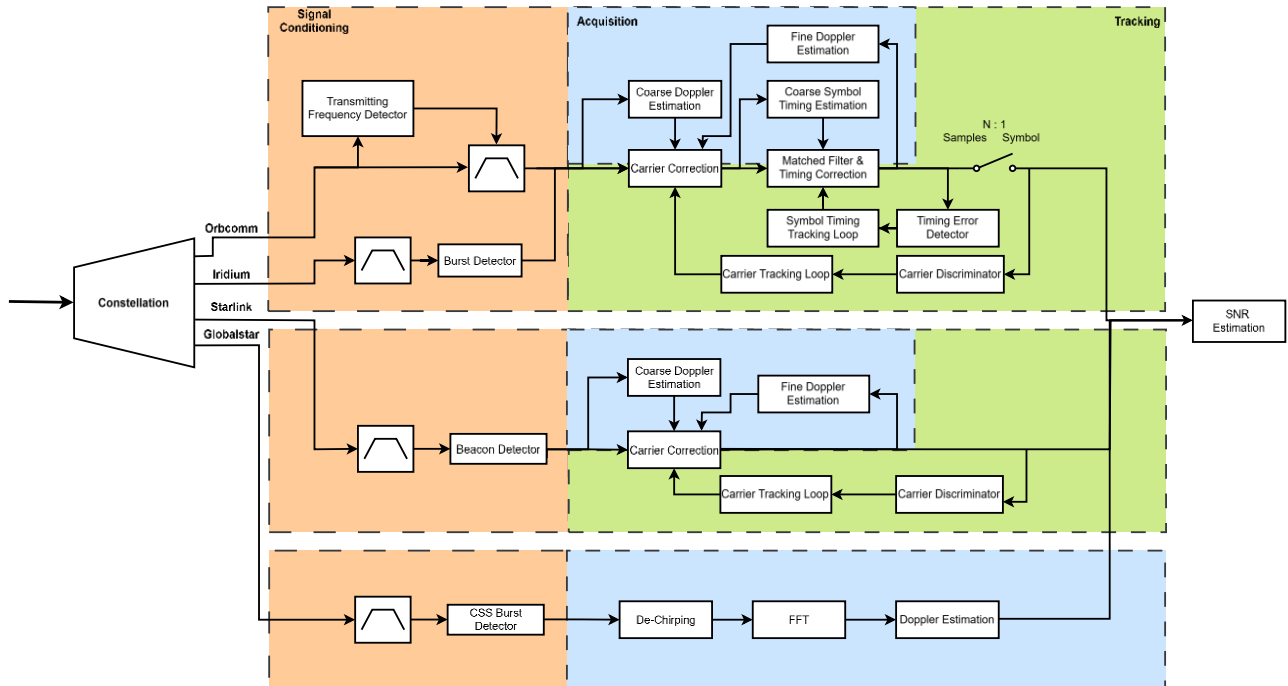


FIGURE 4 LEO-SOP Processing Logic

This diversity of processing methods is a central feature of the LEO-SOP subsystem. It allows the terminal to assess the feasibility of opportunistic navigation observables under different waveform assumptions and to evaluate how these observables can support hybrid PNT, particularly through Doppler and multi-epoch information.

3.4 5G Subsystem

The 5G subsystem provides both communication capability and positioning observables for the UHUT. It has been designed to support terrestrial network operation and non-terrestrial network experiments within the 5G New Radio framework. The architecture combines multi-band antennas, configurable RF front ends, a high-performance processing platform and a modifiable open-source 5G protocol stack.

For terrestrial-network operation, the subsystem uses an Ettus N300 front end, and for NTN-oriented experiments, an Ettus B210 is employed (see FIGURE 5). The baseband and protocol-stack processing are performed using OpenAirInterface, which provides an open-source implementation of 5G NR and allows access to the signal-processing layers required for positioning experimentation ([Palamà et al., 2023], [Palamà et al., 2024]). The software runs on a high-performance workstation based on an AMD Ryzen 9 7900X platform, providing sufficient computational resources for 5G processing, data capture and positioning-related analysis.

In the terrestrial case, positioning is based on downlink Time Difference of Arrival measurements derived from Positioning Reference Signals transmitted by multiple gNBs ([3GPP TS 38.211], [Ghimire et al., 2022]). The receiver processes the raw signal information to estimate relative arrival times, which can then be used for hyperbolic multilateration. The use of TDOA is particularly attractive because common timing offsets can be reduced or eliminated when measurements are formed between pairs of synchronized gNBs.

For the NTN case, the subsystem considers reference signals embedded in the 5G NR downlink, including DMRS associated with the Physical Downlink Shared Channel ([3GPP TS 38.211], [3GPP TS 38.811]). The processing focuses on the extraction of TOA, delay and Doppler-related measurements under LEO-like propagation conditions. Compared with terrestrial links, NTN operation introduces much larger propagation delays, higher Doppler shifts and faster Doppler variations. These effects are therefore explicitly introduced and analysed in the GERMINAL test setup.

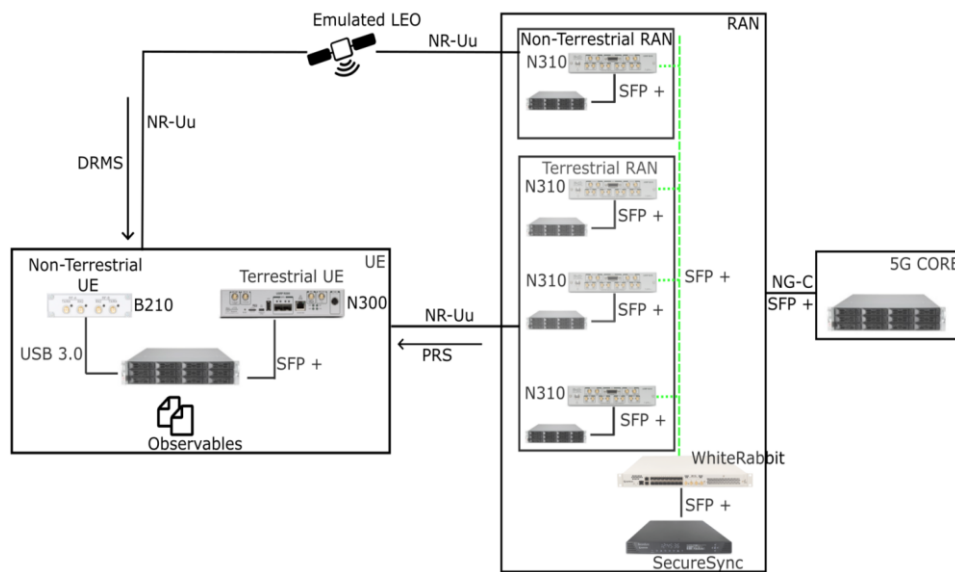


FIGURE 5 5G Subsystem Architecture and NTN emulation

Within the current implementation, NTN conditions are emulated using OpenAirInterface (OAI). The gNB and UE transmit over the air, while propagation delay and Doppler impairments representative of a LEO channel are introduced in a controlled manner. This setup allows validation of the processing chain and measurement-extraction methods before extending the analysis to more general NTN scenarios.

The 5G subsystem is also important from the perspective of Joint Communication and Navigation. In the UHUT, 5G is not treated only as an auxiliary data link; it is also a provider of measurements that can contribute directly to positioning and cross-technology consistency monitoring. The integration of 5G observables with GNSS, LEO-PNT and LEO-SOP measurements is therefore one of the main architectural features of the terminal and provides a basis for future integrity-oriented functions.

4 HYBRID NAVIGATION

4.1 General Approach

The Hybrid Navigation module is responsible for combining the observables generated by the different signal-processing chains into a common PVT solution. While the GNSS/LEO-PNT, 5G and LEO-SOP subsystems perform their own acquisition, tracking and measurement extraction, the final navigation solution is computed in a unified estimation framework that can work in real-time and in offline modes.

The main difficulty is that the available measurements are heterogeneous ([Mata et al., 2020]). GNSS and LEO-PNT provide pseudorange, carrier-phase and Doppler observables. The 5G TN subsystem provides mainly Time Difference of Arrival (TDOA) measurements derived from Positioning Reference Signals transmitted by gNBs. The 5G NTN subsystem contributes with Time of Arrival (TOA), delay and Doppler-related measurements under emulated LEO-like dynamics. Finally, the LEO-SOP subsystem provides Doppler, carrier-phase and timing-related observables extracted from communication signals of opportunity.

To handle this diversity, the navigation engine is measurement-driven rather than source-specific. Each observable is associated with a measurement model, a noise model and quality indicators such as C/No, SNR, tracking status or correlation-peak quality. This allows the same estimator to operate with different combinations of sources, from a single-technology solution to a fully hybridized configuration (individual sources can be activated or deactivated while preserving the same processing architecture).

Two estimation strategies are implemented. A Non-Linear Least Squares (NLS) algorithm is used for batch estimation, initialization and independent solution computation ([Gavin, 2019]). The main hybrid navigation solution is obtained with an Extended Kalman Filter (EKF), which recursively propagates the receiver state and incorporates the available measurements as they arrive, following the tightly coupled EKF approach commonly adopted for GNSS, 5G and LEO-PNT hybrid positioning ([Alghisi et al., 2026], [Jia and Kassas, 2022]).

In parallel with the tightly coupled hybrid solution, standalone or partially hybridized solutions can also be computed for GNSS/LEO-PNT, 5G and LEO-SOP subsets. These solutions are useful for subsystem validation and for checking the consistency of the final hybrid estimate ([Formaggio et al., 2019]).

4.2 State Vector and Measurement Models

The navigation state is expressed in an Earth-Centered Earth-Fixed (ECEF) frame. A generic state vector can be written as:

$$X_k = [x, y, z, v_x, v_y, v_z, b_1, \dots, b_n, d_1, \dots, d_n]^T$$

where:

(x, y, z) : Receiver position in ECEF coordinates.

(v_x, v_y, v_z) : Receiver velocity components in ECEF.

$(b_1 \dots b_n, d_1, \dots, d_n)$: Receiver clock bias and drift per constellation or technology used. The use of several timing states allows the estimator to represent the different synchronization assumptions of GNSS, LEO-PNT, 5G and LEO-SOP measurements

All measurements are represented through a nonlinear observation model:

$$z = h(x, s) + \varepsilon$$

where z is the measurement, $h(\cdot)$ is the predicted observation, s contains the transmitter position, velocity and timing information, and ε represents the measurement error.

For GNSS and LEO-PNT **pseudorange** measurements, the predicted observable follows the standard range model:

$$\hat{\rho} = ||\mathbf{r} - \mathbf{r}_s|| + c b_i + \delta + \varepsilon_\rho$$

where $\mathbf{r}_s$ is the transmitter position, c is the speed of light, b_i is the relevant receiver clock-bias state and δ represents additional corrections or residual propagation terms.

Doppler measurements are related to the line-of-sight relative velocity between transmitter and receiver:

$$f_D = -1/\lambda \cdot \hat{\mathbf{e}}^T (\mathbf{v} - \mathbf{v}_s) + d_i + \varepsilon_D$$

where λ is the carrier wavelength, $\hat{\mathbf{e}}$ is the line-of-sight unit vector and $\mathbf{v}_s$ is the transmitter velocity. This model is applicable to GNSS, LEO-PNT and LEO-SOP Doppler observables, with source-specific adaptations. For LEO, Doppler observables can also be employed in FDOA-like formulations when measurements from different transmitters or epochs are combined ($\mathbf{f}_{Dab} = -1/\lambda \cdot (\hat{\mathbf{e}}_b^T (\mathbf{v} - \mathbf{v}_b) - \hat{\mathbf{e}}_a^T (\mathbf{v} - \mathbf{v}_a)) + \varepsilon_{FDOA}$).

For 5G TN positioning, **TDOA** measurements are modelled as the difference between ranges to two gNBs:

$$\hat{r}_{ab} = (||\mathbf{r} - \mathbf{r}_b|| - ||\mathbf{r} - \mathbf{r}_a||) / c + \Delta t_{ab} + \varepsilon_{TDOA}$$

where $\mathbf{r}_a$ and $\mathbf{r}_b$ are the gNB positions and Δt_{ab} represents residual synchronization or calibration errors. For 5G NTN, TOA and Doppler measurements are modelled in a similar way to satellite-based observables, while accounting for the larger delays and Doppler shifts associated with LEO dynamics.

All the positioning signal sources (i.e. 5G gNBs, LEO-SOP satellites, etc) must have known positions in the same reference system, ECEF in this case. The measurement innovation function is then defined for every different positioning scheme. In a general sense, the innovation is defined as the difference between the actual and the predicted measurement:

$$\Delta \mathbf{m} = \mathbf{m} - \mathbf{f}(\mathbf{r}_r, \mathbf{v}_r, \mathbf{r}_1^b \dots \mathbf{r}_n^b, \mathbf{v}_1^b \dots \mathbf{v}_n^b, \mathbf{b}_1 \dots \mathbf{b}_n, \mathbf{d}_1, \dots, \mathbf{d}_n)$$

where:

$\mathbf{m}$: Vector containing all measurements

$\mathbf{r}_r, \mathbf{v}_r$: Vectors containing all components of the position and velocity of the receiver

$\mathbf{r}_1^b \dots \mathbf{r}_n^b, \mathbf{v}_1^b \dots \mathbf{v}_n^b$: Vectors containing all components of the position and velocity of all transmitting sources

$(\mathbf{b}_1 \dots \mathbf{b}_n, \mathbf{d}_1, \dots, \mathbf{d}_n)$: Receiver clock bias and drift per constellation or technology used.

In the case of tight coupling schemes, all the measurement innovation functions can be inserted into a single vector. The Jacobian of this vector is then computed and used to perform the EKF state update. Weights are assigned to the measurements through a weighting matrix $\mathbf{W}$, derived from source-specific uncertainty models and signal-quality indicators such as SNR. For the EKF, the initial covariance matrix is obtained from a priori knowledge and uncertainty assumptions.

4.3 NLS and EKF Estimation

The NLS solution is obtained by minimizing the weighted residuals between the measured and predicted observables ([Gavin, 2019]):

$$\mathbf{J}(\mathbf{x}) = \mathbf{v}^T \mathbf{W} \mathbf{v}$$

where $\mathbf{v} = \mathbf{z} - \mathbf{h}(\mathbf{x})$ is the residual vector and $\mathbf{W}$ is the weighting matrix. The weights are derived from the expected accuracy of each measurement source and from signal-quality indicators. The NLS estimator is mainly used for initialization, benchmarking and standalone solution generation.

The EKF is the main estimator used for hybrid navigation ([Alghisi et al., 2026], [Jia and Kassas, 2022]). The prediction step propagates the state and covariance according to the selected motion and clock models. When measurements are available, the innovation is computed as:

$$\mathbf{v}_k = \mathbf{z}_k - \mathbf{h}(\hat{\mathbf{x}}_k)$$

and the update is performed using the corresponding measurement Jacobian and covariance. The measurement covariance matrix is built from source-specific uncertainty models, allowing GNSS, LEO-PNT, 5G and LEO-SOP observables to be fused in a statistically consistent way.

A tightly coupled formulation is used so that raw or partially processed measurements can contribute to the solution even when a standalone position fix cannot be computed from one subsystem alone. This is particularly relevant in degraded environments, where partial 5G or LEO-SOP information may still help constrain the hybrid solution.

4.4 Consistency Monitoring

The availability of multiple independent positioning sources also enables consistency checks between technologies. The Hybrid Navigation module can compare standalone or partially hybridized solutions against the full EKF solution and can monitor the residuals of individual measurements.

Large discrepancies between independent solutions, or persistent residuals inconsistent with the assumed measurement covariance, may indicate multipath, synchronization errors, degraded tracking, incorrect transmitter information or other anomalies. This capability is intended to improve the trustworthiness of the final hybrid PNT solution. Therefore, the Hybrid Navigation module is not only used to improve accuracy through measurement fusion, but also to exploit the redundancy and diversity of the different signal sources for robustness and consistency assessment.

5 TESTING

5.1 Test plan

The UHUT validation is being carried out progressively, starting from the verification of the individual signal-processing chains and continuing with the assessment of the complete integrated system. The first part of the testing activity focuses on confirming that each subsystem is correctly integrated at hardware and software level and that it is able to generate the observables required by the Hybrid Navigation module.

The tests reported in the following subsections cover the GNSS and LEO-PNT processing chain, the LEO-SOP observable-extraction chain, and the 5G TN/NTN processing chain. These results constitute the basis for the progressive hybrid-navigation validation, in which measurement sources are processed jointly and the performance of the hybrid navigation solution is assessed. The system-level tests are designed to evaluate different combinations of signal sources, from standalone configurations to initial hybrid configurations. The objective is to analyse the behaviour of the terminal in representative conditions and to quantify the added value of combining GNSS, LEO-PNT, 5G TN, emulated 5G NTN and LEO-SOP measurements within the same navigation framework.

The tests are organized as subsystem validation first, and then as integrated hybrid-navigation assessment. To make the testing logic explicit, the experiments are organized according to the role that each signal family plays in the terminal. The GNSS/LEO-PNT tests verify satellite-signal acquisition, tracking and observable generation. The LEO-SOP tests assess the availability and Doppler/timing observability of communication signals of opportunity. The 5G TN tests evaluate PRS-based TDOA positioning, while the emulated 5G NTN tests verify the ability of the processing chain to detect controlled delay and Doppler impairments representative of LEO propagation. Finally, the integrated tests combine measurements from different sources to evaluate the feasibility and potential benefit of the hybridized navigation solution with respect to standalone configurations.

TABLE 1 Unified Hybrid User Terminal Tests

Test block	Main measurements	Purpose
GNSS & LEO-PNT	Pseudorange, carrier phase, Doppler, C/N_0	Verify acquisition/tracking and satellite-navigation observables
LEO-SOP	Doppler, timing-related observables, SNR	Verify visibility, geometry diversity and Doppler observability from LEO-SOP
5G TN	PRS-derived TOA/TDOA	Verify terrestrial 5G positioning using multiple gNBs
Emulated 5G NTN	Delay and Doppler under LEO-like conditions	Verify processing response to controlled NTN impairments
Initial Integrated Hybrid Navigation	GNSS + 5G TN measurements	Assess HPE performance of the hybridized solution
Full Integrated Hybrid Navigation	GNSS + LEO-PNT + LEO-SOP + 5G TN + 5G NTN measurements	Assess HPE performance of the hybridized solution. Target configuration for future extended validation beyond the results reported here.

5.2 Results

5.2.1 GNSS and LEO-PNT

The GNSS and LEO-PNT tests are intended to verify that the reception and signal-processing chains operate correctly both independently and in combination. In particular, the objective is to confirm that the RF front end, acquisition, tracking and measurement-generation functions are able to provide valid observables for subsequent PVT computation.

For both signal families, the terminal is configured in a suitable test environment and processes the received or simulated signals to obtain the measurements required by the navigation algorithms. After each test, the generated outputs are analysed to verify compliance with the applicable requirements.

The GERMINAL project defines requirements covering several aspects of GNSS and LEO-PNT operation, including signal reception, satellite visibility, support to Galileo E1 Quasi-Pilot processing and the quality of the observables generated after acquisition and tracking ([OS SIS ICD, 2025]).

During the tests performed so far, measurements have been successfully obtained from simulated LEO satellites, identified as "L0X", using the simulated "leol1" signal. This has enabled the extraction of the parameters required for PVT processing, including pseudorange in meters, Doppler in hertz and carrier-phase measurements in meters.

For GNSS, GPS and Galileo satellites and their corresponding signals are correctly detected and processed. The receiver is therefore able to generate the observables and navigation data required to support the PVT solution.

The following figures show representative post-processing results obtained from the GNSS and LEO-PNT tests:

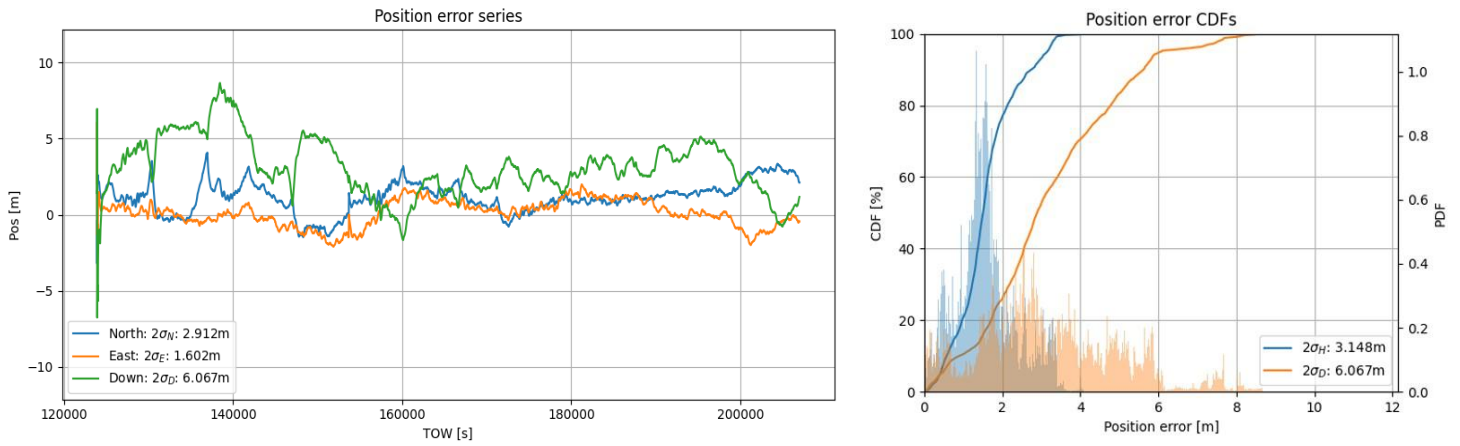


FIGURE 6 GNSS Position Error. Left: Time evolution (North, East, Down); Right: CDF (Horizontal, 3D)

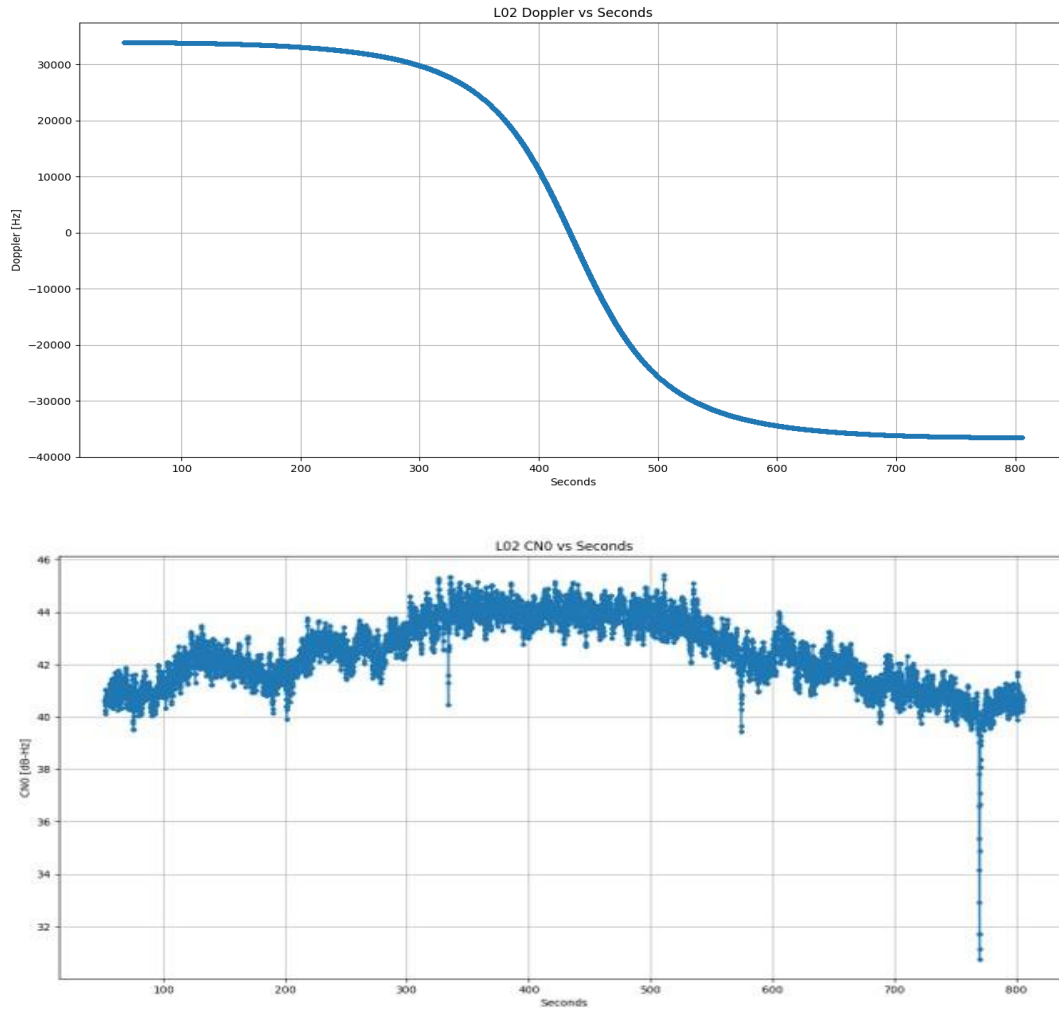


FIGURE 7 Doppler and C/N0 [dB-Hz] measurements of simulated LEO satellite L02

FIGURE 6 shows the GNSS position error estimated by a NLS expressed in the North, East and Down components and the horizontal and 3D error Cumulative Distribution Functions (CDFs). The results show horizontal meter-level positioning performance in this test configuration, although acceptability of the observed error levels is application-dependent. FIGURE 7 presents the Doppler and C/N0 measurements obtained from one of the simulated LEO satellites, L02. The curve illustrates the complete evolution of the measurements during the satellite pass, from initial detection through its closest approach and up to

the end of visibility. The Doppler profile verifies that the receiver can follow the high-dynamic frequency variation expected from a LEO transmitter, while the C/N_0 evolution provides a signal-quality indicator during the same pass.

5.2.2 LEO-SOP

The LEO-SOP tests analyse real measurements obtained from Orbcomm satellites in order to characterize the observables that can be extracted from communication signals of opportunity. The objective is to assess the suitability of these measurements for their later use in the hybrid navigation process.

FIGURE 8 shows the skyplot of the tracked Orbcomm satellites. The figure illustrates the dense and repetitive coverage provided by the constellation over the visible hemisphere. Due to the low Earth orbit of the satellites, the passes evolve rapidly across the sky, providing frequent changes in geometry. This behaviour is beneficial for positioning, especially when measurements are accumulated over several epochs. In this context, the figure is intended to show the availability and angular diversity of LEO-SOP observables that may support multi-epoch estimation.

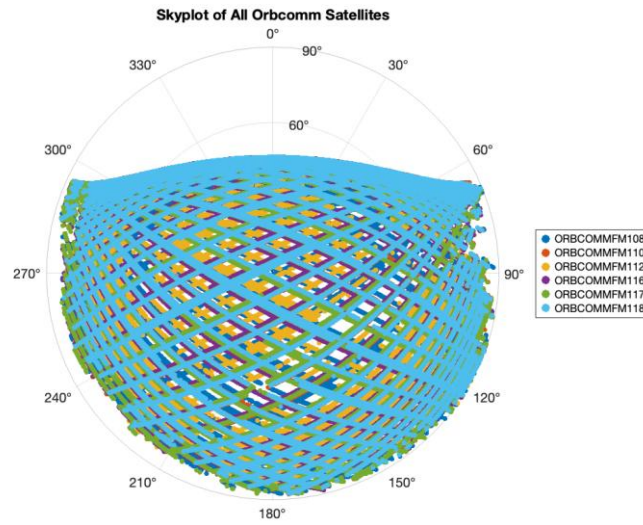


FIGURE 8 Skyplot of tracked Orbcomm Satellites

FIGURE 9 shows the measured Doppler shifts obtained from Orbcomm satellites over time. The measurements span approximately ± 3 kHz, which is consistent with the high relative velocity associated with LEO satellites. The Doppler arcs corresponding to individual passes are clearly visible, indicating that the receiver is able to track the signal evolution in a stable and continuous manner. The observed Doppler continuity is important because Doppler-based or FDOA-like positioning benefits from persistent measurements collected over time as the line-of-sight geometry changes.

The contribution of LEO-SOP to navigation resilience comes from measurement diversity, independent communication infrastructure, frequent LEO visibility and error sources that differ from those affecting GNSS. In this sense, the density and continuity of LEO-SOP Doppler observations can provide complementary constraints when GNSS availability or quality is degraded, especially in multi-epoch hybrid estimation.

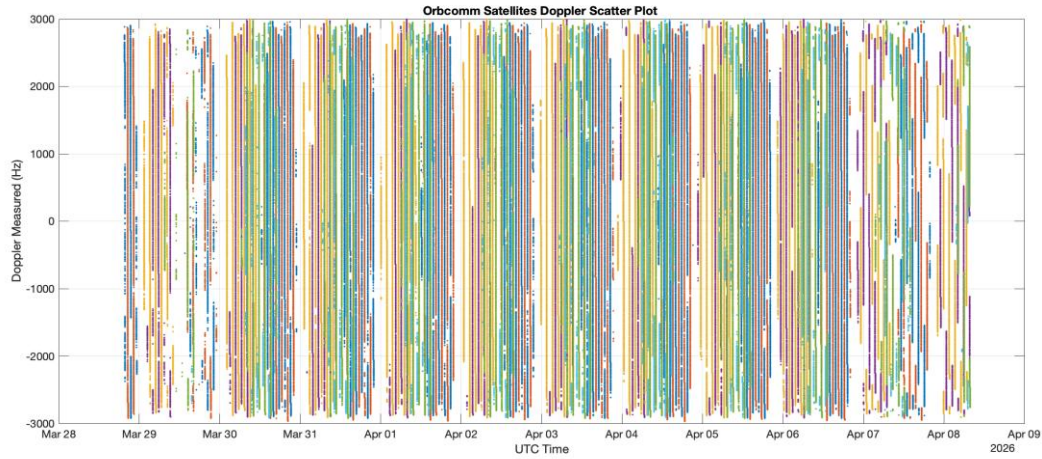


FIGURE 9 Time series of measured Doppler shifts from Orbcmm satellites

5.2.3 5G TN and NTN

The 5G validation and experimentation activities include terrestrial-network positioning tests and NTN-oriented signal-processing tests. For the terrestrial case, initial experiments were performed using three gNBs transmitting PRS signals with a bandwidth of 100 MHz. The PRS transmission periodicity was set to 10 ms, and the acquisition interval lasted 60 s. The objective of this test is to verify the complete 5G TN positioning chain, from PRS reception and TOA/TDOA estimation to position computation using the known gNB geometry.

The processing identified a global/common offset at TOA level. However, this offset does not directly affect the position solution because the positioning algorithm relies on TDOA measurements. Residual differences in the estimated arrival-time dispersion can still affect the final position estimate and are therefore relevant for calibration and measurement weighting.

The position estimates of the initial TN test were obtained using a Non-Linear Least Squares (NLS) approach with Levenberg-Marquardt optimization. FIGURE 10 shows the spatial distribution of the resulting position estimates together with the true UE position and the estimated peak. The heatmap represents the normalized horizontal estimate density. The results show a very low standard deviation, but the separation between the peak estimate and the true UE position is therefore an indication of residual bias, geometry effects or calibration errors in the TDOA measurements, and it motivates the subsequent use of calibration, weighting and hybridization with other sources.

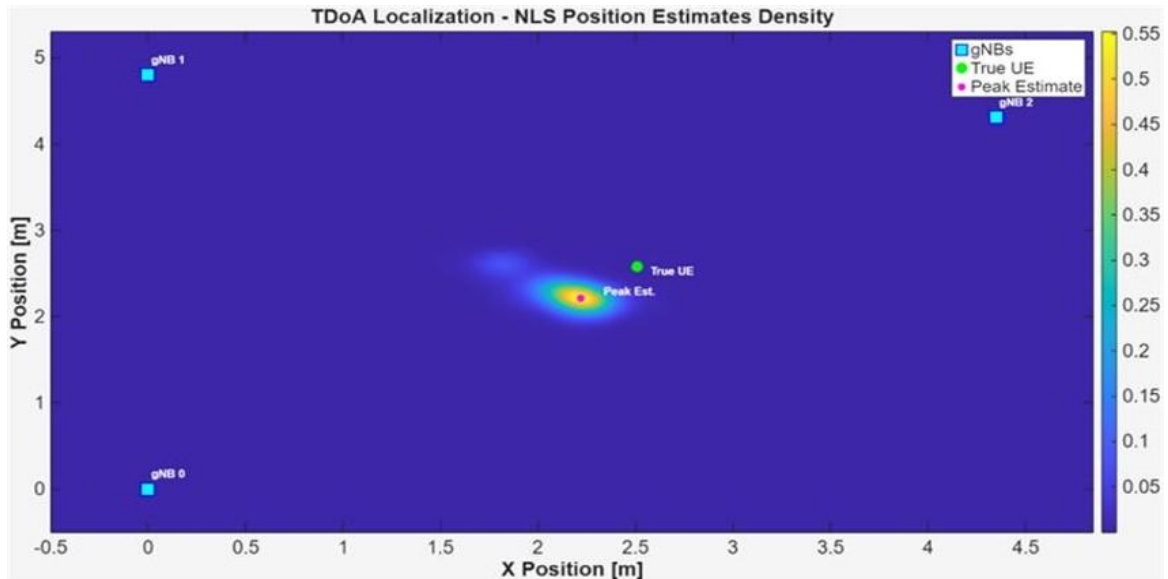


FIGURE 10 5G TN Position Estimation (color scale: normalized horizontal estimate density)

Additional tests have been carried out for NTN-like conditions ([3GPP TS 38.811]). In these tests, propagation delay and Doppler impairments were artificially introduced in order to emulate the behaviour of a LEO channel. Specifically, a delay of 5 ms and

a Doppler shift of 20 kHz were applied to a 5 MHz NR waveform with 15 kHz subcarrier spacing. The purpose of this experiment is not to demonstrate standalone NTN positioning, but to verify that the 5G processing chain can detect controlled delay and Doppler effects representative of LEO-like propagation.

The cross-correlation results in FIGURE 11 show that the detected peak shifts match the expected displacement in the sample domain, confirming that the processing chain is able to capture the delay and Doppler effects introduced in the emulated NTN scenario. The presence of the expected correlation peaks demonstrates that the receiver can identify the imposed timing displacement. This provides a first validation step for using NTN-like delay and Doppler observables within the hybrid navigation framework.

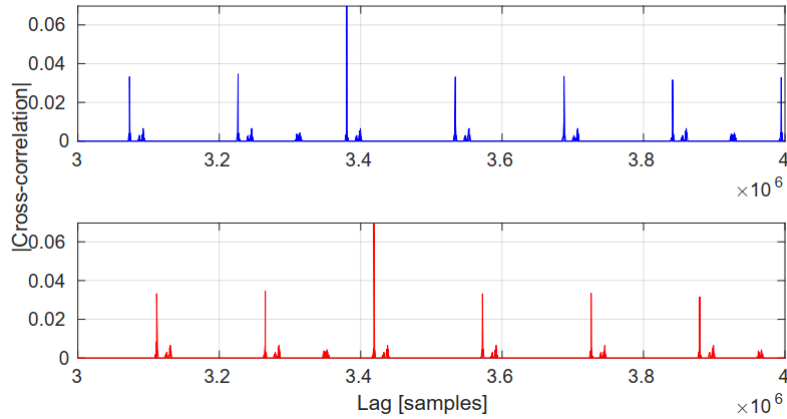


FIGURE 11 Magnitude of the cross-correlation between the transmitted 5G NR reference and the recorded IQ samples captured from the OAI baseband chain

5.2.4 Integrated Hybrid Navigation Results

Once the individual subsystems have been validated, the next validation step consists of processing and combining measurements from different sources within the Hybrid Navigation module. This stage evaluates the UHUT as an integrated multi-source PNT terminal. In the present paper, the integrated result is limited to a GNSS + 5G TN TDOA NLS solution, while the architecture remains prepared to incorporate LEO-PNT, emulated 5G NTN and LEO-SOP observables in the same estimation framework.

The integrated tests are intended to compare the standalone solutions obtained from the individual technologies with hybrid solutions generated from combined measurement sets using NLS and EKF. However, the integrated result reported in this paper is restricted to an NLS-based GNSS + 5G TN TDOA configuration. The assessment considers positioning accuracy and consistency between measurement sources. In future extended validation, additional 5G NTN and LEO-derived observables will improve the resilience of the solution with respect to GNSS-only positioning.

The expected outcome of the integrated tests is a more accurate and more resilient navigation solution, especially in conditions where one or more individual signal sources are degraded. The first integrated hybrid test focuses on the combination of GNSS + 5G TN measurements. TABLE 2 provides the horizontal positioning error (HPE) statistics obtained with an NLS solution using combined GNSS and 5G TN TDOA measurements, and FIGURE 12 presents the corresponding CDF. This configuration illustrates the first level of hybridization between the satellite-navigation subsystem and the terrestrial 5G positioning subsystem, and shows the improvement achieved with respect to the standalone solutions. The relevant obtained indicators are the median error (~36 cm), the 95th percentile error (less than 73 cm) and the behaviour of the upper tail of the distribution (all errors below 92 cm). These values indicate sub-meter horizontal performance for the tested combined configuration, so when comparing with standalone GNSS solution (see FIGURE 6) we see that the combined solution reduces the horizontal-error percentiles and suppresses large-error events. The results provided in TABLE 2 and FIGURE 12 demonstrate the feasibility of combining satellite and terrestrial measurements within the same least-squares framework.

TABLE 2 GNSS + 5G TN NLS HPE performance results

Combined Measurements	Estimation Algorithm	HPE Statistics (m)					
		Mean	Median	Std	RMS	95%	Max
GNSS+5G	NLS	0.391	0.363	0.178	0.429	0.729	0.917

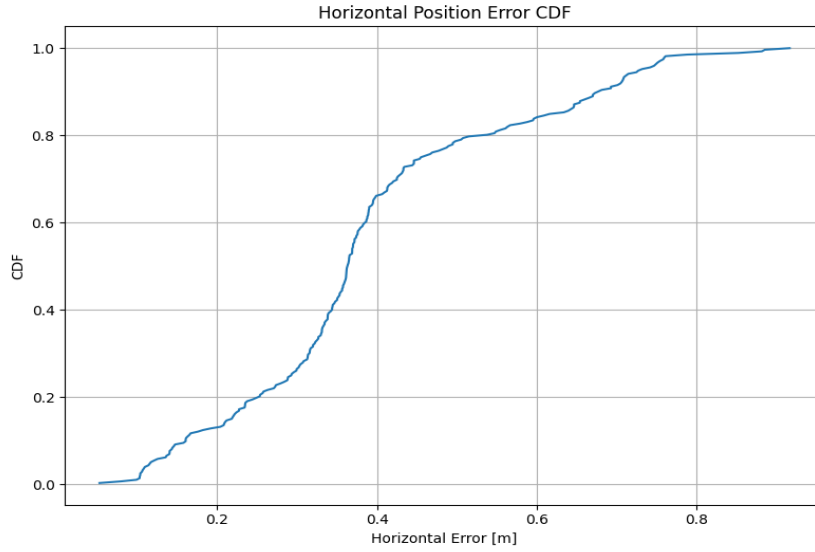


FIGURE 12 CDF of horizontal positioning error for the Least Squares GNSS + 5G TN TDOA solution

5.3 Discussion of Experimental Results

The results presented in Section 5 should be interpreted as a progressive validation of the UHUT processing chain. FIGURE 6 and FIGURE 7 validate the ability of the GNSS/LEO-PNT subsystem to generate satellite-navigation observables, including position-domain GNSS results and high-dynamic LEO-PNT Doppler/ C/N_0 measurements. FIGURE 8 and FIGURE 9 validate the availability and Doppler observability of real LEO-SOP measurements, which are relevant for multi-epoch estimation and cross-source consistency rather than for standalone anti-jam robustness. FIGURE 10 and FIGURE 11 validate the 5G processing chain, first through terrestrial PRS/TDOA positioning and then through controlled emulation of NTN-like delay and Doppler effects. Finally, FIGURE 12 provides an initial integrated result showing how GNSS and 5G TN TDOA measurements can be combined in a common LS/NLS positioning framework.

These results support the main architectural claim of the paper: the UHUT can generate heterogeneous observables from independent terrestrial and space-based sources and make them available to the Hybrid Navigation module.

6 CONCLUSIONS

This paper has presented the design, implementation and validation of the GERMINAL Unified Hybrid User Terminal, a multi-source PNT platform integrating GNSS, LEO-PNT, 5G terrestrial and non-terrestrial positioning signals, and LEO Signals of Opportunity within a common navigation architecture. The terminal has been conceived to address the limitations of conventional single-source navigation by exploiting the complementarity of terrestrial and space-based infrastructures, different signal structures, diverse frequency bands and independent measurement geometries.

The results presented in the paper demonstrate that the individual processing chains are able to generate the observables required by the Hybrid Navigation module. The GNSS and LEO-PNT subsystem provides pseudorange, carrier-phase, Doppler and signal-quality measurements suitable for PVT computation. The LEO-SOP processing chain shows that useful Doppler and timing-related observables can be extracted from operational communication constellations, even though these signals were not originally designed for navigation. The 5G subsystem confirms the feasibility of deriving terrestrial TDOA measurements from PRS processing and of analysing TOA, delay and Doppler effects under NTN-like propagation conditions.

Beyond the validation of the individual subsystems, the initial integrated tests support the feasibility of the GERMINAL approach: the combination of heterogeneous positioning sources within a single estimation framework can improve the resilience and quality of the navigation solution with respect to standalone configurations. The hybrid solution is designed to benefit from the maturity and global availability of GNSS, the favourable dynamics and geometry of LEO-PNT, the terrestrial infrastructure density of 5G TN, the additional delay and Doppler information provided by emulated 5G NTN, and the independent Doppler-rich observables obtained from LEO-SOP. The first GNSS + 5G TN result illustrates this potential. The Hybrid Terminal is designed to be able to achieve good positioning accuracy while improving solution availability and continuity in scenarios where one or more individual sources are degraded.

The implemented Hybrid Navigation architecture also demonstrates the importance of treating the terminal as a time-coherent multi-technology receiver rather than as a simple collection of independent subsystems. The common timing infrastructure, the modular observable interfaces, and the defined EKF-based fusion strategy allow measurements with different physical meanings and error characteristics to contribute consistently to the final PVT solution. This capability is particularly relevant in urban, obstructed or GNSS-challenged environments, where partial information from 5G or LEO-derived sources can still provide valuable constraints on the navigation state. The experimental integrated result reported here demonstrates this concept at NLS level for GNSS + 5G TN measurements; full EKF-based all-source validation remains a future extension.

Another important conclusion is that the implemented architecture provides benefits beyond positioning accuracy. The availability of independent measurement sources enables cross-technology consistency checks, residual monitoring and comparison between standalone and hybrid solutions. These capabilities are essential for future resilient PNT systems, where trustworthiness, consistency monitoring, fault detection and resilience against interference or spoofing are as important as nominal positioning performance. In the current implementation, these functions should be understood as consistency-monitoring mechanisms rather than as a formal integrity layer; the latter remains part of the future work.

The work also confirms the relevance of the Joint Communication and Navigation paradigm. In the GERMINAL terminal, 5G and LEO communication signals are not limited to data-transfer functions but are also exploited as sources of navigation information. This dual use of communication infrastructures opens a practical path toward future receivers capable of combining dedicated navigation signals, standardized communication waveforms and opportunistic transmissions within the same PNT engine.

Overall, the GERMINAL UHUT is a step toward next-generation hybrid navigation terminals. The results show that the terminal can process GNSS, LEO-PNT, 5G TN, emulated 5G NTN and LEO-SOP observables and that an initial GNSS + 5G TN combination can provide sub-meter horizontal positioning in the tested configuration. The broader all-source architecture is expected to support accurate multi-source positioning and increase resilience against signal degradation, limited visibility and infrastructure-dependent failures, with direct relevance for road, rail, maritime, UAV and location-based applications. Here, resilience refers to the use of independent infrastructures, complementary observables and cross-source consistency checks, rather than to anti-jam robustness of any individual signal.

Future work will extend validation to additional environments, complete the EKF-based all-source hybrid assessment, refine measurement weighting, enhance consistency monitoring, include an integrity positioning layer, optimize the real-time Hybrid Navigation implementation, and improve the platform cost-effectiveness. It will also address new LEO-PNT and 5G/6G positioning capabilities and the progressive integration of more advanced signals of opportunity, further strengthening hybrid terrestrial and space-based PNT.

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