Unified Navigation and Communication Hybrid Terminal

Enrique Domínguez, *GMV*
Francisco José Mata, *GMV*
Freddy Albert Pinto, *GMV*
Marcelo Meneses, *GMV*
David García, *GMV*
Javier Fidalgo, *GMV*
Domenico Giustiniano, IMDEA
Giuseppe Santaromita, IMDEA
Timothy Otim, IMDEA
Francesco Pigato, IMDEA
José A. López-Salcedo, UAB
Gonzalo Seco-Granados, UAB
Fran Fabra, UAB
Antoni Reus, UAB
Marc Fernández, UAB

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 algorithms, integrity algorithms, localization systems for autonomous driving vehicles and 5G positioning.

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.

Freddy A. Pinto-Benel is 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.

Marcelo Meneses Marín obtained a B.Sc in Aerospace Engineering from the Politechnic 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.

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.

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.

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.

José 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.

Gonzalo Seco-Granados received the Ph.D. degree in telecommunication engineering from 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 UAB and Head of the Signal Processing for Communications and Navigation (SPCOMNAV) research group.

Fran Fabra received both the M.Sc. degree in telecommunication engineering and the M.Sc. degree in information and communication technologies in 2007, and the Ph.D. degree in 2013, all of them from UPC, Spain. In November 2019, he joined the SPCOMNAV group at UAB, Spain, where he became an Associate Professor in May 2024. His research interests lie in the field of statistical GNSS signal processing, LEO-PNT, the use of communication signals (LTE, 5G and LoRa) for positioning and sensing applications, SDR-based prototyping, and antenna array analysis.

Antoni Reus holds a double B.Sc. degree in computer engineering and telecommunication systems engineering from UAB, obtained in 2024. He is currently pursuing an M.Sc. degree in telecommunication engineering at the same university. Since 2023, he has been working as a Research Support Technician at the SPCOMNAV group at UAB, with a focus on processing LEO satellite signals of opportunity for navigation purposes.

Marc Fernández-Temprado graduated with a B.Sc. degree in telecommunication engineering from UPC in 2025. Since 2024, he has been part of the SPCOMNAV group at UAB, where he has been involved in the investigation of LEO-based satellite positioning techniques, and the development of an SDR-based testbed for LEO signal acquisition and tracking.

ABSTRACT

Emerging Positioning, Navigation and Timing (PNT) sources such as 5G Terrestrial Networks (TN), Non-Terrestrial Networks (NTN) and LEO-PNT will soon be accessible to everyone. When combined with existing sources like GNSS and LEO signals of opportunity (SOP), they will boost navigation performance, robustness, and reliability, while also offering communication capabilities. This integration will ensure continuous, ubiquitous, and reliable navigation, paving the way for numerous innovative applications and services. To take full advantage of these new capabilities, a hybrid receiver, combining all these PNT sources to provide enhanced and reliable navigation, is under development. The purpose of this paper is to report the activities for the specification, design, development and test plan of a Unified Navigation and Communications Hybrid Terminal. This multi-source and powerful platform aim at implementing and demonstrating advanced navigation solutions that leverage a combination of satellite and terrestrial signal sources. By integrating GNSS (including Galileo E1 Quasi-Pilot), LEO-PNT signals, 5G TN and -NTN - signals, and LEO SOP from various satellite constellations, the Hybrid Terminal shall enable precise, reliable navigation in a variety of challenging and harsh environments and provide increased robustness.

1 INTRODUCTION

The convergence of emerging PNT sources—such as 5G TN, NTN, and LEO-PNT—with existing systems like GNSS and LEO SOP, introduces a transformative leap in navigation, significantly enhancing accuracy, robustness, and service continuity, while additionally enabling communication functionalities, ensuring continuous, ubiquitous, and reliable navigation, which paves the way for numerous innovative applications and services. A hybrid receiver that combines all these PNT sources is being developed. The purpose of this paper is to present the specification, design, development and test plan of the Unified Navigation and Communications Hybrid Terminal. By integrating GNSS (including Galileo E1 Quasi-Pilot), LEO-PNT signals, 5G TN and NTN signals, and LEO SOP from various satellite constellations, the Hybrid Terminal shall enable precise, reliable navigation in a variety of challenging and harsh environments and provide increased robustness.

The work is performed in the frame of the GERMINAL (Connectivity: Enabling next generation NAV/COM Hybrid Terminal) project, co-funded by the European Union and contracted by EUSPA (EU Agency for the Space Programme) as part of its Fundamental Elements Grants program and aimed at studying the combination of navigation and communication signals such as GNSS, 5G, LEO-PNT and LEO-SOP. The project's consortium is led by GMV with IMDEA Networks (Instituto Madrileño de Estudios Avanzados) and UAB (Universitat Autònoma de Barcelona) as partners.

Several applications within different market domains as Maritime, Rail, Road, Unmanned Aerial Vehicles (UAVs) or LBS, especially the ones operating in challenging environments, could benefit from the improved PNT performances and additional communication capabilities, for example, to share the computed position through the 5G wireless connection. In particular, the processing of multiple signals could improve the accuracy, availability and continuity of the PNT solution, especially relevant in environments such as urban. In addition, the processing of different signals allows to improve the robustness against different threats such as jamming, spoofing, constellation wide failure, etc.

Overall, the lifecycle of the GERMINAL Hybrid Terminal includes the following:

- Identification of PNT Domains and Target Applications that could benefit from a Unified Navigation and Communications Hybrid Terminal and analysis of their User Needs,
- Specification of the Hybrid Terminal,
- Design of the Hybrid Terminal,
- Development of the Hybrid Terminal,
- Testing of the Hybrid Terminal,
- Business and Dissemination activities.

As shown in **FIGURE *1***, the high-level architecture of the Unified Hybrid User Testbench includes a 5G testbench, to generate TN and NTN signals, and the Unified Hybrid User Terminal, which includes several units to process the different signals including the:

- Multi-constellation GNSS: dual-frequency GPS and Galileo, including the innovative Galileo Quasi-Pilot signal.
- 5G TN and NTN, using measurements such as Time Difference of Arrival (TDOA)
- LEO-PNT, with a similar approach to that of GNSS signals.
- LEO-SOP, with acquisition and tracking stages.

A Testing campaign will be conducted to validate the main functionalities of the Hybrid Terminal and assess the performances achievable. The Test Plan is briefly explained in this paper while the experimentation results will be provided in a future publication. The paper starts with a brief description of the Target Applications for the Hybrid Terminal and their User Needs as well as a discussion of the a-priori benefits that the Hybrid Terminal could provide for the PNT market.

Then, the main features of the specification of the Hybrid Terminal are presented, including performance targets for both standalone and combined PNT solutions. Then, the high-level Architecture of the Hybrid Terminal is described as well as key algorithmic aspects. Finally, the Test Plan for the verification of the main functionalities and the assessment of the performances achievable is presented, together with a description of the Unified Hybrid User Testbench as well as some preliminary results.

2 TARGET APPLICATIONS AND BENEFITS OF THE HYBRID TERMINAL

This Section starts by an a-priori identification of the benefits that the Unified Hybrid Terminal could provide and based on this, the target market domains and applications are identified.

2.1 Benefits of the Hybrid Terminal

The Hybrid Terminal developed in GERMINAL project addresses key limitations of standalone GNSS receivers by integrating additional PNT sources such as 5G, LEO-PNT, and LEO-SOP. This multi-source approach enables improved positioning accuracy, availability, and continuity in environments where GNSS signals are degraded or unavailable, such as urban canyons, indoors, or polar regions.

First, a set of improvements in terms of PNT performance can be identified, mainly due to the processing of additional signals for navigation purposes such as LEO-PNT, LEO-SOP and 5G:

- Improvement of Availability, Continuity and Accuracy performances, especially relevant for applications operating in harsh environments such as Urban or even Indoor, thanks to the availability of additional signals (LEO, 5G) on top of the classical GNSS signals. Also, the typical limited performances of GNSS in polar areas could be improved.
- The use of additional signals - 5G and LEO - could improve the Integrity of the PNT solution with respect to GNSS standalone, as new data sources become available. Different approaches could be adopted, from the simplest ones as performing cross-checks between PNT solutions computed with different signals to detect and exclude faulty signals, to the most sophisticated ones as defining novel integrity concepts for PNT solutions combining GNSS with LEO and 5G. The Hybrid Terminal could be evolved in the future to include advanced integrity capabilities.
- Time To First Fix (TTFF) improvement: fast signal acquisition achievable by the processing of Galileo Quasi-Pilot (QP) signals would improve the TTFF performance.

The Hybrid Terminal will provide also benefits in terms of additional robustness and communication capabilities:

- Improved robustness to Jamming and Spoofing: The use of additional 5G and LEO signals will help improve the robustness of the PNT solution against Jamming and Spoofing as these new additional signals could be used to conduct checks for detection and fall-back modes for reversion.

- Improved robustness to a constellation wide failure and back-up to GNSS: the additional information sources allow to perform cross-checks and provide fall-back modes in case of a complete constellation failure.
- Communication capabilities will provide added value to these Hybrid Terminals by enabling many different applications, such as, critical communications (i.e. crisis management), aerial and maritime communications for surveillance or transportation, support for massive IoT application, etc. For example, integrated communication links enable real-time dissemination of the computed positions, critical messaging in emergencies, and remote terminal management—particularly relevant in maritime, UAV, and LBS domains.
- Benefits from Galileo QP: Considering that GERMINAL product focuses on the integration of GNSS with Connectivity Systems, when considering the processing of GNSS signals within connected receivers, and in particular, for low power tracking devices, a crucial stage is the signal acquisition since it impacts the TTFF and the overall power consumption. For that reason, the Galileo program is considering the addition of dedicated signals components, particularly suitable for connected/low power tracking devices. An option that is being considered for Galileo 2nd generation is that of the so-called QP signals. Utilizing QP signals is an enabler of Galileo Terminals for being used in the context of IoT applications since Galileo current signal design can be improved to fit IoT needs (bandwidth, power consumption). Given the time dissemination scheme (TDS) that is modulated over the primary code of the QP signal, it is possible to also reduce the TTFF, having much more impact under those cases where the GNSS receiver is assisted.

2.2 Target Applications

Based on the benefits identified in the previous section, this section identifies the target GNSS market domains and applications for the Hybrid Terminal.

- Aviation: Except in Airport environments, Aviation applications usually operate in open sky conditions, the improvements in terms of PNT performances are not very relevant to the Aviation Domain since already, the user requirements are met with GNSS standalone and Standards already exist as RTCA MOPS DO-229 and ED-259A fulfilling different operations. Hence, for Aviation applications, the most relevant added value provided by the Hybrid Terminal are the new Communication capabilities and additional robustness to jamming/spoofing. Examples of applications that could benefit from the Hybrid Terminal are Search and Rescue or ADS-B based on the possible use of the 5G NTN communication channel and the additional robustness against cyber threats provided by the processing of new signals. Besides, contingency operations and emerging airspace domains where GNSS performance alone may be insufficient can also benefit from hybrid terminals. Examples include U-space corridors for drone traffic management or urban air mobility, where 5G NTN and multi-signal redundancy enhance resilience and situational awareness.

- Maritime: Some of the Maritime applications operate in non-open-sky conditions as e.g. operations in ports or near the coast. All the applications operating in these environments could benefit from the added value provided by the Hybrid Terminal in terms of Availability/Continuity/Accuracy performances. Additional robustness to jamming/spoofing is also relevant. Applications with demanding Time-To-First-Fix (TTFF) could also benefit from the Hybrid Terminal. In addition, the Communication capabilities enabled could also be relevant to some Maritime applications even if other communication channels are in use. Among the target applications for the Hybrid Terminal, we can mention: Autonomous vessels, Coastal Navigation, Port Operations, Inland Waterways, etc.

- Rail: All applications that need to operate in non-open-sky conditions such as e.g. urban, mountains, etc. can benefit from the added value provided by the Hybrid Terminal in terms of Availability/Continuity/Accuracy and TTFF performances. Railway systems frequently operate in obstructed environments (e.g. tunnels, stations, mountainous regions), where GNSS signal blockage or multipath severely degrades performance. The Hybrid Terminal's integration of LEO-PNT and 5G TN/NTN can bridge these gaps, enabling reliable applications such as virtual balises, train integrity monitoring, and hazardous cargo tracking. Additional robustness against jamming/spoofing is also relevant.
- Road: Similarly to Rail, all Road applications that need to operate in non-open-sky conditions can benefit from the performance improvements provided by the Hybrid Terminal as well as from the additional robustness to jamming/spoofing. Examples of interesting applications for the Hybrid Terminal are Road User Charging, eCall, Smart Tachographs, Insurance Telematics, etc.
- UAVs could also benefit from improved performances, robustness and Communication channels provided by the Hybrid Terminal.
- Mass market applications within Location Based Services domain would also be interesting for the penetration of Hybrid Terminals.

Based on the selected Target applications and in an analysis of the User Needs of these Target Applications conducted in GERMINAL project (and not presented in this paper for brevity) - by reviewing relevant literature on User Needs as the EUSPA User Consultation Platform Reports - the Specifications of the Hybrid Terminal presented in next section were defined.

3 HYBRID TERMINAL SPECIFICATIONS

3.1 General

The Unified Hybrid User Terminal (UHUT) integrates multiple technologies for positioning and signal processing, including GNSS, LEO-based positioning (LEO-PNT), LEO signals of opportunity (LEO-SOP), and 5G (both terrestrial and non-terrestrial). While each subsystem addresses different frequency bands, signal structures, and processing approaches, the overall architecture is designed to maximize modularity, signal diversity, and hybridization capability. The general requirements cover multi-band antenna configurations, flexible Radio-Frequency (RF) front ends, and scalable digital processing platforms capable of supporting real-time and post-processed observables.

Target performance figures have been defined to ensure positioning continuity and accuracy across diverse scenarios. When all systems are available and operating under open-sky conditions, the hybrid navigation module shall achieve a positioning accuracy below 2 m [95%]. In urban environments with high multipath and degraded satellite visibility, the system is expected to maintain accuracy below 3 m [95%], leveraging non-GNSS sources. In GNSS-denied scenarios, but with available 5G, LEO-PNT, and LEO-SOP signals, the terminal shall still provide positioning accuracy below 5 m [95%] under open-sky conditions. These targets reflect demanding initial objectives which will be validated and refined through experimentation. Additional subsystem-level requirements—such as support for low C/N_0 tracking (down to 28 dB-Hz), minimum acquisition sensitivity at 30 dB-Hz, and real-time signal processing rates—further define the system's expected operational performance envelope.

3.2 GNSS and LEO-PNT

This section describes the requirements of the unified receiver module responsible for processing both GNSS and LEO-PNT signals within the hybrid terminal. While the same hardware components are shared between both systems, the signal processing pipelines are implemented independently, with no assistance or joint tracking logic. Each system follows its own acquisition and tracking stages, but the resulting observables may be combined at a higher level for hybrid PVT computation.

Antenna. A single, multi-band active antenna is used to collect both GNSS and LEO-PNT signals. It supports reception in the L1/E1 and L5/E5 bands, with right-hand circular polarization (RHCP) and an integrated low-noise amplifier (LNA). The antenna provides sufficient gain and low axial ratio across elevation angles, enabling robust signal acquisition even under low signal conditions or multipath environments. Its broadband characteristics allow simultaneous reception of all supported signals, reducing system complexity and facilitating joint RF front-end design. The mechanical and electrical interface ensures seamless integration with the terminal while satisfying gain, impedance, and noise figure requirements.

Front end. The RF front end is shared between the GNSS and LEO-PNT signal paths. It includes three independent channels covering the E1, E5/L2, and E6 bands. The design supports I/Q demodulation with configurable bandwidth from 4 to 80 MHz, ADC resolution of 10 bits, and a sampling rate of up to 100 Msps. The front end delivers digitized I/Q samples to the downstream digital processing block, with synchronized timing and minimal signal distortion.

GNSS signal processing. GNSS signal processing is structured around a two-stage architecture: acquisition and tracking. Acquisition is performed by a dedicated Fast Acquisition Unit (FAU), which is optimized for GNSS signals such as GPS L1 C/A and Galileo E1C. It supports configurable coherent and non-coherent integration, with the default mode based on shuffled search. Once acquisition is complete, signal tracking proceeds through separate Delay Locked Loops (DLL), Frequency Locked Loops (FLL), and Phase Locked Loops (PLL), each configurable in loop filter characteristics and aiding mechanisms. Observables such as code and carrier phase, Doppler, and C/N_0 are computed in real time. The receiver supports tracking of GPS L1/L5 and Galileo E1/E5a/E5b signals.

LEO-PNT signal processing. LEO-PNT signals are acquired and tracked using an independent processing pipeline, despite sharing the same antenna and front-end. The receiver assumes a GNSS-like waveform, allowing the reuse of baseband architecture while maintaining logical separation. Acquisition and tracking follow the same principles as in the GNSS chain, including PLL/FLL/DLL loop control, configuration of correlator spacing, and signal-specific integration windows. Observables such as Doppler, carrier phase, and pseudorange are extracted per satellite, and used for downstream positioning when a minimum of four LEO-PNT satellites are visible. No cross-assistance with GNSS signals is used during acquisition or tracking, though measurements may later be fused for hybrid navigation performance.

3.3 LEO-SOP

The specifications for the LEO-SOP module of the hybrid terminal are related to the different LEO constellations that this module is targeting to process, namely Orbcomm, Iridium, Globalstar and Starlink. The specifications are divided into different levels addressing the antennas, radio-frequency front end and digital signal processing, as discussed next.

Antennas. The hybrid terminal has a set of dedicated antennas to gather signals for each of the LEO constellations of interest. This means that a total of four antennas is needed. The first one is devoted to gathering signals from Orbcomm satellites and thus is required to operate in the 137 to 138 MHz band. Linear polarization antennas are often used for the reception of Orbcomm signals, but due to the right hand circularly polarized (RHCP) nature of such signals, the use of a specific RHCP antenna is encouraged to improve the overall signal reception. The second antenna is devoted to gathering signals from Iridium satellites and thus is required to operate in the 1626.0 to 1626.5 MHz band, corresponding to the Iridium downlink channel. Again, the use of an RHCP antenna is convenient. The third antenna is devoted to obtaining signals from Globalstar satellites and thus should operate in the 2483 to 2500 MHz band. In this case, a left-hand circularly polarized (LHCP) antenna is required to match the LHCP downlink signals transmitted by Globalstar satellites and to avoid polarization mismatch. While polarization matching can be a relevant consideration for many LEO constellations, it becomes critical for Globalstar signals due to their significantly lower received signal power. In this context, every decibel gained in the reception chain makes a difference. Finally, the fourth antenna is devoted to retrieving signals from Starlink satellites, and thus is required to operate in the 10.7 to 12.7 GHz band.

Front end. Four independent RF chains are required in order to process the signals gathered by each dedicated antenna. The RF front end is required to have a minimum bandwidth of 1 MHz for conditioning signals from Orbcomm, Iridium and Starlink satellites, in the latter case, assuming that only the Starlink beacons shall be processed. For the case of Globalstar signals, the RF front end should have a minimum bandwidth of 16.5 MHz, to be able to process the full Globalstar bandwidth. Apart from the bandwidth requirement, the RF front end should be able to provide an oversampling factor of at least a factor of four, and analog to digital conversion with at least eight bits.

Digital signal processing. The hybrid terminal should be able to process the IQ samples provided by the RF front end, and provide key observables such as the measured Doppler, carrier phase, symbol time-delay and signal to noise ratio (SNR), for each of the LEO signals under consideration. Such processing should follow a record-and-process approach whereby the IQ samples coming from the front end are stored first in a recorded file, and subsequently, this file is processed offline by a set of software routines. The overall processing should be implemented in a general-purpose computer, thus in line with the offline or post-processing approach considered herein.

3.4 5G

The proposed 5G architecture of the UHUT is designed to operate seamlessly across both 5G TN and NTN, in alignment with 3GPP Release 17 specifications. Its main objective is to ensure interoperability with existing infrastructure and the other part of UHUT, while also providing advanced signal processing capabilities for positioning. The terminal architecture combines a reconfigurable RF front-end, a high-performance signal processing platform, and open-source software, enabling experimentation, adaptation to multiple deployment scenarios, and support for positioning techniques. Here we briefly describe the requirements for the components that will make the proposed 5G architecture.

The terminal's antennas must support operation in the 5G FR1 frequency band, which is the reference band for both TN and NTN as defined in Release 17. To ensure broad compatibility and simplify deployment, the antenna should provide Omni directional transmissions in the horizontal plane and a minimum gain of 3 dBi gain. This design guarantees reliable reception regardless of terminal orientation and enables efficient integration into diverse environments.

The 5G RF front-end of the UHUT is required to operate across multiple 5G frequency bands, with a focus on FR1 due to its prevalence in commercial terrestrial deployments and its use in NTN scenarios. The front-end must be capable of amplifying weak incoming signals, providing at least 15 dB of gain, and should be flexible enough to adapt its processing pipeline based on the use case or deployment context. This adaptability is essential to support both standard 5G communication and advanced localization tasks.

On the signal processing side, the terminal must include a complete, open-source implementation of the 5G New Radio (NR) protocol stack. This includes components for the Base Station (BS, gNB), the User Equipment (UE), and the 5G Core Network (CN). The software must provide the possibility to be modified to find, read, store and analyze the I/Q samples, particularly for Reference Signals (RSs) relevant to positioning. Furthermore, it must support integration with a variety of RF front-end hardware and include specific support for 5G-NTN operation. To handle high-throughput signal processing workloads, the terminal shall incorporate a high-performance workstation equipped with a CPU operating at no less than 3.7 GHz. This Digital Signal Processing (DSP) module will be responsible for capturing and storing RF samples from the front-end, and for processing auxiliary input information used in emulating or acquiring 5G NTN signals. The system must be capable of supporting multiple positioning algorithms and shall include connectivity options suitable for both Ettus N3x0 SDRs, via 10 Gbps Ethernet, and Ettus B210 SDRs, via USB 3.0 (see Section 4.5 for details on Ettus boards).

In terms of Observables, the UE must support both transmission and reception of 5G NR signals in full compliance with Release 17. A key enabler for positioning in this context is the Positioning Reference Signal (PRS), a standardized downlink RS standardized for 5G positioning techniques. Finally, the UHUT must be capable of performing signal-based positioning using the raw RF data. In particular, it should support the computation of Downlink Time Difference of Arrival (DL-TDOA), a technique that estimates the position of the UE by leveraging the PRS signal transmitted by a set of gNBs and received by the

UE to measure the TDOA between each pair of TN gNBs. These measurements are then used in multilateration or trilateration calculations based on hyperbolic geometry, to obtain accurate UE location estimates.

4 HYBRID TERMINAL DESIGN AND DEVELOPMENT

This Section provides a description of the UHUT design. At the time of this writing, the Hybrid Terminal is still in development phase and soon, the different components will be integrated.

4.1 High-Level Design

The HT GNSS, LEO-PNT, LEO-SOP, and 5G systems to create a robust, hybrid navigation solution, enhancing positioning performances and resilience across diverse operational environments. Besides above system, the UHUT also includes:

- **Hybrid Navigation Module**: The Hybrid Navigation (NAV) module within the UHUT fuses data from GNSS, LEO-PNT, LEO-SOP, and 5G sources to provide a unified PVT solution. The EKF-based fusion process combines measurements from these sources, adjusting dynamically to environmental conditions and ensuring robust, accurate navigation.
- **Timing and Synchronization**: An Oven-Controlled Crystal Oscillator (OCXO) and an OctoClock for timing and synchronization, ensuring precise alignment of data from various sources. This is essential for maintaining accurate measurements and effective data fusion.
- **Data Storage**: A Hard Disk Drive (HDD) for storing measurement and navigation data, supporting real-time processing (GNSS, LEO-PNT and 5G) and post-processing analysis. High-data-rate sources, such as SDR-based LEO-SOP signals, are stored on dedicated storage units to accommodate large data volumes efficiently.

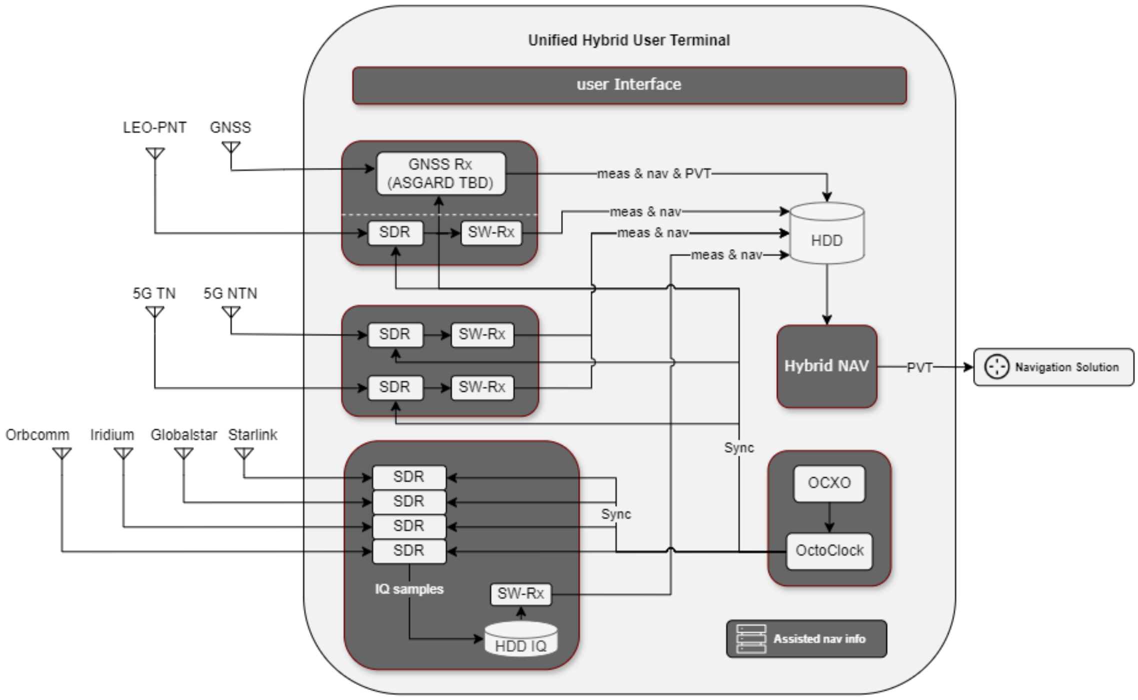


FIGURE 1: Unified Hybrid Terminal - High level Architecture

UHUT operates on a high-performance HW processing unit specifically chosen to handle the intensive processing and data fusion requirements of the hybrid navigation module. This HW processing unit is equipped with advanced hardware features to ensure efficient real-time performance, seamless data handling, and robust visualization capabilities.

4.2 GNSS & LEO-PNT

GNSS module includes front-end and signal processing design. The multi-constellation GNSS Receiver will operate in GPS Standard Positioning Service and Galileo Open Service. It will be based on the GMV GNSS receivers developed previously, used as a COTS, and only modifications related to the form factor, interfaces and new functionalities (e.g. in case Galileo QP or LEO-PNT signal processing are added) will be included.

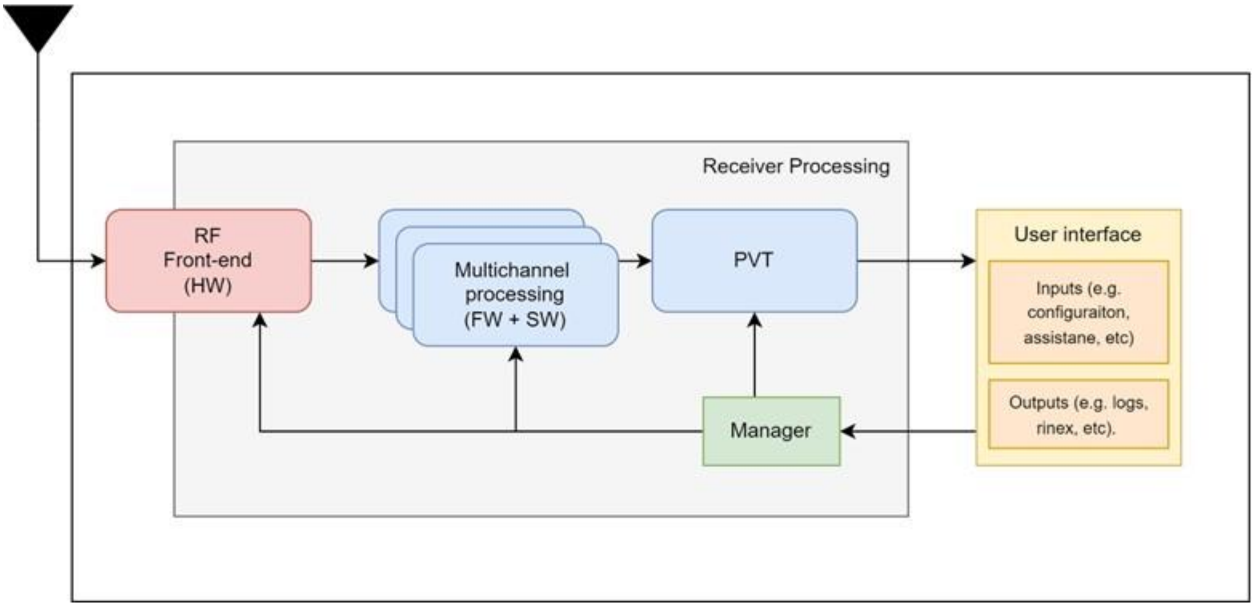


FIGURE 2: GNSS receiver architecture

Antenna. The antenna must meet the following requirements:

- To be an active antenna.
- To support [1164 – 1191] MHz (L5/E5aQ band) and [1559 - 1591] MHz (L1/E1 band).
- To have at Right-Handed Circular Polarization (RHCP).
- To have a gain of -8 dBi at 5° elevation and maximum antenna gain of 4 dBi
- To have a low noise figure (around 2.5 dB).
- To have a LNA gain of, at least, 20 dB.
- Since the antenna is intended for out-door uses, it is also expected to meet the following:
- Operating temperature from -40º C to 85º C.
- Minimum IP rating: IP67.
- At least 95% humidity proof.
- And finally, it is also expected that the antenna is compliant with the CE marking.

In this sense, the antenna model HX-CVX603A has been selected.

Front-end. The GNSS receiver is based on three hardware components:

- **Mercury XU1:** This SOM is a complete and powerful embedded processing system in a compact, space-saving form factor. It is based on a Zynq Ultrascale+ MPSoC (XCZU15EG-2FFVC900I).
- **Mercury ST1** (ARX_RX_GMV-ST1): is a carrier board designed to work with the Mercury XU1. It serves as a baseboard that expands the connectivity and functionality of the attached FPGA module, making it easier to integrate the FPGA.
- **THOR Front-End**: This element, has been develop by GMV, and allows to process the RF signal in order to downconvert to baseband and finally digitized them. The main features of this element are:
    - 3 channels: E1, E5/L2 and E6
    - I/Q demodulation
    - High sampling frequency, up to 100MHz
    - ADC resolution of 10 bits
    - High gain, up to 87dB
    - Bandwidth configurable from 4 to 80MHz

Signal processing. The signal processing module is based on the following stages:

1. Acquisition: This is dedicated to the search done per satellite, and it is considered the entry point of the receiver processing. The signal acquisition process is done by means of a Fast Acquisition Unit (FAU). The design driving factors are acquisition speed, sensitivity, and FPGA resources consumption.

   The FAU design is targeted to signals with lower bandwidth in the main lobe. This allows to define long enough coherent integration periods while keeping bounded the number of points in the FFT. Moreover, the resulting frequency bin is, under these assumptions, low enough to allow the tracking lock by means of a FLL or PLL with high noise bandwidth. Taking into account these considerations, the GNSS receiver exploits acquisition of Galileo E1C/QP and GPS L1 C/A as starting point.

   Finally, the number of coherent and non-coherent accumulations is a design parameter that depends on the power budget used to set a specific working point. The acquisition manager can adopt different strategies, all of them valid. By default, shuffled search is used.

   Note that GNSS and LEO-PNT signals will be acquired independently.

2. Tracking: This module aims to refine the estimation performed during acquisition and to continuously track the signal while compensating for the various effects caused by dynamics. To achieve this, each signal of interest is processed through a dedicated tracking channel.

   The signal replica is, for each tracking channel, the best reconstruction of the received signal being evaluated, and is characterized by several parameters. Some of these parameters are known a-priori, like the signal modulation or the code ranging sequence, while others remain subjected to the propagation conditions, namely, carrier Doppler frequency, carrier-phase and code-phase. These parameters are initially estimated in the acquisition but is the objective of tracking control loops to reduce their initial noise within some target performance and to monitor their evolution through time.

3. Galileo Signals: The Galileo signals covered in the design and the different uses they will have in the GNSS receiver are detailed in **Table *1***.

Table 1: Galileo Signals coverages and use in GNSS receiver

Signals	ACQ*	TCK	Synchronization	Pseudorange Gen.	Data Retrieval	Data Exploitation	Obs in PVT
E1							
E1B		**X**		**X**	**X**	**X**	**X**
E1C	**X**	**X**	**X**	**X**			**X**
E1-QP	**X**	**X**	**X**	**X**			**X**
E5							
E5aI		**X**		**X**	**X**		
E5aQ		**X**	**X**	**X**			**X**

* ACQ: Understood as the initial signal for satellite search

* The acquisition of the QP component is constrained to cases where its central frequency is within ±2 MHz of the central frequency of E1.

Regarding the coverage of the data retrieval and exploitation, **Table *2*** shows the different features and services provided by the navigation messages envisioned for Galileo and indicates the coverage achieved by the GNSS receiver.

Table 2: Galileo data services retrieval and exploitation

Feature	Word Type	Exploit	Used for
I/NAV (E1B & E5b)			
Preamble Synch	All	**X**	Synch, Tracking check
CED	1, 2 3, 4	**X**	PVT
Corrections (TOW, clock, Iono, BGD, etc.)	4, 5	**X**	PVT
UTC conversion	6	**X**	PVT
SSP	Odd pages (E1B)	**X**	TAR Synch
F/NAV (E5aI)			
Preamble Synch	All	**X**	Synch, Tracking check

Feature	Word Type	Exploit	Used for
Corrections (TOW, clock, Iono, BGD, etc.)	1, 4	**X**	PVT
CED	2, 3, 4	**X**	PVT

Finally, it is also important to mention that the coverage of a signal type will be limited by the number of channels available for each signal. It will be guaranteed that at least one signal of each type will be exploited at all levels indicated in the Table above.

4. Measurements: The receiver provides several essential GNSS measurements that are recorded at a default rate of 1 Hz, with the option to configure the rate up to 10 Hz. The key measurements generated by the GNSS receiver include:
    - Pseudoranges: These are the approximate distance measurements between the GNSS receiver and the satellites.
    - Doppler: This measurement captures the change in frequency of the received signals, allowing for the estimation of the relative velocity between the receiver and the satellites.
    - Carrier-Phase: This measurement tracks the phase of the GNSS signal carrier wave, enabling more precise position estimates.
    - C/N0: Carrier-to-noise ratio. Measure of the received carrier strength relative to the strength of the received noise

4.3 LEO-SOP

The LEO-SOP module is composed of two main constituent blocks, as shown in the high-level architecture illustrated in FIGURE 3. The first block, on the left-hand side of that figure, comprises all the hardware elements of the multi-constellation RF front end. This includes:

Antennas. Dedicated antennas for each LEO constellation, including an UC-1374-531-R quadrifilar helix antenna for Orbcomm, a Maxtenna M1621HCT-EXT antenna for Iridium, a Globalstar GAT-17HX antenna for Globalstar and a MegaSat 0400072 low-noise-block (LNB) for Starlink beacons. A Lotus Comm. Inc. low-noise amplifier (LNA) LNA700M6G2S is used at each antenna, except for the Starlink LNB which already incorporates a 70 dB gain amplification stage.

Front end. An RF front end for each LEO constellation is used, based on a COTS software-defined radio (SDR) device. The latter is based on a bladeRF, which is a mid-priced SDR that has the advantage of accepting the input signal from an external clock, thus facilitating the synchronization of several SDR units. This feature will simplify the PVT computation using signals from different LEO constellations recorded at the same time instant, because no additional parameters need to be estimated in order to determine the clock offset among different LEO recordings.

The second block of the high-level architecture illustrated in FIGURE 3 consists of the LEO-SOP software module, which runs on a general-purpose computer and carries out the actual processing of the LEO received signal samples. The LEO-SOP software is in charge of two main tasks:

- The first task is the orbit prediction of the satellites whose signals are to be processed. Such prediction is important in order to determine when such satellite will be visible, and therefore, be able to record its received signals. This task is carried out by the so-called recording manager, which not only performs the orbit prediction based on publicly available TLE files but also carries out the scheduling of LEO signal captures so that the recording can be automated.
- The second task is the processing of the recorded LEO signal samples. This task is carried out by a LEO-SOP software receiver that performs blind Doppler, carrier phase and symbol timing estimation of the LEO signals under consideration. The output of the LEO-SOP software receiver is a JSON file containing the different observables measured at each epoch for the visible LEO satellites.

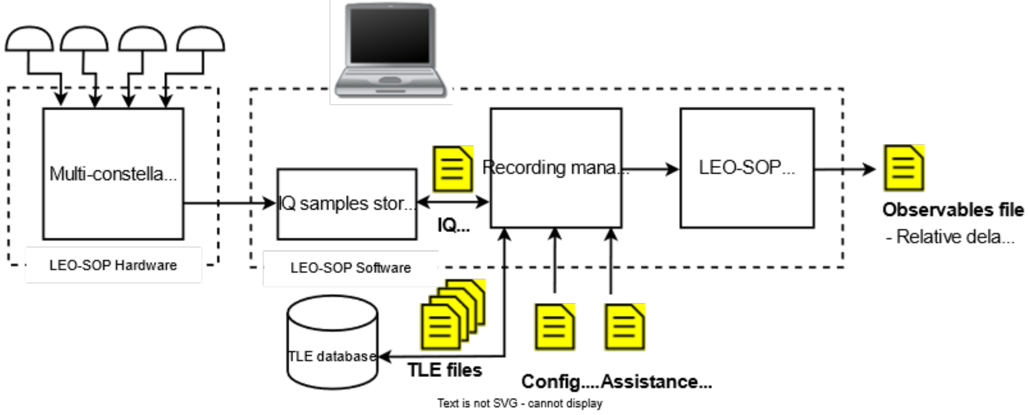


FIGURE 3. High-level architecture of the LEO-SOP module.

As previously mentioned, the LEO-SOP software receiver can be configured to process signals from Orbcomm, Iridium, Globalstar and Starlink LEO constellations. The reasons to do so are the following. For the case of Orbcomm, this is a small LEO constellation providing barely one to two visible satellites at a given location and time. While this may seem a disadvantage, a key feature is that Orbcomm satellites broadcast continuous signals in a relatively low frequency band (137–138 MHz) as compared to other satellite signals. This makes Orbcomm signals particularly convenient for indoor reception due to the good penetration properties of such frequency band. On the opposite side, the Starlink constellation is a huge one, providing tens of visible satellites at a given location and time. However, Starlink signals operate in the super high frequency band, with carrier frequencies on the order of 10 GHz, thus being prone to severe attenuation indoors. It is for this reason that the combination of Orbcomm and Starlink seems convenient to cover both indoor and outdoor applications.

Unfortunately, the structure of Starlink signals is not publicly disclosed and all the available information is based on reverse engineering carried out by different research groups worldwide (Humphreys et al. 2023, Kozhaya et al. 2025). Furthermore, the very large bandwidth of Starlink signals, about 240 MHz wide, makes processing Starlink signals a very demanding and challenging task. It is for this reason that the focus in the present activity is placed on processing just a set of beacons that are observed in-between adjacent Starlink channels. While processing of these beacons has been demonstrated in the existing literature (Kozhaya et al. 2025), the uncertainties surrounding the role and the availability of these beacons, poses some concerns on their use as the sole source of information for LEO-SOP-based positioning. This is the reason why the combination of Starlink and other LEO signals is often considered a safer approach. However, relying solely on Orbcomm signals as an alternative to Starlink signals is not adequate due to the very limited number of Orbcomm visible satellites. This concern motivates the use of a third LEO constellation to securely complement both Orbcomm and Starlink signals.

Such third LEO constellation is Iridium, which operates in the L band, similarly to GNSS. The triplet composed of Orbcomm, Iridium and Starlink is considered a safe and reliable set of LEO constellation for LEO-SOP positioning and it will be the default configuration henceforth.

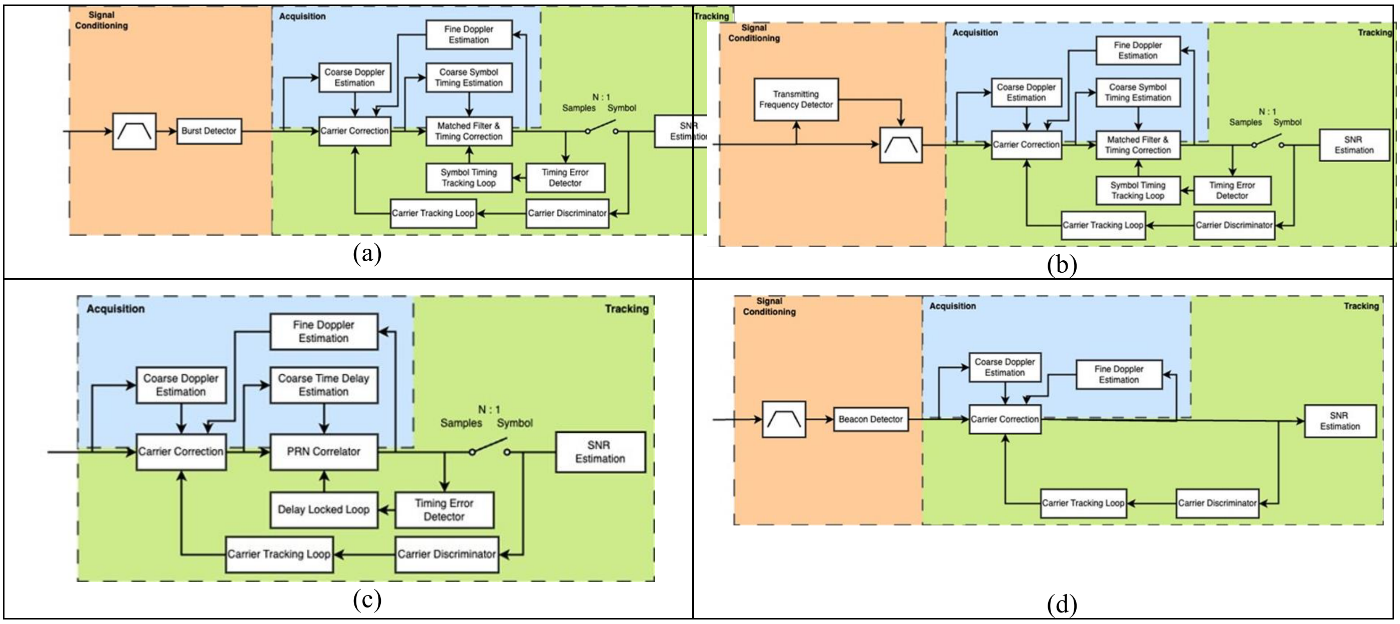
While such triplet of LEO constellation is considered enough, the possibility of adding a fourth LEO constellation is addressed in this activity. Such constellation is Globalstar, which has a two-fold advantage. First, it is based on CDMA technology and therefore its receiver implementation shares many synergies with conventional GNSS receivers. Second, Globalstar signals operate in the S band, thus bringing an additional degree of freedom and providing many synergies as well with the existing plans for the deployment of future dedicated LEO-PNT constellations operating in such band. Despite such strong points, the main disadvantage of Globalstar signals is that their spreading codes are not publicly available, as opposed to what happens with GNSS open services. This poses unsurmountable obstacles to the processing of Globalstar signals, and it is the reason why very few contributions can be found in the existing literature on this topic. Fortunately, this problem has recently been addressed in Peña et al. 2024, where a set of Globalstar spreading codes have been partially determined. Despite being partially known, the results have shown that processing Globalstar signals with these spreading codes is possible, and consistent observables have been reported.

Signal processing. Each LEO constellation has a dedicated module within the LEO-SOP software receiver for implementing its signal processing. The architecture of each of these dedicated modules is schematically depicted in FIGURE 4. The main features of each module are briefly summarized next:

- **Iridium:** The received signal is first filtered using a bandpass filter centered at 1626.270833 MHz, where the ring alert subchannel is located. This filter has enough bandwidth to include any ring alert channel regardless of its Doppler shift, which for the case of Iridium can take values between +40 kHz and -40 kHz. After applying the channel filter, the signal is down converted to baseband, and a burst detector is applied. This detector is intended to identify if an Iridium burst is present in the current frame, since Iridium uses TDMA, and the data is transmitted in bursts. If this detection is successful, the burst is provided to the next stage, the acquisition, otherwise, the frame is discarded, and the receiver will hop to the next snapshot. The acquisition stage is intended to provide an initial value of the Doppler shift and the timing error to make it easy for the tracking loop to estimate the phase and timing error accurately. To do so, it has three main blocks, the coarse Doppler estimator, which through a spectral analysis of the signal after removing the modulation, provides an approximate Doppler shift and corrects it, the coarse symbol timing estimator, which provides an initial timing error, and finally the fine Doppler estimator, which provides a more accurate Doppler shift estimation. After these initial estimations, the tracking stage comes into play. This last stage implements two main loops, a third-order Phase Lock Loop that estimates the phase and thus the Doppler shift at each symbol, and a Delay Lock Loop, which estimates the time delay at each sample to demodulate correctly the symbols. Finally, this last stage also has an SNR estimation.
- **Orbcomm:** The main difference with respect to the Iridium processing lies in the first stage, as a result of the media access technique employed by this Orbcomm, which is FDMA instead of TDMA, as in Iridium. This means that each Orbcomm satellite transmits at a different frequency. Indeed, each Orbcomm satellite transmits at two different frequencies simultaneously, and the receiver needs to tune the channel filter to any of these two satellite transmitting frequencies. Since the symbol rate used by Orbcomm is smaller than the one used by Iridium Next,

and the transmitting frequency of Orbcomm satellites is around 137 MHz, its signals suffer a Doppler shift much smaller than Iridium. In particular, Doppler values between +3.5 kHz and -3.5 kHz are common in Orbcomm signals, and hence the bandwidth of the input channel filter will be smaller.

- **Globalstar:** In this case, the processing is slightly different than in previous cases, due to the fact that Globalstar is using a CDMA scheme, similar to that adopted in most GNSS. Each Globalstar CDMA signal conveys in turn a set of 128 data channels that are code multiplexed using Walsh orthogonal codes. Among these data channels, the first one is actually not carrying any data at all but a constant pilot signal, and this will be the channel targeted by the LEO-SOP receiver. Being based on a CDMA scheme, the processing chain shares many similarities to the building blocks of a GNSS receiver, including code/carrier acquisition and tracking.
- **Starlink:** Despite the huge signal bandwidth of Starlink signals, the objective within the scope of this activity is to process and track the narrowband beacons that seem to be present in the guard bands between adjacent downlink channels. Since an FDMA multiple access technique used by this constellation, with different channels located at different frequencies, the receiver should first detect in which channel the pilot is present, and then, if it is detected proceed with the acquisition and tracking stages. In this chain, no timing tracking is implemented due to lack of data in the beacon signal, simplifying the processing. The Starlink constellation uses a much higher frequency than the other constellations, around 11.7 GHz, producing a Doppler shift within the +/- 290 kHz range.



(a) (b) (c) (d)

FIGURE 4. Architecture of the signal processing module for each LEO constellation: (a) Iridium, (b) Orbcomm, (c) Globalstar, (d) Starlink beacons.

4.4 5G

The proposed UHUT integrates a carefully selected set of hardware and software components to enable robust 5G connectivity across both TN and NTN environments as shown in FIGURE 5**Error! Reference source not found.**. The design emphasizes modularity and openness, supporting positioning features while ensuring compatibility with existing infrastructure. Key elements include a multi-band antenna system, a flexible RF front-end, a high-performance signal processing platform, and a customizable open-source 5G NR stack. FIGURE 5**Error! Reference source not found.** shows the complete e nvironment, including Radio Access Network (RAN), 5G Core and UE. In this section we will describe the hardware and software components that are part of the UE.

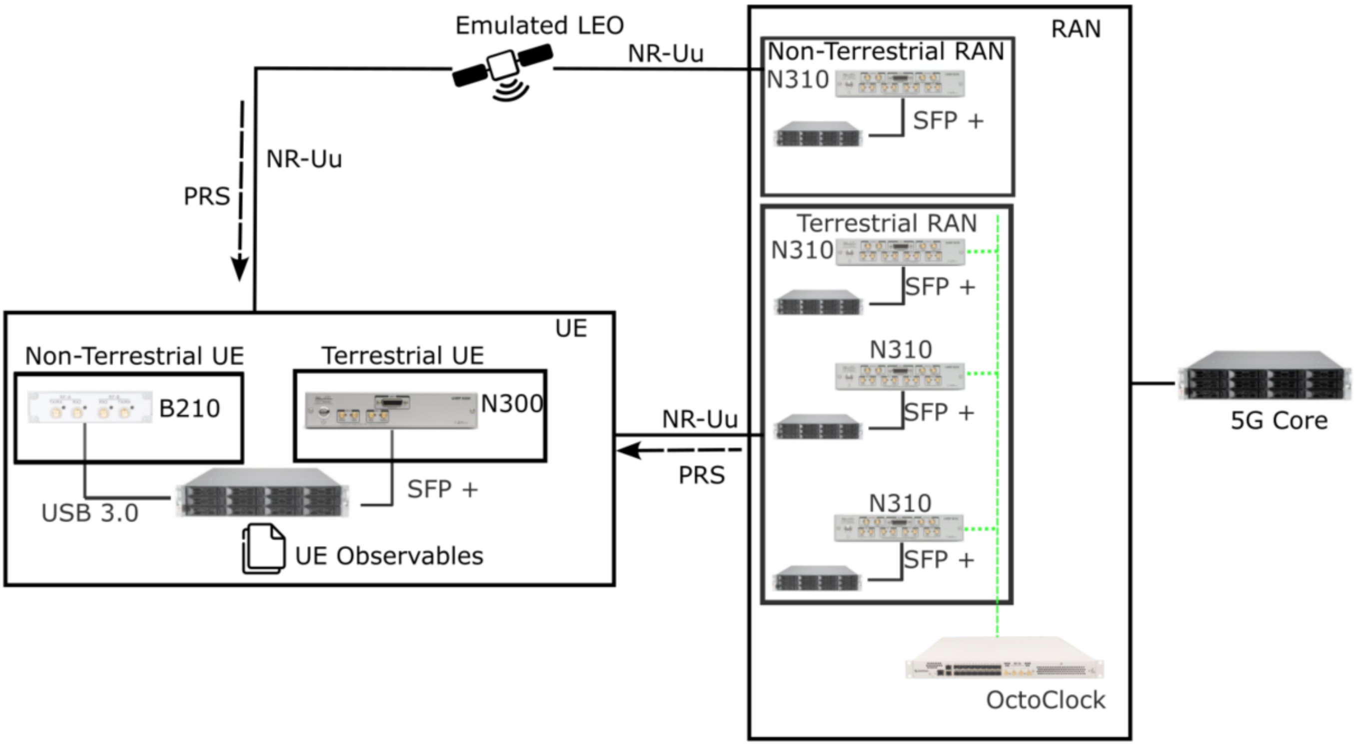


FIGURE 5: High-level architecture of the 5G Terrestrial and Non Terrestrial Network and Interfaces of the UE and the Testbench.

Antennas: ANT-5GWWS6-SMA[1]. Fully complies with specifications, it is compatible with the 5G frequency bands in 5G TN and NTN defined in 3GPP standards, specifically in Release 17. Its 5.5 dBi gain is above the minimum requirement to ensure sufficient gain of 5G transmission, improving overall system sensitivity and coverage on the horizontal plane.

TN Front-end: Ettus N300[2]. The Universal Software Radio Peripheral (USRP™) N300 baseband processor uses the Xilinx Zynq-7100 SoC to deliver a large user-programmable field-programmable gate array (FPGA) for real-time and low-latency processing and a dual-core ARM CPU for stand-alone operation. Users can deploy applications directly on to the preinstalled embedded Linux operating system or stream samples to a host computer using high-speed interfaces such as 1 Gigabit Ethernet, 10 Gigabit Ethernet, and Aurora over two SFP+ ports. Its BW up to 100 MHz and its Configurable Sample Rates (122.88, 125 or 153.6 MS/s), satisfying the features of interest for 5G TN and make this SDR suitable for the purpose.

NTN Front-end: Ettus B210[3]. The USRP B210 platform provides a fully integrated, single-board, continuous frequency coverage from 70 MHz – 6 GHz. Designed for low-cost experimentation, it combines the AD9361 RFIC direct-conversion transceiver providing up to 56MHz of real-time bandwidth, an open and reprogrammable Spartan6 FPGA, and fast SuperSpeed USB 3.0 connectivity with convenient bus-power. Its BW up to 56 MHz and its Configurable Sample Rates (61.44 MS/s quadrature), satisfying the features of interest for 5G NTN and make this SDR suitable for the purpose.

Open-Source Software (OSS) for full 5G NR stack: OpenAirInterface[4]. The most common 5G state-of-the-art open source software are: OpenAirInterface (OAI), SrsRAN[5], Aether[6]. SrsRAN and Aether are not as widely used as OAI and lag behind OAI in the implementation of several 5G features, especially concerning localization (implementation of PRS and low TN bandwidths available). OAI serves as an OSS platform that provides a comprehensive fully compliant with the 3GPP Release 17 reference implementation of the complete 5G-NR stack, including gNB, UE and 5G CN. The OAI software stack is designed to run on general-purpose high frequency processors. OAI can meet the software specifications stated above in addition to being widely used across scientific community as the main OSS platform for developing 5G-NTN innovations, for example the 5GOA from the European Space Agency (ESA)[7].

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[1] Cellular Sub-6 5G Antenna. https://es.rs-online.com/web/p/antenas-multibanda/2625407
[2] https://www.ettus.com/all-products/usrp-n300/
[3] https://www.ettus.com/all-products/ub210-kit/
[4] https://openairinterface.org/
[5] https://www.srslte.com/
[6] https://aetherproject.org/
[7] https://connectivity.esa.int/projects/5ggoa

Signal processing platform. The signal processing shall be performed by a combination of the OAI, the Ettus N300 and B210 SDR as the front-end and a High-performance workstation with a CPU operating at no less than 3.7 GHz, according with the specifications. **A+ Supermicro AMD Ryzen 9 7900X, AM5(Raphael), 12C/24T 170W, 4.7 - 5.6 GHz Server** represents a perfect fit for this purpose. This combination can handle the signal processing required for having up to 100 MHz Bandwidth 5G TN signals and up to 40 MHz Bandwidth 5G NTN signals. The high-performance servers shall incorporate a 10 Gbps Ethernet card to be connected to the corresponding Ettus N310 SDR and the USB 3.0 for the B210 to be connected to the host PC. The server can handle the Low-Density Parity Check (LDPC) operation, important for 5G channel coding, that requires high computational power for a short period of time using OAI.

UE Observables. Over the legacy TN, the following observables shall be measured at the UE: Time of Arrival (TOA), Signal-to-Noise Ratio (SNR) , Channel State Information (CSI), Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), Timing Advance (TA). In addition to the observables measured over TN, the NTN segment of the UE shall also measure the Doppler shift.

From Raw data to Positioning. The raw data used in this context is represented by the Positioning Reference Signal (PRS), a standardized downlink Reference Signal (RS) standardized for 5G positioning techniques. All the 5G RSs are widespread in 5G NR since they allow for more efficient use of radio resources and higher quality and reliability of wireless communication. These signals have peculiar properties which are valuable for avoiding cell and inter-cell interference and keeping their computation power efficient (Ghimire et al., 2022). Specifically, RSs are derived from pseudo-random sequences such as *Gold sequences*, *m-sequences* and *Zadoff-Chu (ZC) sequences*. These sequences are a pseudo-random sequence with constant amplitude and orthogonal to each other. In fact, the sequence has zero autocorrelation and can be cyclically shifted to obtain orthogonal signals. These characteristics help reduce the interference caused by the RSs sent in the same OFDM slot by other UEs. The gNB and the UE exchange the configuration parameters to obtain the same known sequence. 3GPP introduces different RSs for different purposes and the 5G NR PRS features are defined in 3GPP TS 38.211. DL-TDOA is a technique that can be used to leverage the PRS signal transmitted by a set of gNBs and received by the UE, to measure the TDOA between each pair of TN gNBs. This measurement is then employed in the multilateration and/or trilateration calculation, based on the principles of hyperbolic geometry, to obtain the position of the UE. The index of maximum cross correlation between PRS in time transmitted, meaning expected, and PRS in time received, returns the sample difference shift between the two sequences. Thus, dividing it by sampling rate f_s and by *2* (round-trip-time), the estimated Time of Arrival (TOA) can be obtained. Then:

$$\widehat{TOA}_i = \max\_index\left(\mathrm{idft}(r_{tx}) * \mathrm{idft}(r_{rx})^*\right)\frac{1}{2f_s}$$

To use triangulation/multilateration algorithms, it is necessary to calculate the TDOA between 2 PRSs transmitted by 2 different gNBs (*i* and *j*):

$$\widehat{TDOA}_{ij} = \widehat{TOA}_i - \widehat{TOA}_j$$

This raw TDOA Measurements can be improved using techniques such as moving average and Oversampling. Moving average techniques can improve the reliability, robustness, and stability of 5G localization results by eliminating the impact of outlier ranging measurements. Oversampling can improve the accuracy of TOA/TDOA estimation by increasing the number of samples collected. After collecting all TDOA between each pair of gNBs, DL-TDOA technique includes the possibility of using different algorithms for final position estimation, such as Closed-Form Solution, Brute-Force and Non-Linear Least Squares (NLLS) (Palamà et al., 2023, Palamà et al., 2024.).

Finally, the implementation shall involve the use of Extended or Unscented Kalman Filters. These filter techniques play a critical role in accurately estimating the position and tracking of user equipment by fusing information from multiple sources. 5G signal processing also includes the processing of 5G NTN signals considering the effect of Doppler variations in LEO NTN scenarios. The TDOA signal processing for 5G localization mainly works in TN with at least 3 gNBs. Using the NTN gNB (emulated transparent satellite), it is challenging to use TDOA together with the TN segment, as its accuracy is not as good as in TN (at best 30 MHz BW signal). Instead, we must use the TOA NTN measurements for integrity proposes, verifying if the position provided by the terrestrial segment is correct or not and in addition use it for vertical accuracy measurements. The UE shall compute the frequency Doppler shift of the service links and pre-compensate it in the uplink transmissions. Then, the UE shall be able to continuously update the Timing Advance and Doppler pre-compensation. While the pre-compensation of the instantaneous Doppler shift experienced on the service link is to be performed by the UE for the uplink, the management of Doppler shift experienced over the feeder link is left to the network implementation. Finally, the estimated RTT will be affected by both links, with the effect of the feeder link that needs to be removed.

OAI NTN LEO (Emulated Channel). The channel models for emulating or simulating the 5G NR NTN channels can be a flat fading narrowband channel or a frequency selective fading Tapped Delay Line (TDL) channel defined by 3GPP TR 38.811 Section 6.7.1 and 3GPP TS 38.811 Section 6.9.2, respectively. The path gains of NTN channel models are generated by applying the Doppler shift due to satellite movement for the path gains generated from a base channel model, according to:

$$f_{d,shift} = (v_{sat} / c) \times \left(\frac{R}{R+h} \cos \alpha_{model} \right) \times f_c ,$$

Where $\boldsymbol{v_{sat}}$ denotes the satellite speed, $\boldsymbol{c}$ denotes the speed of light, $\boldsymbol{R}$ denotes the earth radius, $\boldsymbol{h}$ denotes the satellite altitude, $\boldsymbol{\alpha_{model}}$ is the satellite elevation angle, and $\boldsymbol{f_c}$ denotes the carrier frequency. Though there are several other propagation impairments such as Iono-effects, which are depends on several factors such as on location, geomagnetic activity, etc, which correspond to a fluctuation of the received signal amplitude and phase, the main impairment for the 5G signals are the Round Trip Delay (RTD) / Round Trip Time (RTT) and the Doppler effect. According to 3GPP TR 38.811, the RTT, the Doppler shift and the Doppler rate depends on the altitude and the elevation of the satellite, with the last two that also depend on frequency. For FR1, we have that the doppler and doppler rate shall be within the values showed in TABLE 3.

Round Trip Time	28.4÷51.7 ms
Doppler shift	40÷48 kHz
Doppler rate	180÷544 Hz/s

TABLE 3: Expected Impairments for LEO satellite according to 3GPP TR 38.811

The channel between the NTN UE and the NTN RAN shall be emulated using OAI. Therefore, specific 5G-NTN adaptions shall be made to the legacy 5G TN OAI code. For instance, for the LEO satellite system, one of the major concerns is the excessive RTD which is approximately ≈ 30ms. Delay of such extent is way more than the TN 5G-NR can tolerate, and the following processes start to fail: HARQ processes, PHY procedures such as Adaptive Coding and Modulation, Power Control, Random Access Procedures, Timing Advance (TA), Timers in PDCP, RLC, and RRC layer of the expiry of the timers. To perform the adaptation of the OAI code for NTN proposes, we leverage the recent work done in the OAI system for the 5G-NTN in the GEO[8] and LEO[9] projects. According to the 3GPP, the gNB must broadcast the ephemeris information and common TA parameter in each NTN cell so that the UE is able to compensate for the doppler and propagation delay through the SIB19 packets. The description of SIB19 Information Element as defined in 3GPP Specification 38.331. The main SIB19 key elements are

- **ntn-Config**: Provides parameters needed for the UE to access NR via NTN access such as Ephemeris data, common TA parameters, k_offset, validity duration for UL sync information and epoch.
- **t-Service**: Indicates the time information on when a cell provided via NTN quasi-Earth fixed system is going to stop serving the area it is currently covering.
- **referenceLocation**: Reference location of the serving cell provided via NTN quasi-Earth fixed system

These parameters are to compensate for the propagation delay and are sent to the UE from the network via SIB19. However, for initial access of the UE to the satellite before SIB19 is received, some parameters such as ntn-ta-commondrift (drift rate of the common TA) and an approximation of the propagation delay must be provided to the UE.

Interfaces between Unified Hybrid User Terminal and Testbench. FIGURE 5 show the selected Hardware of 5G TN and 5G NTN that shall be deployed and their corresponding interfaces:

- **SMA connector**: ANT-5GWWS6-SMA antennas shall be connected to the Front-ends via SMA connector.
- **USB 3.0**: The B210 (NTN-UE front-end) shall be connected to the Supermicro AMD Ryzen 9 7900X server (DSP) using the USB 3.0 cable.
- **SFP+**: The N300 (TN-UE front-end) shall be connected to the Supermicro AMD Ryzen 9 7900X server (DSP) using the SFP+ cable. Also, the synchronization signal is spread using these cables.
- **NR-Uu**: Radio interface in 5G networks, connecting the UE to the gNB. It is responsible for the transmission of data, control signals, and user information between the UE and the 5G network.

5 TEST PLAN

The proposed test plan for the Unified Hybrid User Terminal, is described in this section.

In the first instance, multiple integration tests are planned for the validation of the UHUT elements to demonstrate and verify their operational capabilities. These tests will be conducted in different locations and situations where they can be performed without altering the results of each test.

- GNSS integration test
- LEO.PNT integration test
- 5G TN integration test
- 5G NTN integration test

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[8] https://connectivity.esa.int/projects/5ggoa

[9] https://connectivity.esa.int/projects/5gleo

After demonstrating the operational capability of each of its components, the next step is to demonstrate the complete operation of the UHUT and the achieved performances. After successfully completing this integration test, the following performances tests will be run to check its operation in different situations:

- With low multipath, typical of open sky environments
- With high multipath typical of deep urban environments
- Without GNSS service to assess the performances achievable in GNSS denied situations and the added value provided by the alternative positioning sources (LEO-PNT, LEO-SOP and 5G).

6 CONCLUSION

In this paper, the development of a Unified Hybrid Terminal including the processing of GNSS, LEO-PNT, LEO-SOP and 5G signals for PNT has been presented.

First, the Hybrid Terminal's added value was assessed to identify key PNT domains and applications for market deployment. Several applications within Maritime, Rail, Road, UAVs or LBS could benefit from the improved PNT performances and additional communication capabilities, especially applications operating in harsh environments such as Urban. In particular, the processing of multiple signals could improve the accuracy, availability and continuity of the PNT solution. In addition, the processing of different signals can improve the robustness against different threats such as jamming, spoofing, constellation wide failure, etc.

Based on the selection of target applications and considering their user needs, the Specifications for the Hybrid Terminal are defined, from a general perspective and also focusing on the different systems processed (GNSS, LEO-PNT, LEO-SOP and 5G). Requirements for the different functional blocks (e.g. Antennas, RF front-end, Digital Signal Processing and User Interface) have been defined as well as Performance Requirements for Navigation. In particular, ambitious accuracy requirements are defined for open-sky conditions (2m 95%) and for urban (3m 95%) when all systems are available and also particularly interesting, in GNSS-denied situations, an accuracy of 5m 95% is required only using LEO-PNT, LEO-SOP and 5G.

The high-level design of the Hybrid Terminal is described, focusing first, on the overall design and then, on the building components. Its modular architecture facilitates scalability and future integration with evolving PNT technologies such as 6G or LEO-PNT constellations like Xona. Its design balances performance and flexibility, enabling deployment across civilian, commercial, and safety-critical applications.

In potential future evolutions, the Hybrid Terminal could also incorporate user-level PNT integrity algorithms such as Receiver Autonomous Integrity Monitoring (RAIM), Advanced RAIM (ARAIM) (see Blanch et al., 2014) or Isotropy Based Protection Level (IBPL) (see Azaola et al., 2009). These additions would enhance the trustworthiness of the navigation solution, particularly in safety-critical or regulated environments.

Finally, in order to verify the fulfillment of the Hybrid Terminal Specifications and to assess the Performance of the device, a Test Plan is proposed with multiple Test Cases. Particularly interesting are the Test Cases to assess the PNT performances in real operational environment for both the overall PNT solution (GNSS + LEO-PNT + LEO-SOP + 5G) and the PNT solution in GNSS-denied situations. At the time of this writing, experimentation results are pending and will be presented it in a future publication.

ACKNOWLEDGMENTS

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