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Citation for the original published paper (version of record):
Saleh, S., Zheng, P., Liu, X. et al (2025). Integrated 6G TN and NTN Localization: Challenges, Opportunities, and Advancements. IEEE Communications Standards Magazine, In Press.
http://dx.doi.org/10.1109/MCOMSTD.2025.3569014

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This article has been accepted for publication in IEEE Communications Standards Magazine. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/MCOMSTD.2025.3569014

Integrated 6G TN and NTN Localization: Challenges, Opportunities, and Advancements

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***Abstract*—The rapid evolution of cellular networks has introduced groundbreaking technologies, including large and distributed antenna arrays and reconfigurable intelligent surfaces in terrestrial networks (TNs), as well as aerial and space-based nodes in non-terrestrial networks (NTNs). These advancements enable applications beyond traditional communication, such as high-precision localization and sensing. While integrating TN and NTN enablers will lead to unparalleled opportunities for seamless global localization, such integration attempts are expected to face several challenges. To understand these opportunities and challenges, we first examine the distinctive characteristics of the key 6G enablers, evaluating their roles in localization from both technical and practical perspectives. Next, to identify developments driving TN-NTN localization, we review the latest standardization and industrial innovation progress. Finally, we discuss the opportunities and challenges of TN-NTN integration, illustrating its potential through two numerical case studies.**

***Index Terms*—6G, low-Earth-orbit (LEO) satellites, localization, non-terrestrial network (NTN), reconfigurable intelligent surface (RIS), terrestrial network (TN).**

I. Introduction

With the anticipated arrival of 6G, we stand on the brink of a transformative generation in advanced communication services. Like its predecessors, 6G aims to deliver higher data rates, improved reliability, and ubiquitous connectivity [1]. The foundational enablers of 6G include both terrestrial networks (TNs) and non-terrestrial networks (NTNs). While TNs serve as the foundation of the global communication infrastructure, NTNs are set to complement TNs and extend connectivity into remote and rural areas. Thus, the integration of TNs and NTNs will create a robust three-dimensional (3D) network that is essential to achieve the ambitious goals of 6G communication. However, communications is not the only goal of future 6G networks. Over the past years, cellular communication systems have increasingly integrated positioning services, a trend that is becoming even more pronounced in 6G [2]. Positioning information is essential for a wide range of applications, including autonomous vehicles, smart cities, industrial internet of things (IoT), emergency response systems, and augmented reality. These applications impose rigorous requirements on positioning systems, demanding not only high accuracy, typically ranging from meters to centimeters, but also wide coverage, high reliability, low latency, and resilience in challenging environments. Generally, existing TNs and NTNs cannot fully meet these demanding requirements independently. For example, the coverage of TNs is constrained by the availability and density of infrastructure, whereas satellite signals in NTNs experience significant degradation due to obstruction and attenuation in dense urban areas [3]. Addressing these challenges requires *an integrated approach that leverages the strengths of both TNs and NTNs* to deliver precise and reliable positioning under diverse conditions. However, the community's focus over the past years has been on TN-NTN integration for communication purposes [1], or on localization using standalone TNs [4]–[6] or NTNs [7], [8], rather than on the integration of TN and NTN for localization purposes. This represents a clear gap in the literature.

The purpose of this article is to provide a vision for TN-NTN integration from technical and standardization perspectives. We do that by first analyzing the characteristics of key 6G enablers in both networks and their interactions across various 6G frequency ranges (from FR1 to sub-THz frequencies). This analysis will help identify the most suitable combinations of enablers and frequency ranges for effective integration. We then review the latest 3GPP standardization efforts for TN and NTN positioning, alongside recent advancements in proprietary NTN positioning, navigation, and timing (PNT) solutions, shedding light on anticipated industrial trends. Next, we highlight the challenges and opportunities of integrating TN and NTN, providing the research community with a list of key problems that require immediate attention. Finally, we present two numerical case studies of tightly integrated TN-NTN systems, further demonstrating the potential of this integration.

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This work is supported by the European Commission through the Horizon Europe/JU SNS project Hexa-X-II (Grant Agreement no. 101095759), the Swedish Research Council through Grants 2022-03007 and 2024-04390, the Spanish R+D project PID2023-152820OB-I00, the Catalan ICREA Academia Program, the King Abdullah University of Science and Technology (KAUST) Office of Sponsored Research (OSR) under Award ORA-CRG2021-4695, and Vinnova FFI project 2023-02603.

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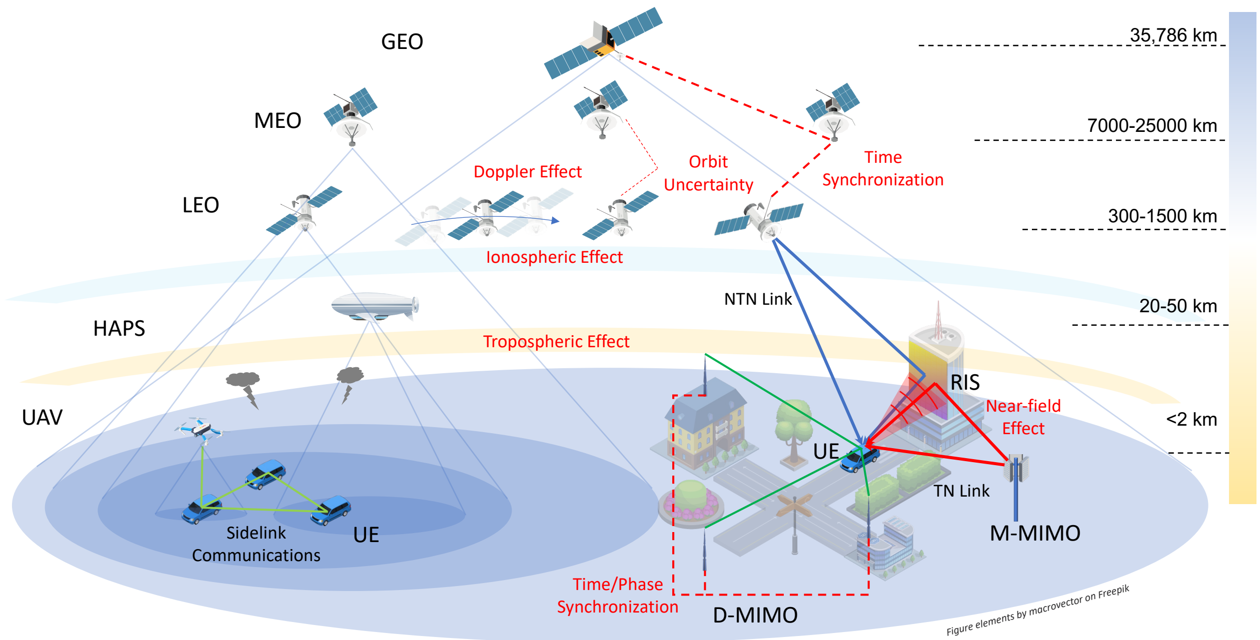

Fig. 1. Illustration of various NTN (GEO, MEO, LEO, HAPS, and UAV) and TN enablers (M-MIMO, D-MIMO, RIS, and sideline communications) and their characteristics (Doppler effect, orbit uncertainty, near-field effect, and time/phase synchronization).

II. 6G Localization Enablers and Characteristics

The enablers of 6G localization in both TN and NTN, shown in Fig. 6, come with distinct, yet complementary, characteristics, offering unique opportunities and challenges. These characteristics are shaped by the fundamental properties of these technologies, their operational frequency bands, and the localization environment. For example, the high altitudes of NTN systems enable extensive coverage but introduce latency and propagation challenges, distinguishing them from TN systems. Similarly, the envisioned operation of 6G across a broad frequency spectrum—from FR1 to FR4[1]—further diversifies the behavior and performance of these technologies across various scenarios. This section explores the characteristics of each 6G enabler, emphasizing their interplay with different frequency ranges and environmental conditions.

A. Terrestrial Networks

Massive multiple-input multiple-output (MIMO), distributed MIMO (D-MIMO), reconfigurable intelligent surfaces (RISs), and sidelink communications play a central role in enabling 6G TN-based localization. Each technology involves specific hardware requirements, algorithmic challenges, and benefits, as well as mobility considerations across various frequency bands under unique propagation conditions. The following sections will explore their distinct characteristics.

[1]While FR1 (sub-7.125 GHz) and FR2 (mmWave) are well-defined in the context of cellular communication standards, FR3 (7.125-24.25 GHz) and FR4 (90-300 GHz) are currently being studied and are not yet officially defined by 3GPP.

1) Massive MIMO: M-MIMO employs large antenna arrays at the base station (BS) to simultaneously serve multiple users over the same time-frequency resource, significantly increasing spectral efficiency through spatial multiplexing. Large antenna arrays also enable high-resolution angle estimation, making M-MIMO fundamental for achieving high-accuracy 6G localization. At FR1 (and likely FR3), digital arrays with dedicated RF chains per antenna element provide accurate angle estimation and robust multipath separation in dense propagation environments, avoiding the time-consuming beam sweeping required by hybrid and analog arrays. However, challenges include high hardware complexity and power consumption from the large number of RF chains, intricate multipath propagation (e.g., multi-bounce reflections and diffraction) and limited bandwidth, resulting in poor range resolution [9]. At FR2 (and likely FR4), M-MIMO accommodates denser antenna arrays under half-wavelength spacing and broader bandwidths, enabling narrow, high-gain beams that boost signal-to-noise ratio (SNR) and improve delay and angular resolution. The beam squint effect at these frequencies may also offer additional spatial cues for localization by illuminating different spatial regions at varying frequencies. However, localization with M-MIMO at FR2 and FR4 suffers from hardware imperfections (e.g., power amplifier nonlinearity and phase noise), analog/hybrid array constraints limiting mobility support and angle estimation, and harsh propagation conditions including line-of-sight (LoS) blockage and diffuse scattering [4].

2) Distributed MIMO: D-MIMO technology employs multiple geographically distributed access points (APs), coordinated to function as a unified system, providing improved SNR, in-

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creased uniformity of service quality, and superior interference management compared to M-MIMO systems. The benefits of D-MIMO in 6G localization include extended coverage through spatial diversity and enhanced multipath resolvability via phase-coherent processing in rich propagation environments [5]. At FR1 and FR3, D-MIMO systems can operate in phase-coherent mode, which transforms the entire network into an extremely large sparse array, substantially improving angular resolution. Due to relatively small bandwidths available at FR1 and FR3, phase coherence among distributed APs is crucial for high-accuracy localization as geometric information is conveyed through phase measurements [5]. Conversely, small phase and positional misalignment can severely deteriorate localization performance, placing stringent requirements on synchronization and geometry calibration. Moving higher up in frequency, phase-coherence across distributed nodes becomes more challenging. Therefore, at FR2 and FR4, D-MIMO typically shifts from phase-coherent to time-coherent mode and offers favorable delay resolution through large available bandwidths. Although time synchronization is less demanding than phase synchronization from both hardware and algorithmic perspectives, which benefits localization at FR2 and FR4, worsening hardware impairments can still degrade localization accuracy compared to that observed at FR1 and FR3.

3) Reconfigurable Intelligent Surfaces: RISs can dynamically control wireless signal propagation, enhancing coverage and signal quality in complex environments [6]. RIS technology includes various types, such as passive (low cost), active (high SNR), and simultaneously transmitting and reflecting (STAR)-RIS (wider coverage), each with unique operational characteristics. In all RIS types, out-of-band control can be exploited to share geometric information, which can aid in coordinating multiple RIS units and dynamically adjust their phase shifts. Acting as an extra anchor (i.e., a location reference node), a RIS can significantly improve localization by offering additional reference points for positioning, especially in non-line-of-sight (NLoS) scenarios. However, calibration of the surveyed position and orientation of RIS, non-ideal beam patterns, and variations in reflection coefficients are essential to achieve high-precision positioning. In addition to RIS calibration, the key challenges to be addressed include the computational complexity of optimizing RIS configurations in real-time and the high path loss caused by the RIS's multiplicative/cascaded double-fading channel.

4) Sidelink Communications: By leveraging sidelink communication, nodes, such as vehicles and unmanned aerial vehicles (UAVs), can share absolute or relative measurements to achieve higher positioning accuracy and robustness [10]. This approach allows for both explicit cooperation (sharing exact location information) and implicit cooperation (using relative geometric measurements between nodes), enhancing localization accuracy. However, cooperative localization requires an increased demand for bandwidth and efficient resource allocation to handle the extra data exchange. Privacy and security are also concerns, as sharing location or relevant measurement data can expose sensitive information. Advanced solutions like federated learning can address these privacy issues, while decentralized scheduling can reduce the data load and energy consumption to ensure scalability.

B. Non-terrestrial Networks

NTNs come in many variants and can be broadly categorized into space-based and aerial-based segments. In the former category, we count geosynchronous Earth orbit (GEO) satellites, medium Earth orbit (MEO) satellites, and low Earth orbit (LEO) satellites. In the latter category, we count high-altitude platform stations (HAPSs) and UAVs. In the following, we will discuss the technologies in each segment, highlighting their characteristics, opportunities, and challenges.

1) Space-based NTNs: Satellites share common traits such as high altitude above ground, susceptibility to atmospheric effects, and orbital state uncertainty. GEO satellites orbit at $35,786$ km, MEO satellites at $7,000$–$25,000$ km, and LEO satellites at 300–$1,500$ km above sea level. Their altitudes impact latency, path loss, beam footprint size, and LoS/NLoS characteristics, influencing link budgets, SNR, and susceptibility to jamming and spoofing. In addition, high satellite altitude results in poor positioning information gained from angle-based measurements. Hence, positioning with an independent satellite system requires access to multiple satellites to perform positioning, which might not be feasible in all scenarios. Next, atmospheric effects include ionospheric (more prominent in S and L bands, similar to FR1) and tropospheric effects (more prominent in Ku/FR3 and Ka/FR2 bands). These effects, categorized as fast (e.g., scintillation) or slow (e.g., absorption), can distort signal phases and must be modeled, estimated, and compensated to avoid positioning errors. Finally, orbital state uncertainty arises from factors like gravitational forces, atmospheric drag, and solar radiation pressure, which disturb satellite trajectories and require correction to enhance positioning accuracy.

A key distinction among these anchors is orbital mobility. GEO satellites, geosynchronous with Earth, experience minimal Doppler effects. On the other hand, MEO satellites, with approximately 12-hour orbital periods, exhibit moderate Doppler shifts, while LEO satellites, which typically take between 90 minutes and 2 hours to complete one full orbit, experience significant shifts. These Doppler shifts aid positioning but necessitate advanced estimation techniques. Differences in satellite footprints also matter. LEO systems require mega-constellations for global coverage, MEO constellations need fewer satellites, and GEO satellites, fixed above the equator, provide wider coverage. LEO and MEO constellations, offering diverse geographic observations, improve geometric dilution of precision (GDoP) and positioning accuracy but introduce coordination challenges that will be discussed later. Lastly, satellites are equipped with clocks that vary in quality and stability. For instance, GEO and MEO satellites, being less numerous and typically heavier, are equipped with atomic clocks, which are far more stable then the clocks in the more abundant and

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smaller LEO satellites. Hence, extra attention must be directed towards modeling of these clocks and estimating their biases to avoid loss in localization accuracy [11].

2) Aerial-based NTNs: Aerial nodes, encompassing HAPSs and UAVs, operate at lower altitudes than space-based systems, typically between $20 - 50$ km for HAPSs and a few hundred meters to several kilometers for UAVs, depending on the local regulations. Their proximity to Earth results in lower signal delays, transmission power, and path losses compared to satellites. HAPSs offer quasi-stationary wide-area coverage, similar to GEO satellites, making them suitable for remote and rural areas, while UAVs provide flexible and dynamic coverage in urban or emergency scenarios. Both systems primarily contend with tropospheric effects like rain attenuation and fog, as well as state uncertainties due to wind drift, affecting positioning accuracy. Furthermore, mobility varies between these systems. For instance, HAPSs are relatively stable, experiencing minimal Doppler shifts, whereas UAVs can introduce moderate Doppler effects due to their rapid movements, providing additional positioning information and adding complexity to using them as anchors. Despite these challenges, HAPSs and UAVs enhance localization performance by increasing the number of anchor points, enhancing the vertical GDoP, offering adaptable coverage, and bridging coverage gaps. However, they also introduce complexities in terms of real-time coordination, power management, interference handling, and path planning (in the case of UAVs), which must be carefully addressed to realize their full localization potential [11].

C. Frequency Dependencies

Table I summarizes the interaction of both terrestrial and non-terrestrial segments and the various envisioned 6G frequency ranges. The table shows that, in general, TN and NTN networks operating at lower frequency ranges are more mature, have higher coverage, are less affected by hardware impairments, environmental effects, and user mobility, and can achieve low to medium levels of positioning accuracy. On the other hand, operating at higher frequencies holds the potential of achieving higher positioning accuracy but at the cost of complexity of addressing high signal attenuation, LoS blockage, environmental effects, user equipment (UE) mobility issues, and hardware impairments. Hence, more research work needs be done to tackle these aspects in order to achieve the highest potential of these 6G enabler technologies.

III. 3GPP Standardization Activities

While 6G standardization is expected to commence with 3GPP's Release 20 by 2025, the groundwork for TN and NTN localization enablers has already been laid in 5G and 5G-Advanced standards (Releases 16 to 19). In this section, we will review the already established standards and will speculate on what the 6G standards might bring to the table.

A. 5G TN Standardization

Positioning services have been supported in all generations of cellular networks, starting from supporting emergency services and evolving the 5G system to also support commercial services with tighter positioning requirements. In terms of technology, one of the major innovations occurred in the 4G era, where dedicated reference signals for positioning, such as downlink (DL) positioning reference signals (PRS) and uplink (UL) sounding reference signals (SRS), were introduced. These came along with various positioning techniques, such as the DL-time difference of arrival (TDOA), UL-TDOA, and enhanced cell-ID (e-CID) [12]. In 5G, further enhancements were introduced, such as the usage of higher frequency (FR2) and M-MIMO to enable beamforming-based transmission and reception, which together with other enhancements, allowed new target requirements of 20 cm in accuracy and less than 10 ms in latency to be achieved. Furthermore, challenging scenarios where NLoS becomes dominant were also investigated. These resulted in enhancements and new positioning techniques being introduced in 3GPP Release 17 [13]. In 3GPP Release 18, even further positioning enhancements, such as the use of carrier phase measurements, and device-to-device positioning were introduced [13]. In the current 3GPP Release 19, a new feature on the usage of artificial intelligence/machine learning (AI/ML) for positioning enhancements is being specified.

B. 5G NTN Standardization

NTN was first studied in 3GPP Release 16 and then specified in Release 17. Although positioning procedures and solutions are still primarily developed for the TN, NTN still continuously evolves with new features for NR and IoT devices. Among these features, there is a limited positioning operation in NTN that was introduced in 3GPP Rel-18 with the purpose of supporting network-verified UE location with extremely coarse positioning accuracy (i.e., of the order of 10 km) [13]. This is to ensure that the UE is connected to the appropriate core network, particularly for a UE close to country borders. For this purpose, the method uses multiple satellite-UE round-trip time (RTT) measurements at different time instances as described in [7].

C. 6G NTN and TN Standardization

In the 6G time frame, NTN positioning is expected to have tighter requirements to support more use cases. The legacy positioning measurements in TN positioning, such as angle-based measurement (e.g., angle-of-arrival (AoA) and angle-of-departure (AoD)) and timing-based measurement (e.g., DL-TDOA, UL-TDOA, and multi-RTT), can be extended to NTN positioning. In NTN positioning, deployment scenarios where the UE sees either one or multiple satellites need to be considered, as they significantly affect how the positioning measurements are performed. Furthermore, at the advent of 6G, there is an opportunity to investigate new reference signals/waveforms for positioning. Such new signals could be adopted, especially

TABLE I
LOCALIZATION PROS AND CONS ACROSS DIFFERENT FREQUENCY RANGES

Frequency Range	TN		NTN	
	Pros	**Cons**	**Pros**	**Cons**
FR1: <7.125 GHz L and S bands	Mature technologies, phase-coherence exploitation in D-MIMO	Poor localization performance due to limited bandwidth and need for several visible BSs	Wide coverage, penetration capabilities	Lower range accuracy, ionospheric effects
FR3: 7.125–24.25 GHz X, Ku, and K bands	Improved localization flexibility due to wider spectrum and availability of angle-based measurements	Fragmented spectrum and need for several visible BSs	Balanced localization performance, low interference risks	Intermediate accuracy, tropospheric effects
FR2: 24.25–52.6/57–71 GHz Ka and V bands	High capacity for accurate localization, low latency positioning	Limited coverage in obstructed areas, higher cost of dense deployments, impairments, mobility limitations	High-precision localization and intermediate coverage	High signal attenuation, dependence on LoS links, tropospheric effects
FR4: 90–300 GHz sub-THz bands	Massive potential for high-accuracy positioning, minimal latency	LoS limitations, high cost of infrastructure, impairments, less mature technology, mobility limitations	Ultra-high precision localization, high security and privacy	Extreme path loss, sensitive to weather and environment, misalignment, less mature technology

when they prove beneficial in comparison to the legacy PRS and SRS. The network architecture to support NTN positioning is expected to be developed based on the legacy TN positioning architecture by involving the location management function (LMF). However, it is expected that there will be some enhancements through adding new features/functions and also in the signaling mechanism between network nodes. Although TN and NTN positioning have operated independently and have been used for different purposes in 5G, we envision that 6G TN and NTN will be co-designed from the start. This will facilitate a common signal design and network architecture, enabling a smooth integration of TN and NTN.

IV. Industrial Advancements

Industrial players, such as SpaceX, play a crucial role in exploring alternative and complementary solutions that have not been addressed by 3GPP standardization. In particular, the use of LEO satellites for PNT has attracted significant attention in recent years. These efforts include the deployment of dedicated LEO constellations for PNT services, as well as leveraging signals of opportunity (SoOP) from constellations originally designed for communication purposes. In this section, we discuss advancements in both dedicated and opportunistic NTNs.

A. LEO PNT with Dedicated Systems

LEO constellations specifically designed for PNT are being developed as complementary systems to GNSS or as standalone alternatives. Initiatives such as the European Space Agency's efforts to develop a dedicated LEO-PNT constellation highlight this trend. Companies like TrustPoint, Xona Space Systems, Geely, and Future Navigation are actively developing their own LEO satellite constellations, consisting of 288, 258, 240, and 160 satellites respectively, to deliver high-accuracy PNT services. These systems are required to transmit ephemeris data, clock bias, and drift corrections, and may include atmospheric effects, providing the essential information for precise PNT solutions. Different signal structures are under investigation for LEO-PNT applications, including orthogonal frequency division multiplexing (OFDM) signals, direct-sequence spread spectrum (DSSS) signals, and chirp spread spectrum (CSS) signals, each with specific advantages and challenges [14]. Direct-sequence spread spectrum (DSSS) signals, commonly employed in GNSS systems, can face challenges in acquisition and tracking due to the rapid motion of LEO satellites, necessitating modifications from standard GNSS receivers. In contrast, CSS signals can avoid the two-dimensional Doppler-delay search required for acquisition in the GNSS architecture, enabling lower complexity solutions in scenarios with large Doppler shifts. However, further investigation is required to achieve accurate ranging, access multiple satellites, and enable data transmission using CSS signals for LEO-PNT. Currently, many aspects of these dedicated LEO-PNT systems are still under development, with ongoing efforts to refine technology and deploy infrastructure.

B. LEO PNT via SoOP

LEO satellites, originally designed for non-navigation purposes, can also serve as valuable resources for localization by opportunistically utilizing their signals. Existing LEO constellations suitable for PNT via SoOP include Starlink, Orbcomm, Argos, Iridium, Globalstar, and others, each operating with distinct frequency bands and modulation schemes [8]. Currently, thousands of satellites from multiple operators are in orbit, with tens of thousands anticipated in the near future. A key advantage of SoOP is its ability to utilize a wide variety of ambient satellite signals, increasing signal diversity and maximizing resource efficiency. However, the absence of signal specifications, often due to business security or privacy concerns, introduces considerable challenges in signal processing and synchronization. Currently, efforts are underway to develop advanced signal processing techniques and receiver architectures capable of extracting key observations for po-

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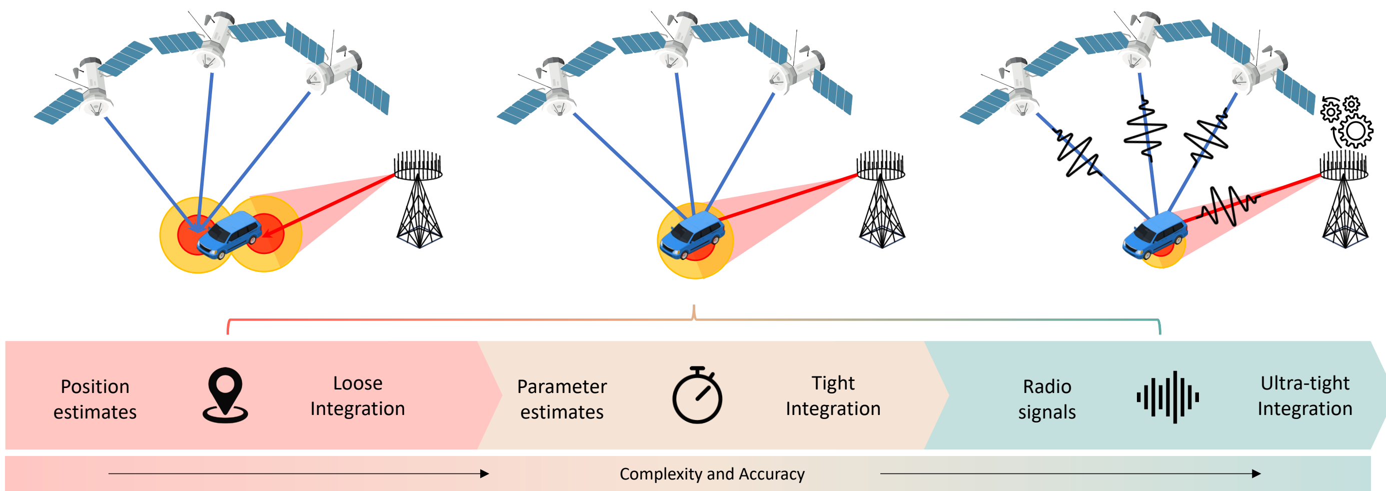

Fig. 2. Levels of TN-NTN integration. Loose integration (left) combines the final position estimates from each network. Tight integration (middle) fuses parameter estimates such as range and angle measurements to determine the UE's position. Ultra-tight integration (right) co-designs and processes raw I/Q samples from both networks for ultimate enhancement of positioning performance. Higher integration levels offer improved accuracy but come with increased complexity.

sitioning applications, including Doppler shift, carrier phase, and pseudo-range. This can be achieved by leveraging the inherent characteristics of these signals, along with techniques such as blind beacon estimation, machine learning-based signal processing, and other advanced methods [8].

V. Integration Challenges, Opportunities, and Case Studies

While both TN and NTN offer advanced localization capabilities, their integration remains largely unexplored. Combining these networks promises higher accuracy and a seamless, globally unified localization service. Integration can occur at various stages of the localization pipeline, which includes designing the communication system, estimating geometric channel parameters, and fusing those parameters to determine the user's position. Hence, integration is typically categorized into three levels: loose, tight, and ultra-tight, as shown in Fig. 7. *Loose integration* combines the final position estimates from each system. For instance, it requires independent multilateration from at least four non-terrestrial anchors, along with a positioning solution from one or more terrestrial BSs, which are then fused to enhance accuracy. *Tight integration*, by contrast, operates on geometric measurements, removing the need for independent multilateration from multiple non-terrestrial anchors. It can fuse a single range measurement from an NTN anchor with range and angle measurements from a BS or an RIS, offering greater flexibility and accuracy at the cost of increased system complexity. *Ultra-tight integration* takes this further by modifying both networks at earlier stages. These modifications, ranging from joint resource allocation to unified physical-layer design, significantly boost performance but also add complexity. Although every integration schemes has its pros and cons, all of them share a set of challenges to be solved and opportunities to be reaped. Hence, this section outlines

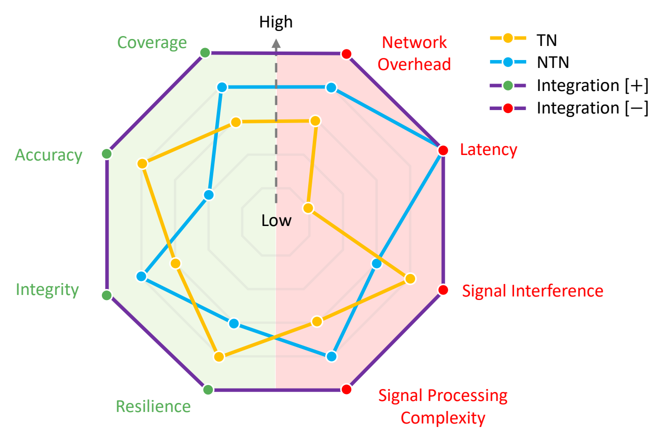

Fig. 3. Evaluation of characteristics of TN, NTN, and their integration for localization purposes. The characteristics on the left-hand side are positive (further from the center is better) and the characteristics on the right-hand side are negative (closer to the center is better).

the key challenges and opportunities of TN-NTN integration, summarized in Fig. 8, and explores its potential through two tight integration case studies to highlight the opportunities in this domain.

A. Challenges

Integrating TN and NTN for localization presents several technical challenges, including increased network overhead, higher processing latency, stronger signal interference, and greater signal processing complexity, as highlighted in red in Fig. 8. These challenges need to be addressed before we are able to reap the benefits of the TN-NTN integration.

1) Network Overhead: The integration of TN and NTN requires frequent information exchange among terrestrial base

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stations, gateways, non-terrestrial anchors, and user terminals, leading to increased signaling overhead. This is particularly evident in managing handovers, synchronization, and control signaling across diverse links. Such overheads will be exacerbated as the TN-NTN integration becomes tighter. Having an increased network overhead will have a negative effect on the communication rate, counteracting the primary goal of such an integration in the first place

2) Latency: Compared to TN, the long propagation distances inherent to NTN links introduce significant delays, which can impair time-sensitive applications such as vehicular networks and autonomous systems. Such latency is expected to increase due to the extra signaling needed for integration. Increased latency will, in turn, cause positioning errors in scenarios where the user is mobile. For instance, if a vehicle is driving at 72 km/h, a latency of 100 ms will cause a positioning error of 2 m, which exceeds the lane-level accuracy requirements for autonomous vehicles.

3) Signal Interference: The coexistence of terrestrial and non-terrestrial links creates complex interference scenarios, which can arise from overlapping frequency bands, multipath propagation, or inter-satellite, HAPS, and UAV links. Managing such interference in a dynamic environment adds further complexity to system design and operation. If not properly managed, interference can cause severe degradation in positioning accuracy.

4) Signal Processing: Achieving high localization accuracy in integrated systems requires advanced signal processing algorithms to address challenges, such as varying observations, non-stationary fading, fluctuating SNR levels, and coupled external factors (e.g., atmospheric effects, hardware impairments, mobility, and anchor state uncertainty). These factors collectively contribute to a significant increase in computational complexity.

B. Opportunities

Integrated TN-NTN systems will offer significant opportunities in terms of coverage, accuracy, integrity, and resilience, as highlighted in green in Fig. 8.

1) Coverage: Both TN and NTN have coverage limitations. NTN struggles in urban canyons, dense indoor areas, and regions with signal blockage, while TN faces challenges in remote or rural areas. The integration of TN and NTN overcomes these limitations by combining NTN's global coverage with TN's regional reach, ensuring seamless localization across all environments and providing ubiquitous coverage.

2) Accuracy: TN-NTN integration can enhance localization accuracy for the following two reasons: (i) it leverages multi-source data fusion, and (ii) the dispersed localization anchors in ground, air, and space environments significantly improve the GDoP, leading to more accurate localization performance.

3) Integrity: TN-NTN systems offer higher localization integrity, i.e., enhanced trustworthiness and reliability, by cross-validating information from multiple sources. This is critical for safety-sensitive applications such as aviation, maritime navigation, and autonomous driving.

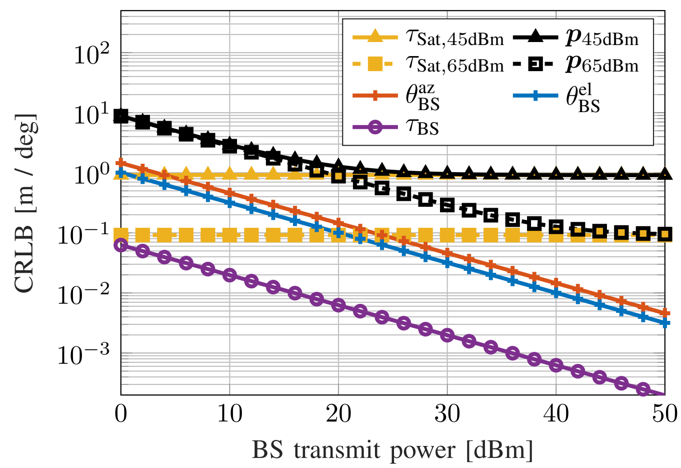

Fig. 4. Case study 1: Illustration of localization performance in a single-LEO single-BS scenario. The CRLB of delays and position estimates are in meters and the CRLB of angles are in degrees. Two satellite transmission powers were tested, 45 dBm and 65 dBm, illustrated in solid lines with triangle marks and dotted lines with square marks, respectively. The setup operates at 2 GHz carrier frequency, 50 MHz bandwidth, single antenna at the UE (80 km/h) and the satellite, 2x2 array at the BS, 15 dB noise figure, 4 OFDM symbols, 1200 km LEO satellite altitude, 250 m UE-BS distance, and UE-network clock bias and carrier frequency offset (CFO) assumptions.

4) Resilience: TN-NTN integration improves resilience against jamming and spoofing by leveraging signal diversity and redundancy across terrestrial and non-terrestrial networks. Non-terrestrial anchors, being less vulnerable to ground-based jamming, provide an additional layer of robustness, while advanced signal processing techniques, like jammer localization, enable interference suppression and anomaly detection.

C. Integration Case Studies

In this section, we use two case studies to illustrate the potential of TN-NTN integration in localization. Both case studies are examples of tight TN-NTN integration (i.e., integration on the measurement level). However, there are slight differences when it comes to their positioning accuracy due to the different setups and channel models used.

1) Single-BS-Single-LEO Localization: The first case study explores the integration of a terrestrial BS with a single LEO satellite to localize a vehicular user in an urban scenario. This case study focuses on the effectiveness of arbitrarily increasing the BS's transmission power on the localization performance without coordination with its NTN counterpart. In this scenario, two LEO transmission power levels were tested while the BS transmission power was varied from 0 dBm to 50 dBm. The simulation results, shown in Fig. 9, present the CRLB on the BS's delay and angle estimation, the LEO's delay estimation, and the user's position estimation. The results show that increasing the BS's transmission power enhances BS-based measurements, leading to improved positioning accuracy. However, this improvement continues only up to a certain point, beyond which the positioning accuracy saturates, constrained by the quality of satellite-based delay estimates. This is further verified as the saturation point was lowered when using higher

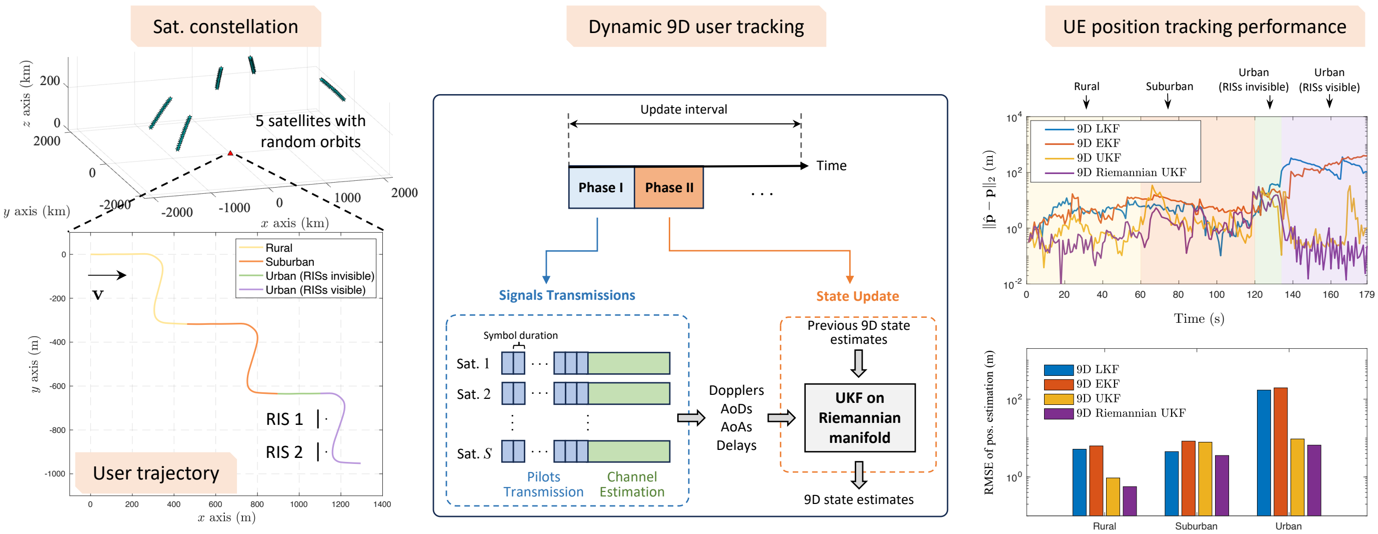

Fig. 5. Case study 2: Illustration and performance evaluation of a LEO- and RIS-empowered 9D user tracking system. Based on the estimated channel parameters—such as Doppler shifts, AoDs, AoAs, and channel delays—derived from the received pilot signals, we filter and update the 3D position, 3D velocity, and 3D orientation of the UE using a designed unscented Kalman filter (UKF) on a Riemannian manifold [15], benchmarked against the classical linearized Kalman filter (LKF), extended Kalman filter (EKF), and UKF. The performance has been comprehensively evaluated across various environments.

transmission power at the satellite's side. This study highlights the need for proper coordination between NTN and TN to avoid wasting valuable resources without achieving significant improvements in positioning performance.

2) Multi-LEO- and Multi-RIS-empowered User Tracking: In the second case study, we investigate a hybrid system that integrates LEO satellites and terrestrial RISs for user-tracking applications. Fig. 10 illustrates a cooperative DL framework to coordinate different satellite transmissions and RIS reflections. By exploiting the acquired channel parameters and the UE's motion dynamics, a tracking algorithm, proposed in [15], enables comprehensive tracking of the 3D position, velocity, and orientation of the UE. The algorithm is based on a UKF and Riemannian manifold theory to address inherent challenges such as nonlinear observation models, constrained unknown states, and time-varying observation uncertainties. From Fig. 10, we observe that the considered system gains a significant performance improvement in the RIS-visible areas, compared to RIS-invisible areas. This suggests that integrating RIS with LEO satellites holds substantial potential for enhancing user tracking performance, with appropriate signal-processing algorithms.

VI. Conclusions and Outlook

The integration of terrestrial and non-terrestrial networks offers a promising yet challenging path toward high-precision 6G localization. In this article, we examined the strengths and weaknesses of 6G enablers in both segments, demonstrating that by leveraging the complementary advantages of TN and NTN, 6G systems can provide seamless localization in various environments. However, significant challenges remain, including network interoperability, high overhead, Doppler effects, synchronization issues, and the need to mitigate overlapping sources of errors and hardware imperfections. Addressing these challenges requires the development of both innovative signal processing and networking techniques, along with aligned standardization and industrial solutions to ensure effective TN-NTN integration. Moving forward, the community should carefully study and decide on the optimal combination of integrated 6G enablers, the frequency of operation, and the level of integration for each application scenario to balance performance gains with solution complexity and operational constraints.

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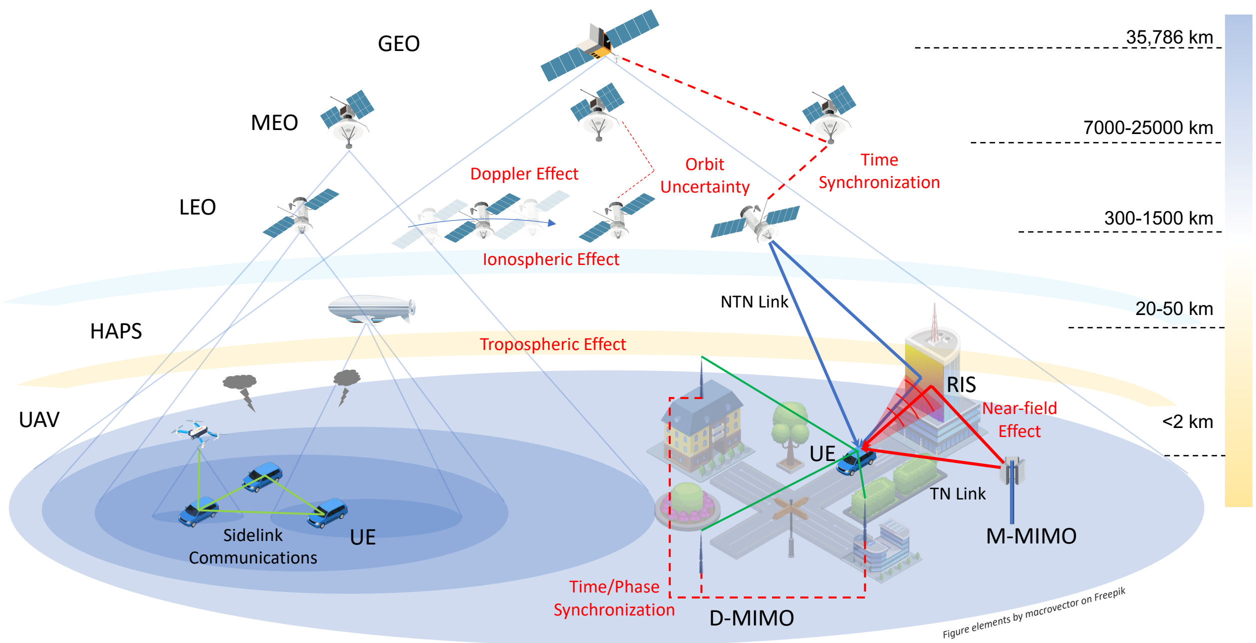

Fig. 6. Illustration of various NTN (GEO, MEO, LEO, HAPS, and UAV) and TN enablers (M-MIMO, D-MIMO, RIS, and sideline communications) and their characteristics (Doppler effect, orbit uncertainty, near-field effect, and time/phase synchronization).

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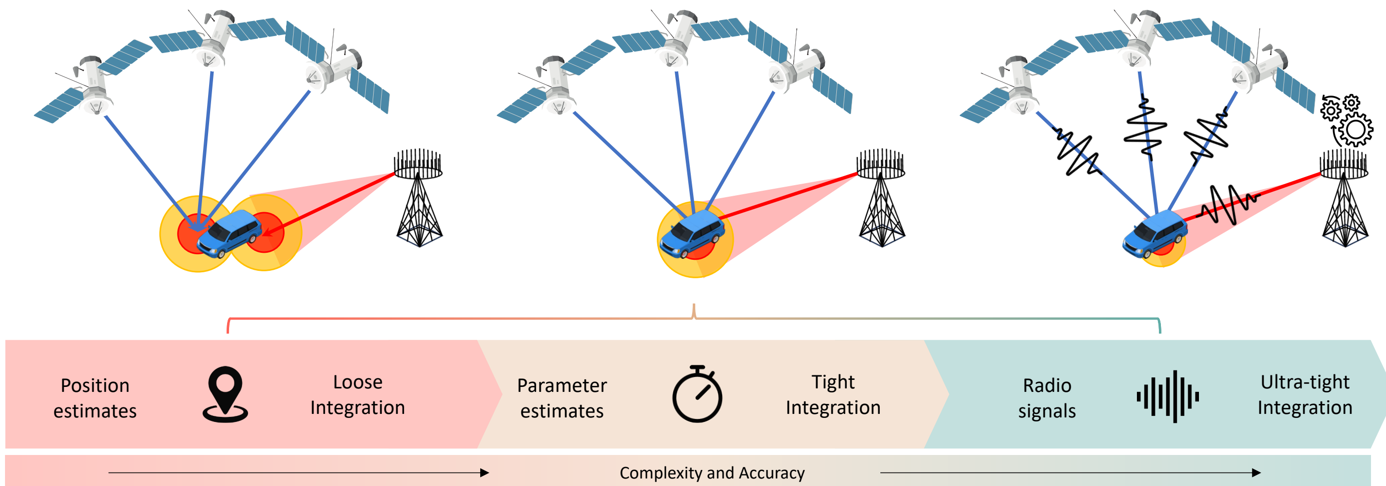

Fig. 7. Levels of TN-NTN integration. Loose integration (left) combines the final position estimates from each network. Tight integration (middle) fuses parameter estimates such as range and angle measurements to determine the UE's position. Ultra-tight integration (right) co-designs and processes raw I/Q samples from both networks for ultimate enhancement of positioning performance. Higher integration levels offer improved accuracy but come with increased complexity.

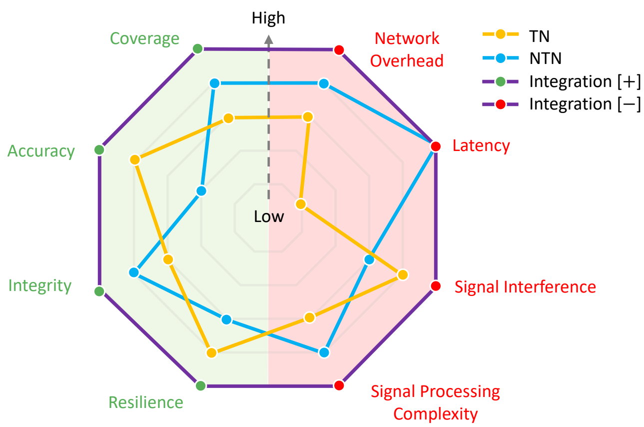

Fig. 8. Evaluation of characteristics of TN, NTN, and their integration for localization purposes. The characteristics on the left-hand side are positive (further from the center is better) and the characteristics on the right-hand side are negative (closer to the center is better).

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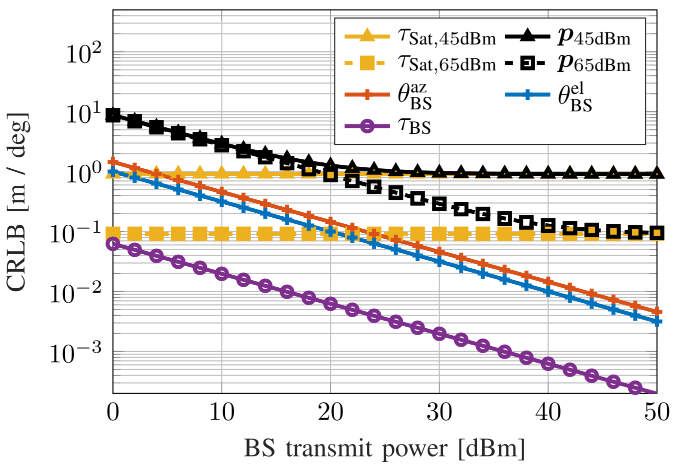

Fig. 9. Case study 1: Illustration of localization performance in a single-LEO single-BS scenario. The CRLB of delays and position estimates are in meters and the CRLB of angles are in degrees. Two satellite transmission powers were tested, 45 dBm and 65 dBm, illustrated in solid lines with triangle marks and dotted lines with square marks, respectively. The setup operates at 2 GHz carrier frequency, 50 MHz bandwidth, single antenna at the UE (80 km/h) and the satellite, 2x2 array at the BS, 15 dB noise figure, 4 OFDM symbols, 1200 km LEO satellite altitude, 250 m UE-BS distance, and UE-network clock bias and carrier frequency offset (CFO) assumptions.

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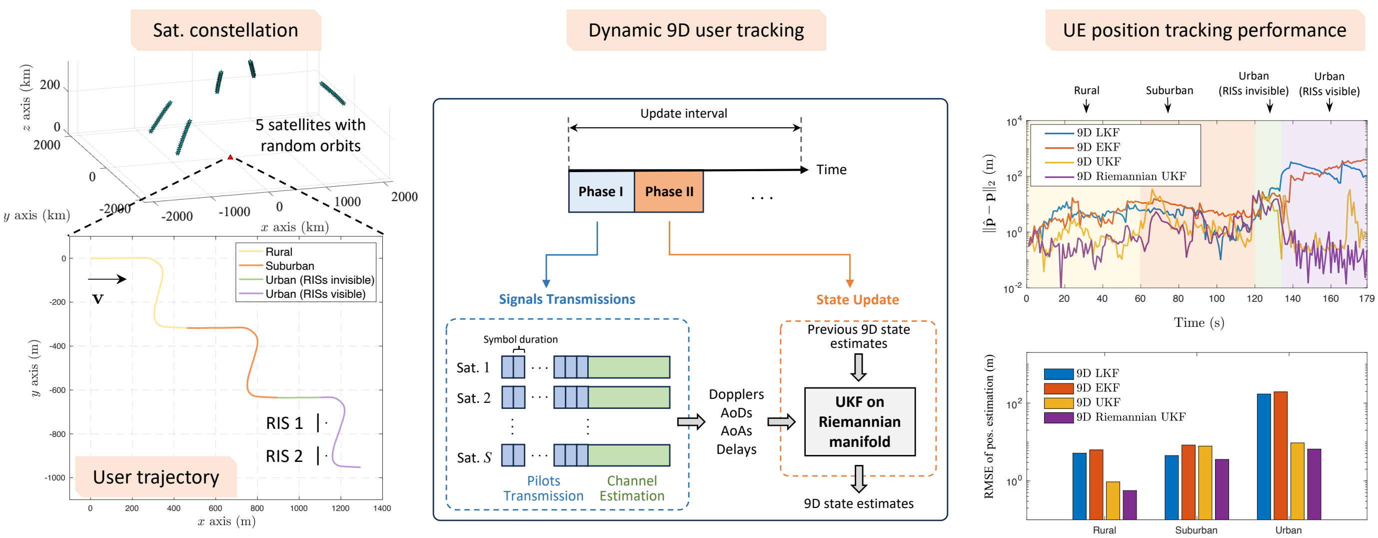

Fig. 10. Case study 2: Illustration and performance evaluation of a LEO- and RIS-empowered 9D user tracking system. Based on the estimated channel parameters—such as Doppler shifts, AoDs, AoAs, and channel delays—derived from the received pilot signals, we filter and update the 3D position, 3D velocity, and 3D orientation of the UE using a designed unscented Kalman filter (UKF) on a Riemannian manifold [15], benchmarked against the classical linearized Kalman filter (LKF), extended Kalman filter (EKF), and UKF. The performance has been comprehensively evaluated across various environments.