Vision: Leveraging Low Earth Orbit Satellites for Future Ubiquitous Positioning

Sherif Mostafa*
sherif_mostafa@aucegypt.edu

Mahmoud Elsanhoury†
mahmoud.elsanhoury@uwasa.fi

Jaakko Yliaho†
jaakko.yliaho@uwasa.fi

Janne Koljonen†
janne.koljonen@uwasa.fi

Heidi Kuusniemi†
heidi.kuusniemi@uwasa.fi

Mohammed Elmusrati†
mohammed.elmusrati@uwasa.fi

Khaled A. Harras‡
kharras@cs.cmu.edu

Moustafa Youssef*
moustafa-youssef@aucegypt.edu

Abstract

Designing a globally ubiquitous positioning system that works seamlessly in all environments remains a critical area of ongoing research. While Global Navigation Satellite Systems (GNSS), such as GPS, are the predominant technology for global outdoor positioning, they fail in areas with physical obstructions (e.g., dense urban regions and indoors) and are prone to jamming. These limitations significantly restrict their global accessibility and dependability, highlighting the need for supplementary positioning technologies.

Recently, private companies like SpaceX have started deploying Low Earth Orbit (LEO) satellites for various applications, primarily communication. LEO satellites operate at much lower altitudes than GNSS satellites, offering higher signal penetration capabilities and reduced susceptibility to jamming, making them a promising complementary positioning technology. In this paper, we present our vision for opportunistically leveraging LEO satellite signals to achieve ubiquitous and reliable global positioning. We explore diverse opportunities enabled by our vision and discuss the multidisciplinary challenges that must be addressed for its realization.

CCS Concepts

• **Information systems** → **Global positioning systems**; • **Human-centered computing** → **Ubiquitous and mobile computing**.

Keywords

Ubiquitous positioning, LEO satellites, GNSS, Navigation

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*S. Mostafa and M. Youssef are with The American University in Cairo, Cairo, Egypt.
†M. Elsanhoury, J. Yliaho, J. Koljonen, H. Kuusniemi, and M. Elmusrati are with University of Vaasa, Vaasa, Finland.
‡K. A. Harras is with Carnegie Mellon University, Doha, Qatar.

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1 Introduction

Global Navigation Satellite Systems (GNSS), including the US GPS, the European Galileo, the Chinese BeiDou, among others [16], are widely recognized as the standard for global outdoor positioning. These systems rely on government-controlled Medium Earth Orbit (MEO) satellite constellations, currently totaling 139 satellites, which orbit Earth at high altitudes of *20,000* to *35,000* km above sea level [16] (Table 1). Although GNSS systems are dedicated to providing positioning and navigation services, they face several challenges that compromise their universal availability and reliability. Specifically, high orbital altitudes cause GNSS satellite signals to reach Earth significantly attenuated, making them unavailable in areas with physical obstructions, e.g., tunnels, canyons, dense urban areas, regions with heavy vegetation, and; most notably; **indoor environments** [1, 11]. Moreover, GNSS signals are vulnerable to jamming due to their weak strength [9], affecting their dependability. *These limitations highlight the need for alternative positioning technologies that can complement GNSS-based solutions to achieve truly ubiquitous global positioning, both outdoors and indoors.*

Recently, several private companies have begun to deploy satellite constellations in Low Earth Orbit (LEO), operating at much lower altitudes of *160* to *2000* km above sea level (Table 1). To provide worldwide coverage at these low altitudes, LEO constellations comprise a much larger number of satellites than GNSS constellations, currently totaling over 5000 satellites with plans to surpass **50,000** satellites before the decade's end [3]. These LEO constellations are typically deployed for applications other than positioning, including global communication and Internet service (e.g., SpaceX

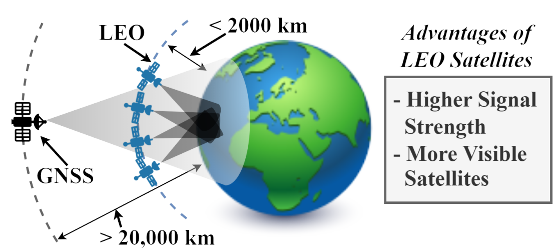

Figure 1: Altitude of GNSS satellites vs. LEO satellites.

Table 1: Comparison Between GNSS and LEO Constellations

Constellations	Altitude	Orbital Period	Number of Satellites	Dedicated to Positioning	Examples
GNSS	20,000-35,000 km	12-24 hours	Current: 139	✓	GPS, Galileo, BeiDou
LEO	160-2000 km	90-120 minutes	Current: >5000; Planned: >50,000	✘	Starlink, Kuiper, OneWeb, Argos

Starlink, Amazon Kuiper, and Eutelsat OneWeb), Earth observation and surveillance (e.g., Argos) and IoT applications (e.g., Astrocast).

Although not part of their mission, LEO satellites, with their closer proximity to Earth and significantly larger number compared to GNSS satellites, present substantial advantages for potential use as positioning technology (Figure 1). First, lower orbital altitudes cause LEO satellite signals to be up to **three orders of magnitude** stronger than GNSS signals [5]. This makes them more capable of penetrating physical obstructions and hence can reach GNSS-deprived areas, including **indoor environments** [5]. Moreover, the higher LEO satellite signal strength makes them **less susceptible to jamming** [9], improving their reliability. Second, simulations indicate that fully deployed LEO constellations will provide up to **75 times** more visible satellites per Earth point compared to GNSS [5], offering a much richer source of information for ubiquitous positioning and navigation systems. Although these advantages position LEO satellites as a promising complementary technology to GNSS, their application in positioning is under-researched.

Our vision *is to leverage LEO satellite constellations to enable truly ubiquitous and reliable global positioning*. Since LEO constellations are not specifically designed for positioning (unlike GNSS), conventional GNSS-based positioning techniques cannot be directly applied to LEO satellite signals. Instead, to realize our vision, LEO satellite signals can be *opportunistically* utilized for positioning by extracting information from the received signal characteristics, similar to the fingerprinting and range-based methods that use terrestrial communication infrastructure for positioning [10].

In this paper, we demonstrate how the benefits of LEO satellites over GNSS satellites, combined with their global coverage compared to indoor positioning technologies, can create opportunities for positioning systems *(Section 2)*. We also highlight the multi-disciplinary research challenges that must be addressed to materialize the vision *(Section 3)*.

2 Opportunities

Building on the advantages of LEO satellites compared to GNSS satellites, we now explore the different opportunities enabled by leveraging them for future ubiquitous positioning.

2.1 Outdoor Positioning Opportunities

To address the GNSS signal unavailability in outdoor areas with physical obstruction such as tunnels and dense urban regions, current systems propose fusion with inertial sensors to perform dead-reckoning during periods of GNSS unavailability [1]. However, common inertial sensors suffer from high noise that causes rapid location error accumulation in case of prolonged GNSS unavailability, reaching up to **100 meters** after just one minute [2]. Leveraging LEO satellite signals with their higher penetration capabilities can enhance the robustness of available systems and allow **seamless outdoor positioning** even in GNSS-deprived areas. Furthermore, in case of fusion with inertial sensors, LEO satellite signals can provide more calibration opportunities to reset sensor errors, improving accuracy compared to systems based only on GNSS signals.

2.2 Indoor Positioning Opportunities

Since GNSS cannot be used indoors, several indoor positioning systems have been proposed based on alternative technologies that rely on *indoor infrastructures* [6, 7, 10], e.g., WiFi, Bluetooth Low Energy (BLE), and Ultra-Wideband (UWB). Compared to these technologies, leveraging LEO satellite signals can provide opportunities for **infrastructure-free global indoor positioning**.

In particular, available indoor positioning systems require dense indoor infrastructures to function well, which can lead to additional deployment and maintenance costs. Moreover, indoor infrastructure can fail in some emergencies, such as power outages, compromising the reliability of these systems. In contrast, a LEO-based indoor positioning system would leverage globally accessible extraterrestrial satellite constellations, eliminating the need for additional indoor infrastructure deployments and offering higher reliability in emergencies, as LEO satellites are unaffected by local power outages. Furthermore, leveraging LEO satellites for indoor positioning aligns with the vision of realizing a *global indoor positioning system (IPS)* [24] that can work in any building *worldwide*. Current proposals are mainly based on building a global database that maps information from worldwide indoor infrastructures to user locations [24]. Still, the accuracy of these proposals is highly dependent on the density of the indoor infrastructure, e.g., a WiFi-deprived environment cannot be served by such a global IPS. In contrast, using LEO satellite signals provides global coverage, ensuring equal access even in environments lacking indoor infrastructures.

2.3 Extraterrestrial Positioning Opportunities

NASA has recently outlined missions for multi-month stays on the Moon in preparation for sending astronauts to Mars by the 2030s [15]. Moreover, commercial companies like SpaceX [20] have expressed interest in similar missions. The primary goal is to build a sustainable human presence on the Moon and Mars, allowing astronauts to live and work there while ensuring their safe return to Earth. Achieving this goal requires the development of various technologies, including reliable positioning and navigation systems on the surfaces of these extraterrestrial bodies. Currently, reconnaissance satellites orbit around the Moon [17] and Mars [18] in *low orbits* for communication, exploration, and imagery purposes. One approach for designing positioning systems on the Moon and Mars can be to leverage the signals from these reconnaissance satellites, similar to our vision of using LEO satellite signals on Earth. Considering the similarity between these reconnaissance satellites and LEO satellites, studying LEO satellite-based positioning and its challenges can provide opportunities for reliable extraterrestrial positioning, paving the way for space exploration and colonization.

3 Challenges

In this section, we discuss the multi-disciplinary research challenges that must be addressed to realize our vision, grouped into *constellation-related*, *performance-related*, and *user-related.*

3.1 Constellation-related Challenges

3.1.1 Absence of Positioning Parameters. Since LEO constellations are not deployed for positioning services, their signals lack the positioning parameters (e.g., satellite location and speed) needed by typical GNSS-based systems. A possible solution to this challenge is to rely on open-access satellite location estimates published by ground-based tracking stations and on information extracted from signal characteristics (e.g. Doppler shifts and signal strength) to estimate the positioning parameters [5, 9]. This paves the way for the realization of our vision by *opportunistically* leveraging already deployed LEO satellite signals without any modifications.

However, ground-based satellite location tracking estimates typically suffer from poor accuracy [5]. Moreover, extracting signal characteristics incurs a reverse engineering burden since private companies owning the constellations rely on proprietary non-standardized signals with limited public information on their structure [9]. A promising research direction is to employ differential positioning techniques using LEO receiver stations with known locations to provide corrections for positioning parameter errors (similar to differential GNSS). Furthermore, recognizing the advantages and potential global market of using LEO satellite signals for ubiquitous positioning can incentivize these companies to cooperate with positioning service providers to improve accuracy. For example, they can provide positioning parameters in their satellite signals or share information regarding their signal structures. Most LEO satellites track their ephemeris (i.e., location and speed) using attached GNSS receivers [5], so software updates can enable them to share this information without requiring the deployment of new satellites.

3.1.2 High-Speed Orbits. The close proximity of LEO satellites to Earth results in much faster orbital speeds compared to GNSS satellites, leading to non-geosynchronous orbits. This causes frequent handovers at ground receivers and rapid satellite ephemeris updates compared to GNSS satellites, affecting positioning accuracy if not properly managed. Thus, it is crucial to develop techniques that mitigate the effects of high LEO satellite orbital speeds with minimal increase in the complexity of the positioning system. Moreover, this absence of geosynchronicity poses a challenge for fingerprinting-based solutions. Specifically, the same satellite signal characteristics can correspond to multiple different locations as the satellite orbits Earth. This issue can possibly be addressed by including satellite trajectory information within the fingerprint data.

3.1.3 Low Satellite Coverage Area. The low orbital altitudes of LEO satellites result in smaller coverage areas compared to GNSS satellites (Figure 1). This can decrease the positioning accuracy of a LEO-based system if an insufficient number of satellites are visible and also requires long processing intervals to detect and track satellites, increasing location update latency [9]. This challenge can be overcome by the large number of satellites planned for deployment, significantly enhancing the LEO satellites visibility (Table 1). Moreover, leveraging different LEO constellations simultaneously can ensure the necessary visibility to multiple satellites.

3.2 Performance-related Challenges

3.2.1 Enhancing Performance Indoors. The higher coverage range of LEO satellites compared to indoor infrastructures coupled with indoor environment challenges such as fading and multipath effects makes achieving high indoor positioning accuracy with a LEO-based system challenging. Enhancing the performance of a LEO-based indoor positioning system is crucial, as an error of just a few meters can position the user in a completely different room.

LEO satellites are planned to incorporate *massive multi-antenna beamforming* capabilities [23], which can help mitigate indoor multipath effects and enhance positioning accuracy. Moreover, the planned multi-antenna capabilities of LEO satellites can provide more information for the indoor positioning system by employing recent deep learning models to detect spatio-temporal beam patterns from multiple satellites, improving the positioning granularity. This can be further enhanced by relying on multiple satellite constellations simultaneously, increasing the available information for the system. In addition, fusion with inertial sensors, indoor floor plans, and indoor positioning technologies (e.g., WiFi), when available, can be a promising direction to reduce positioning errors.

3.2.2 Absence of Training and Evaluation Datasets. Building reliable LEO-based positioning systems and comprehensively evaluating them requires a large amount of location-labeled training and evaluation signal data covering different challenging scenarios (e.g., tunnels, indoors, and with moving receivers). However, collecting such data incurs significant time and cost overheads. To address this challenge, a collaborative *open-source* dataset can be established where users worldwide contribute location-labeled LEO satellite signal measurements to a public repository. This community-driven initiative can allow us to collect, edit, and update LEO satellite data on a global scale similar to projects such as OpenStreetMap (which maintains open-source global maps). This can substantially reduce the time and cost barriers associated with collecting LEO-based positioning data for future research. *Note that implementing such a data collection approach would require incentive models for user participation, which we discuss in the user-related challenges.*

Another direction is to build a comprehensive simulator that models the different factors affecting a LEO satellite signal, e.g. the satellite orbital dynamics, atmospheric effects, and signal attenuation and multipath effects. This simulator can be used in training and evaluating LEO-based positioning systems. Current research efforts that provide open-access simulators for LEO modeling either focus on the orbital dynamics only [21] or on the wireless channel only [8]. Building a comprehensive simulator that models all factors is open for further investigation.

3.2.3 Robustness Against Attacks. Because of their higher signal strength and proprietary characteristics, LEO satellite signals are less vulnerable to jamming and spoofing attacks compared to GNSS-based systems [9]. Nevertheless, LEO satellite signals can still be subject to interference. Moreover, building an open-source LEO satellite signals dataset can introduce data poisoning vulnerabilities, reducing accuracy. Studying the effects of potential attacks on a LEO satellites-based positioning system and devising security measures to ensure robustness to these attacks, e.g., outlier detection methods to prevent data poisoning, is a direction for future research.

3.3 User-related Challenges

3.3.1 Positioning Services Democratization. Since current GNSS services are **government-operated**, governments can potentially deny or degrade the service quality for certain users in specific circumstances, such as operational needs or national security purposes [22]. On the other hand, LEO constellations are owned by **private companies**, making LEO satellites-based services potentially more *democratized* compared to available GNSS systems, where the control of the entire system rests with the operating company. This enhances the user inclusivity of LEO satellites-based positioning services and reduces the risk that the service provider abuses power, providing a reliable backup in the case of GNSS service denial.

Such democratization of the positioning service parallels how digital currencies challenge traditional banking systems in terms of accessibility and financial inclusivity while spurring innovation among competing private companies to offer better services for the user. However, similar to digital currencies, this democratization presents several challenges such as regulatory uncertainty where governments may impose restrictions or bans on the service, as well as security concerns in case an adversary exploits the service. The extent to which LEO constellations will democratize positioning services depends on its future adoption and regulatory clarity and requires further research to address security challenges.

3.3.2 Open-Access APIs. With the advent of LEO-based communication services, future user devices are expected to include LEO signal receivers to offer satellite communication functions, as seen in recent Apple phones. Designing open-access APIs for processing raw LEO signals similar to currently available GNSS APIs can facilitate the user adoption of LEO-based positioning services by developing applications that use commercial phone receivers.

3.3.3 Handling Receiver Heterogeneity. Building on the previous challenge, future user phone APIs may report varying LEO satellite signal characteristics for the same location due to receiver hardware and software heterogeneity. This can affect the performance of a LEO-based positioning system for certain users if it is not designed to handle the LEO satellite signal data distribution of their specific phones. Investigating the effect of receiver heterogeneity on LEO satellite-based positioning and designing methods to improve robustness to this heterogeneity [13] is an open research direction.

3.3.4 Data Collection Incentive Models. Requiring users to participate in LEO signal data collection to train and evaluate the system requires effective incentives. This can be done implicitly by collecting data while users utilize other LEO-based services (e.g., communication). Moreover, the data collection process can be gamified; e.g., through a web-based game that prompts users to visit different locations while using LEO-based Internet services. Designing new incentive models to facilitate seamless data collection at different locations while considering user profiles, device capabilities, and used LEO-based applications warrants further investigation.

3.3.5 Applications. A point related to user incentives is to study the set of location-based applications potentially enabled or improved by LEO satellites, encouraging users to adopt LEO satellite-based positioning. These include seamless navigation and asset tracking, mobility mode estimation [14] (e.g., by leveraging LEO orbits for more precise Doppler shift calculations [5]), smart environments[4, 19], device-free intrusion detection (e.g., by analyzing the effect of a person on LEO satellite signals), emergency response services (e.g., by providing global infrastructure-free positioning), floor identification in multi-floor environments [12], among others.

4 Conclusion

We presented our vision for leveraging LEO satellites for ubiquitous and reliable future positioning. We showed that the stronger received signals of LEO satellites and their larger number of satellites compared to current GNSS-based systems offer numerous benefits and opportunities for positioning systems. We also highlighted the multi-disciplinary challenges that must be addressed to realize our vision and explored different future research directions.

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