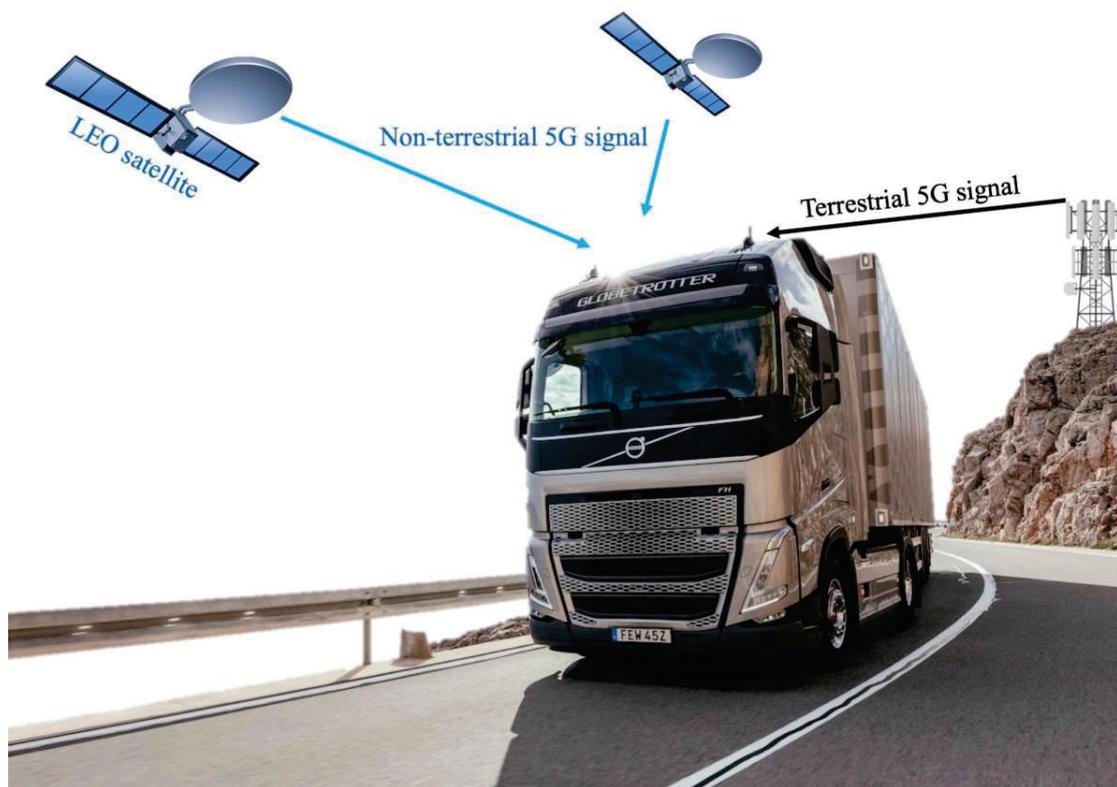# Coordinated 5G LEO-5G cellular positioning for improved safety functions in heavy vehicles

Public report

Project within Traffic-safe automation
Author   Yasaman Ettefagh, Henk Wymeersch
Date   2025-06-24

Content

FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

For more information: www.ffisweden.se

1. Summary

Accurate vehicle positioning is a critical enabler for safety functions in automated driving (AD) and advanced driver assistance systems (ADAS), particularly at higher levels of automation. In level 3 ADAS, where the vehicle must make autonomous decisions, precise positioning is essential to correctly interpret the environment and select the most probable path (MPP). A positioning error can result in the wrong path being chosen, potentially leading to unsafe situations.

Today's positioning solutions typically combine GPS, IMUs, odometers, and on-board sensors such as cameras and radars. However, GPS suffers from limited availability in urban environments and tunnels, while other sensors provide only relative information. Cellular signals offer a promising complement due to their ubiquity and cost-efficiency, and their use in positioning has been emphasized in several automotive-focused research projects.

This project investigates the use of low Earth orbit (LEO) non-terrestrial networks (NTN) as a positioning source and explores how LEO-based data can be fused with terrestrial network (TN) information to enhance positioning accuracy and reliability for heavy vehicles. LEO satellites, which orbit much closer to the Earth than GPS satellites, offer higher signal strength, better penetration into vehicle cabins, and lower latency, all critical for safety applications in AD/ADAS. Additionally, the rapid movement of LEO satellites provides richer positioning data over time, further improving accuracy.

The goal is to leverage combined NTN and TN positioning to support safe and reliable operation of large vehicles, especially in challenging environments where conventional positioning technologies fall short.

2. Sammanfattning på svenska

Projektet har undersökt hur positionering för stora fordon kan förbättras genom att kombinera signaler från lågt flygande satelliter (LEO) och 5G-baserade mobilnät. Målet har varit att öka tillförlitligheten och noggrannheten i positioneringssystem, särskilt i utmanande miljöer som tunnlar, stadsmiljöer och områden med dålig GPS-täckning.

Genom att modellera en realistisk kommunikationskanal mellan LEO-satelliter och marksegmentet, samt utveckla förenklade modeller med olika komplexitetsnivåer, har projektet tagit fram algoritmer för att uppskatta position, hastighet och tids-/frekvensförskjutningar hos ett fordon. Dessa algoritmer har testats i simuleringar och visar på god prestanda under olika scenarier.

Resultaten bidrar till kunskapsuppbyggnad inom hybridpositionering och lägger en grund för framtida lösningar inom automatiserad körning och avancerade förarstödssystem. Arbetet stödjer även FFI-programmets mål genom att främja teknik för säkrare och mer tillförlitlig mobilitet.

3. Background

Cellular (TN-based) Positioning: Cellular positioning leverages 4G and 5G communication networks to infer the location of a user or vehicle. Though originally developed for communication, wireless technologies now support various positioning methods, including multilateration using time difference of arrival (TDoA) across multiple base stations. However, cellular positioning suffers from challenges such as multipath interference, signal fading, and infrastructure limitations. Accurate localization in rural or coverage-limited areas remains a concern due to the high cost of densifying the network [1], [2]. In addition, synchronization among base stations and between devices is often insufficient for high-precision use cases like AD/ADAS [3]– [5].

Satellite (NTN-based) Positioning: GPS, the most well-known satellite positioning system, calculates position by measuring the time of arrival (ToA) of signals from at least four satellites [6]. However, GPS signals are often weak or unavailable in urban environments and tunnels. In response, LEO satellites have emerged as promising alternatives due to their proximity to the Earth (300–1500 km altitude), which enables stronger signals, lower latency, and more frequent signal updates [7], [8]. Recent research has explored LEO-based positioning systems that utilize Doppler information and distributed satellite geometry to enhance accuracy [9], [10]. Despite their advantages, LEO-based NTN systems face issues such as rapidly changing satellite geometries, high Doppler shifts, and narrow communication-focused beam patterns, all of which complicate accurate localization [11], [12].

Integrated Terrestrial-NTN Positioning: Due to the complementary nature of TN and NTN technologies, integrated positioning systems have garnered increasing attention in recent years. Cellular networks offer dense infrastructure and high reliability in urban environments, while NTN systems like LEO satellites ensure availability in GNSS-denied or rural areas [13], [14]–[18]. Fusion-based approaches that combine measurements such as pseudorange and angle-of-arrival (AoA) have shown promise in overcoming low observability and boosting accuracy [18]. For example, hybrid frameworks combining 5G reference signals and LEO-based positioning can address key challenges like Doppler compensation and interference management [15], [16].

Furthermore, NTNs are playing an increasingly critical role in the evolution from 5G to 6G, not only for global connectivity but also for high-precision localization [19]– [23]. Large-scale projects like Hexa-X have recognized the importance of such integration, especially for enabling safety-critical applications in autonomous systems.

4. Purpose, research questions and method

The purpose of this project was to investigate the fusion of LEO satellite-based positioning with 5G cellular positioning to improve positioning accuracy and availability for large vehicles. By integrating the complementary strengths of satellite and cellular signals, we aimed to develop a more robust positioning framework suitable for safety-critical applications in automated driving and driver assistance systems.

To guide the work, we formulated the following research questions:
1. How can LEO satellite signals be realistically modeled for positioning applications in automotive contexts?
2. What algorithmic approaches can effectively fuse satellite and cellular signals for accurate position estimation?

To address these questions, the project followed the below approach:
- **System Modeling:** We considered a scenario where a single-antenna mobile user received signals from a multi-antenna terrestrial base station and a time- and frequency-synchronized single-antenna LEO satellite. The user's position, speed, clock offset, and frequency offset were treated as unknowns. We modeled the channel between the LEO satellite and the ground segment to reflect realistic signal propagation, including Doppler and synchronization effects.
- **Algorithm Development:** We designed and implemented estimation algorithms capable of jointly recovering the user's position, velocity magnitude, clock bias, and frequency offset. These algorithms coordinated satellite and cellular observations to exploit the strengths of both systems and compensate for their respective limitations.
- **Dissemination:** The results of the project were prepared for dissemination through both technical publications and presentations for broader, non-technical audiences. The insights gained contribute to the growing body of research on hybrid positioning systems and provide guidance for future deployments of satellite–cellular integration in vehicular applications.

5. Objective

The main objective of this project was to explore how positioning accuracy and coverage for large vehicles could be improved by fusing signals from LEO satellites and 5G cellular networks. This hybrid positioning approach aimed to overcome the individual limitations of satellite- and cellular-based methods by combining their complementary advantages.
To achieve this goal, we defined the following specific objectives:

1. **Model the channel between LEO satellites and the ground segment:** We developed a realistic signal and channel model that captures the propagation characteristics and dynamic nature of LEO satellite communication links.
2. **Design and implement algorithms**: We created estimation algorithms capable of jointly processing satellite and cellular measurements to estimate position, velocity magnitude, clock offset, and frequency offset.
3. **Disseminate the results**: We prepared the findings for publication and presentation to both technical and non-technical audiences, aiming to contribute to ongoing research and support future development in this area.

6. Results and deliverables

The project successfully developed a hybrid positioning framework that fuses LEO satellite and 5G cellular signals to improve positioning accuracy and availability for large vehicles. The main deliverables include:

- A **generative channel model** capturing the physical-layer characteristics of integrated LEO–cellular positioning.
- A set of **simplified channel models** with varying levels of complexity, enabling practical algorithm design.
- **Low-complexity estimation algorithms** for position, velocity, clock offset, and frequency offset.
- A **performance evaluation framework** using theoretical bounds to guide model selection.
- A **scientific journal paper**, presenting the main technical results, **submitted** to a peer-reviewed venue for publication.

These results directly support the overall FFI goal of improving vehicle safety, efficiency, and automation through technological innovation. The project contributes to building foundational technologies that enable robust, high-precision positioning, which are critical for future ADAS and automated driving systems.

The project aligns with FFI's broader mission of supporting Swedish industrial competitiveness in transportation and mobility by addressing a key technological challenge, which is achieving reliable and accurate positioning in real-world environments. By exploring how satellite and cellular systems can be jointly exploited, the project pushes forward the development of robust digital infrastructure for safe and efficient transport.

In the context of the specific subprogram, the project has contributed by developing advanced communication and signal processing methods for vehicular positioning. It also enhances the understanding of integrated network infrastructures, which is a priority area as vehicles become increasingly connected and dependent on complex digital ecosystems. The modeling and estimation tools developed in this project lay a technical foundation for next-generation localization solutions in connected and automated vehicles.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	The project results contribute to the scientific understanding of hybrid satellite–cellular positioning.
Be passed on to other advanced technological development projects	X	The models and algorithms can serve as a foundation for future research in integrated localization systems.
Be passed on to product development projects		The results are currently at a conceptual and algorithmic stage; further development is needed for products.
Introduced on the market		Market introduction is not planned at this stage but may be possible in the long term.
Used in investigations / regulatory / licensing / political decisions		The project is research-oriented and does not directly target regulatory or political applications.

7.2 Publications

The main results of the project have been compiled into the following papers and a PhD thesis:

Y. Ettefagh, S. Saleh, M. F. Keskin, H. Chen, G. Seco-Granados, and H. Wymeersch, "*Integrated Cellular and LEO-based Positioning and Synchronization under User Mobility*," submitted to IEEE Transactions on Vehicular Technology.

S. Saleh, P. Zheng, X. Liu, H. Chen, M. F. Keskin, B. Priyanto, M. Beale, **Y. Ettefagh**, G. Seco-Granados, T. Y. Al-Naffouri, and H. Wymeersch, "*Integrated 6G TN and NTN Localization: Challenges, Opportunities, and Advancements*," accepted for publication in IEEE Communications Standards Magazine, arXiv:2501.13488.

Y. Ettefagh, "*Positioning, Synchronization, and Communication in 6G: Insights from Massive MIMO, RIS, and NTN*," PhD Thesis, 2025.

8. Conclusions and future research

This project presented a comprehensive study on localization, velocity magnitude estimation, and synchronization for a mobile user in integrated cellular and non-terrestrial networks. A generative model was developed, followed by four simplified models and

corresponding estimation algorithms. Simulations confirmed the effectiveness of the models across diverse scenarios, offering practical guidance for selecting appropriate trade-offs between complexity and accuracy.

Future work may include full velocity vector estimation, support for multiple LEO satellites, modeling handovers, and exploring inter-satellite links to further enhance positioning robustness and continuity.

9. Participating parties and contact persons

Name	Role	Affiliation	Logo
Yasaman Ettefagh	PhD Student	Volvo Group, Chalmers University of Technology	
Henk Wymeersch	Project Coordinator, Supervisor	Chalmers University of Technology	

References

[1] H. Wymeersch and G. Seco-Granados, "Radio localization and sensing—Part I: Fundamentals," *IEEE Communications Letters*, vol. 26, no. 12, pp. 2816–2820, 2022.

[2] H. Wymeersch and G. Seco-Granados, "Radio Localization and Sensing—Part II: State-of-the-Art and Challenges," *IEEE Communications Letters*, vol. 26, no. 12, pp. 2821–2825, 2022.

[3] S. Dwivedi et al., "Positioning in 5G networks," *IEEE Communications Magazine*, vol. 59, no. 11, pp. 38–44, 2021.

[4] H. Li et al., "Analysis of the synchronization requirements of 5G and corresponding solutions," *IEEE Communications Standards Magazine*, vol. 1, no. 1, pp. 52–58, 2017.

[5] J. A. del Peral-Rosado et al., "Survey of cellular mobile radio localization methods: From 1G to 5G," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 2, pp. 1124–1148, 2017.

[6] D. Dardari, M. Luise, and E. Falletti, *Satellite and Terrestrial Radio Positioning Techniques: A Signal Processing Perspective*. Academic Press, 2011.

[7] R. M. Ferre et al., "Is LEO-Based Positioning with Mega-Constellations the Answer for Future Equal Access Localization?," *IEEE Communications Magazine*, vol. 60, no. 6, pp. 40–46, 2022.

[8] F. S. Prol et al., "Position, navigation, and timing (PNT) through low earth orbit (LEO) satellites: A survey on current status, challenges, and opportunities," *IEEE Access*, 2022.

[9] H. K. Dureppagari et al., "NTN-based 6G Localization: Vision, Role of LEOs, and Open Problems," *arXiv preprint arXiv:2305.12259*, 2023.

[10] H. Benzerrouk et al., "LEO Satellites Based Doppler Positioning Using Distributed Nonlinear Estimation," *IFAC-PapersOnLine*, vol. 52, no. 12, pp. 496–501, 2019.

[11] H. K. Dureppagari et al., "NTN-based 6G localization: Vision, role of LEOs, and open problems," *IEEE Wireless Communications*, vol. 30, no. 6, pp. 44–51, 2023.

[12] I. Ali et al., "Doppler characterization for LEO satellites," *IEEE Transactions on Communications*, vol. 46, no. 3, pp. 309–313, 1998.

[13] S. Saleh et al., "Integrated 6G TN and NTN localization: Challenges, opportunities, and advancements," 2025. [Online]. Available: https://arxiv.org/abs/2501.13488

[14] H. Sallouha et al., "On the ground and in the sky: A tutorial on radio localization in ground-air-space networks," *IEEE Communications Surveys & Tutorials*, 2024.

[15] A. Gonzalez-Garrido et al., "5G positioning reference signal configuration for integrated terrestrial/non-terrestrial network scenario," in *2023 IEEE/ION Position, Location and Navigation Symposium (PLANS)*, pp. 1136–1142.

[16] A. Gonzalez-Garrido et al., "Interference analysis and modeling of positioning reference signals in 5G NTN," *IEEE Open Journal of the Communications Society*, 2024.

[17] T. Liang et al., "Toward seamless localization and communication: A satellite-UAV NTN architecture," *IEEE Network*, 2024.

[18] T. Jin et al., "Fusion positioning of GNSS-cellular signals of opportunity under low observability," *IEEE Transactions on Instrumentation and Measurement*, 2024.

[19] G. Araniti et al., "Toward 6G non-terrestrial networks," *IEEE Network*, vol. 36, no. 1, pp. 113–120, 2021.

[20] W. Jiang et al., "The road towards 6G: A comprehensive survey," *IEEE Open Journal of the Communications Society*, vol. 2, pp. 334–366, 2021.

[21] M. M. Azari et al., "Evolution of non-terrestrial networks from 5G to 6G: A survey," *IEEE Communications Surveys & Tutorials*, vol. 24, no. 4, pp. 2633–2672, 2022.

[22] A. Guidotti et al., "The path to 5G-advanced and 6G non-terrestrial network systems," in *2022 11th ASMS/SPSC*, IEEE, pp. 1–8.

[23] A. Behravan et al., "Positioning and sensing in 6G: Gaps, challenges, and opportunities," *IEEE Vehicular Technology Magazine*, vol. 18, no. 1, pp. 40–48, 2022.