Navigation with Multi-Constellation LEO Satellite Signals of Opportunity: Starlink, OneWeb, Orbcomm, and Iridium

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Abstract—**This paper summarizes current state-of-the-art navigation results with multi-constellation low Earth orbit (LEO) satellite signals of opportunity. Experimental results with four LEO satellite constellations are presented: Starlink, OneWeb, Orbcomm, and Iridium. Two receiver designs are presented: (R1) a cognitive opportunistic navigation approach, which utilizes minimal, publicly available prior knowledge about the LEO satellite signal structure and (R2) a blind approach, which assumes no prior knowledge of the signals. Stationary positioning and mobile ground vehicle navigation results are presented. For the ground vehicle, results with two frameworks are presented: (N1) a LEO-aided inertial navigation system (INS) simultaneous tracking and navigation (STAN) and (N2) a LEO-aided differential STAN. The results reveal the tremendous promise of exploiting multi-constellation LEO satellite signals of opportunity for navigation. For positioning: (i) with R1, starting with an initial estimate about 179 km away, by exploiting signals from 6 Starlink, 1 Orbcomm, and 4 Iridium, a final two-dimensional (2–D) position error of 6.5 m was achieved and (ii) with R2, starting with an initial estimate about 3,600 km away, by exploiting signals from 4 Starlink, 2 OneWeb, 1 Orbcomm, and 1 Iridium, a final 2–D position error of 5.1 m was achieved. For navigation, a ground vehicle was equipped with an industrial-grade inertial measurement unit (IMU) and an altimeter. (i) With R1 and N1, the vehicle traversed 4.15 km in 150 seconds (GNSS signals were only available for the first 2.33 km). By exploiting signals from 3 Starlink, 2 Orbcomm, and 1 Iridium, the 3–D position root mean squared error (RMSE) and final 3-D error were 18.4 m and 27.1 m, respectively. The GNSS-aided INS position RMSE and final 3-D error were 118.5 m and 472.7 m, respectively. (ii) With R2 and N2, the vehicle traversed 1.03 km in 110 seconds (GNSS signals were only available for the first 0.11 km). By exploiting signals from 4 Starlink, 1 OneWeb, 2 Orbcomm, and 1 Iridium, the 3–D position RMSE and final 3-D error were 9.5 m and 4.4 m, respectively. The GNSS-aided INS position RMSE and final 3-D error were 205 m and 525 m, respectively.**

Index Terms—**Positioning, navigation, signals of opportunity, Doppler tracking, low Earth orbit satellite, Starlink, OneWeb.**

I. INTRODUCTION

We are witnessing a renewed space race. From technology giants, to startups, to governments, everyone is claiming stake in launching their own LEO constellation. These constellations promise to transform our daily lives, offering broadband connectivity anywhere on Earth [1], and will benefit scientific inquiry in fields such as remote sensing [2], [3]. However, not all such constellations are created equal. So-called meg-constellations comprising tens of thousands of satellites are on their way to become a reality, with SpaceX's Starlink being the clear frontrunner with their plan to deploy nearly 12,000 LEO satellites. These constellations will be welcomed by current constellations inhabiting LEO, and collectively they could usher a new era for positioning, navigation, and timing (PNT) [4]–[8].

The promise of utilizing LEO satellites for PNT has been the subject of extensive recent studies [9]–[18]. These studies can be categorized into three groups. The first considers providing a standalone navigation solution by launching PNT-dedicated LEO constellations or transmitting PNT signals from existing LEO constellations [19]–[26]. The second considers augmenting global navigation satellite systems (GNSS) with LEO constellations [27]–[33]. The third exploits LEO signals from *any* constellation in an opportunistic fashion [34]–[41].

LEO satellites possess desirable attributes for PNT [42], [43]: (i) they are around twenty times closer to the Earth compared to GNSS satellites, which reside in medium Earth orbit (MEO), which could yield significantly higher carrier-to-noise ratio; (ii) they are becoming abundant as tens of thousands of broadband Internet satellites are expected to be deployed into LEO; and (iii) they transmit in different frequency bands and are placed in varying orbits, making LEO satellite signals diverse in frequency and direction.

However, exploiting LEO satellite signals for PNT purposes in an opportunistic fashion comes with challenges [44], as these constellations are owned by private operators that typi-

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cally do not disclose crucial information about the satellites': (i) ephemerides, (ii) clock synchronization and stability, and (iii) signal specifications.

To address the first challenge, several approaches have been proposed, including differential navigation utilizing known base receiver(s) [45]–[47], simultaneous tracking and navigation (STAN) [48], and analytical/machine-learning satellite orbit tracking [49]–[52]. Approaches to address the second challenge have been offered in [53]–[55]. To address the third challenge, the paradigm of cognitive opportunistic navigation [56], which estimates the minimally known LEO satellite signals in a *blind* fashion has been showing tremendous promise [57].

This paper summarizes recent progress with exploiting multi-constellation LEO satellites for PNT. The focus of the paper is to present the navigation solution achieved with real LEO signals of opportunity on stationary and mobile platforms in a standalone and a differential fashion. To the authors' knowledge, these results represent the most accurate positioning and navigation results reported in the literature with multi-constellation LEO signals of opportunity.

Experimental results with four LEO constellations are presented: Starlink, OneWeb, Orbcomm, and Iridium. Two receiver design approaches are presented:

- **R1:** a cognitive opportunistic navigation approach, which utilizes minimal, publicly available prior knowledge about the LEO satellite signal structure
- **R2:** a blind approach, which assumes no prior knowledge of the signals

Stationary positioning and mobile ground vehicle navigation results are presented. For the ground vehicle, results with two frameworks are presented:

- **N1:** a LEO-aided inertial navigation system (INS) simultaneous tracking and navigation (STAN)
- **N2:** a LEO-aided differential STAN (DSTAN).

For positioning: (i) with R1, starting with an initial estimate about 179 km away, by exploiting signals from 6 Starlink, 1 Orbcomm, and 4 Iridium, a final two-dimensional (2–D) position error of 6.5 m was achieved and (ii) with R2, starting with an initial estimate about 3,600 km away, by exploiting signals from 4 Starlink, 2 OneWeb, 1 Orbcomm, and 1 Iridium, a final 2–D position error of 5.1 m was achieved. For navigation, a ground vehicle was equipped with an industrial-grade inertial measurement unit (IMU) and an altimeter. (i) With R1 and N1, the vehicle traversed 4.15 km in 150 seconds (GNSS signals were only available for the first 2.33 km). By exploiting signals from 3 Starlink, 2 Orbcomm, and 1 Iridium, the 3–D position root mean squared error (RMSE) and final 3-D error were 18.4 m and 27.1 m, respectively. The GNSS-aided INS position RMSE and final 3-D error were 118.5 m and 472.7 m, respectively. (ii) With R2 and N2, the vehicle traversed 1.03 km in 110 seconds (GNSS signals were only available for the first 0.11 km). By exploiting signals from 4 Starlink, 1 OneWeb, 2 Orbcomm, and 1 Iridium, the 3–D position RMSE and final 3-D error were 9.5 m and 4.4 m, respectively. The GNSS-aided INS position RMSE and final 3-D error were 205 m and 525 m, respectively. The results presented in this paper reveal the tremendous promise of exploiting multi-constellation LEO satellite signals of opportunity for navigation

The paper is organized as follows. Section II overviews the LEO constellations considered in this paper. Section III presents experimental results with the cognitive opportunistic navigation receiver with Starlink, Orbcomm, and Iridium NEXT on a stationary receiver and a mobile ground vehicle navigating via the LEO-aided STAN framework. Section IV presents experimental results with the opportunistic navigation receiver with Starlink, OneWeb, Orbcomm, and Iridium NEXT on a stationary receiver and a mobile ground vehicle navigating via the LEO-aided DSTAN framework. Section V gives concluding remarks.

II. OVERVIEW OF LEO CONSTELLATIONS

Table I compares the four LEO constellations considered in this paper. The number of satellites specified in the table represent the current number, as of the writing of this paper.

TABLE I
COMPARISON OF LEO CONSTELLATIONS

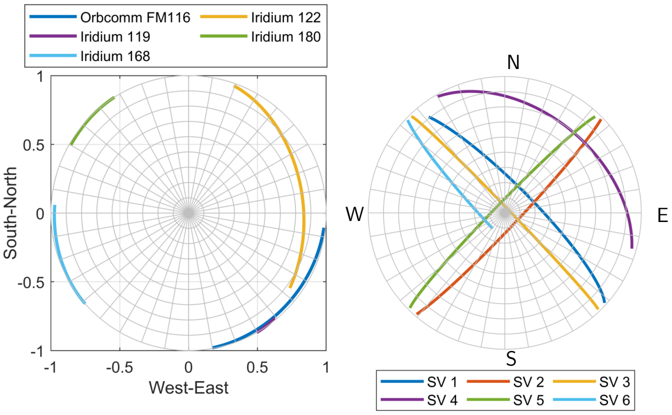
Parameter	**Starlink**	**OneWeb**	**Orbcomm**	**Iridium**
Bandwidth	240 MHz	230 MHz	4.8 kHz	31.5 kHz
Beacon length	4/3 ms	10 ms	1 s	90 ms
Number of satellites	3,660	542	36	66
Modulation	OFDM	OFDM	SD-QPSK	DE-QPSK
Frequency band	Ku, Ka	Ku	VHF	L
Downlink frequency	10.7–12.7 GHz	10.7–12.7 GHz	137 MHz	1.616–1.626 GHz
Number of channels	8	8	2	240
Number of beams	≈ 48	16	N/A	48
Altitude	550 km	1,200 km	750 km	780 km

III. NAVIGATION WITH STARLINK, ORBCOMM, AND IRIDIUM NEXT LEO SATELLITES: A COGNITIVE OPPORTUNISTIC NAVIGATION APPROACH

This section presents multi-constellation navigation results exploiting Starlink, Orbcomm, and Iridium NEXT LEO satellites with R1 and N1.

A. Stationary Positioning

Signals from a total of 11 LEO satellites (6 Starlink, 1 Orbcomm, and 4 Iridium NEXT) were recorded on top of a parking structure at the University of California, Irvine, CA, USA. The receiver presented in [58] was used to process Orbcomm and Iridium NEXT signals, from which it produced Doppler navigation observables. The receiver presented in [59] was used to process Starlink signals, from which it produced carrier phase observables. It is worth mentioning that not all satellites were visible simultaneously, and the signals were recorded as satellites passed overhead. The hardware setup is described in [58], [59]. Fig. 1 illustrates the skyplot of the LEO satellites.



(a) (b)

Fig. 1. (a) Skyplot of 6 Starlink, 1 Orbcomm, and 4 Iridium NEXT LEO satellites which were tracked during the experiment.

The navigation observables were processed through an extended Kalman filter, which estimated the receiver's 2–D position (the receiver's height was known). The EKF was initialized 179 km away from the true receiver position. The EKF's final position estimate converged to within 6.5 m. Fig. 2 illustrates the LEO satellite trajectories, initial estimate and ground truth receiver position, and final estimate along with the 99th percentile estimation error ellipse.

B. Mobile Navigation via LEO-Aided STAN

A ground vehicle was equipped with a Septentrio AsteRx-I V integrated GNSS-INS system with an industrial-grade IMU and an altimeter, from which the ground truth was derived. The hardware setup is described in [48]. The vehicle was driven on the CA-55 freeway next to Irvine, California, USA, for 4.15 km in 150 seconds. During the experiment, signals from 6 LEO satellites (3 Starlink, 2 Orbcomm, and 1 Iridium NEXT) were recorded. The skyplot of satellites' trajectory during the experiment are shown in Fig. 3. The receiver presented in [60] was used to process Orbcomm signals, from which it produced carrier phase navigation observables. The receiver presented in [58] was used to process Iridium NEXT signals, from which it produced Doppler navigation observables. The receiver presented in [61] was used to process Starlink signals, from which it produced Doppler navigation observables. The vehicle navigated via the LEO-aided STAN framework described in [48].

GNSS signals were available for the first 80 seconds of the experiment but were fictitiously cut off for the last 70 seconds, during which the vehicle traveled 1.82 km. The GNSS-INS navigation solution drifted to a final 3-D position error of 472.7 m and a 3-D position RMSE of 118.5 m over the true trajectory. The STAN LEO-aided INS yielded a final 3-D position error of 27.1 m and a 3-D position RMSE of 18.4 m. Fig. 4 summarizes the experimental results. For details about the data processing, EKF formulation, and additional results and analyses, the reader is referred to [48].

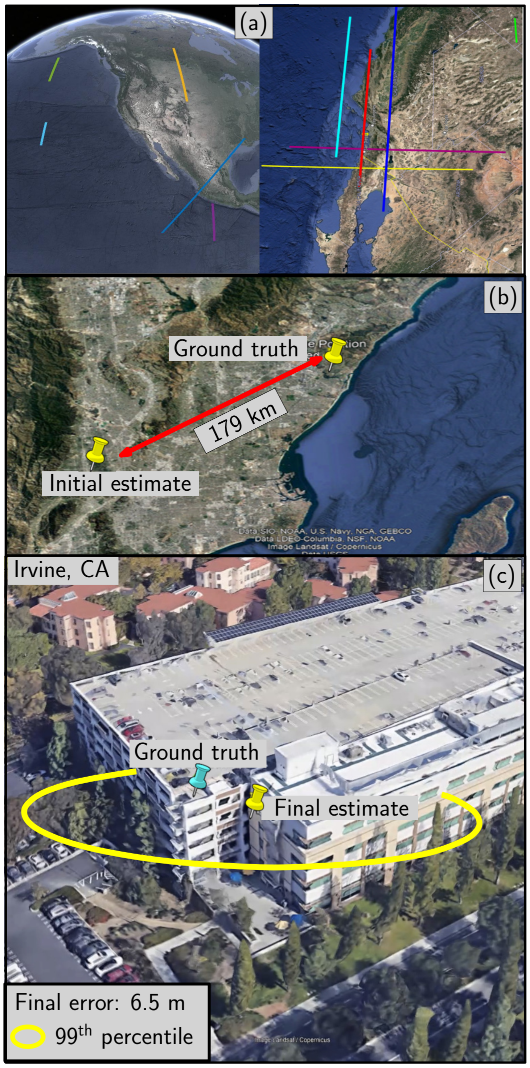


Fig. 2. (a) Trajectories of 11 LEO satellites (6 Starlink, 1 Orbcomm, and 4 Iridium NEXT) used to localize the stationary receiver. (b) Initial and final estimated positions. (c) Final errors relative to the receiver's true position.

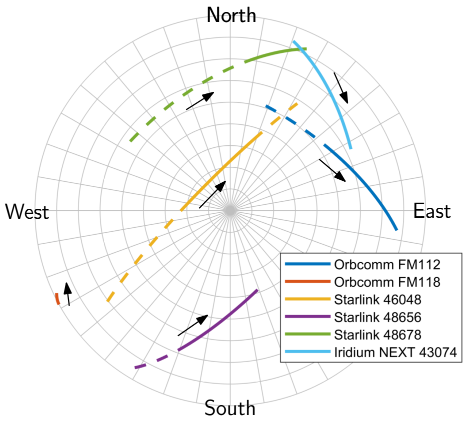


Fig. 3. Skyplot of 3 Starlink, 2 Orbcomm, and 1 Iridium NEXT LEO satellites which were tracked during the experiment.

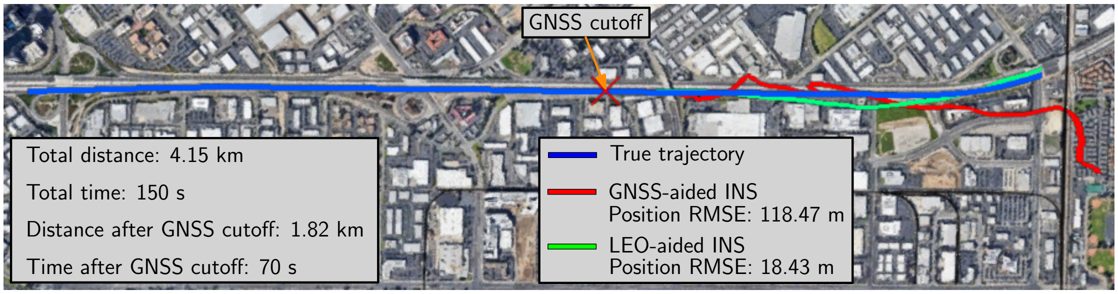


Fig. 4. Experimental results showing the ground vehicle's trajectory and estimated trajectory with GNSS-aided INS and STAN with LEO-aided INS using signals from 3 Starlink, 2 Orbcomm, and 1 Iridium NEXT satellites. Map data: Google Earth.

IV. NAVIGATION WITH STARLINK, ONEWEB, ORBCOMM, AND IRIDIUM NEXT LEO SATELLITES: A BLIND NAVIGATION APPROACH

This section presents multi-constellation navigation results exploiting Starlink, OneWeb, Orbcomm, and Iridium NEXT LEO satellites with R2 and N2.

A. *Stationary Positioning*

Signals from a total of 8 LEO satellites (4 Starlink, 2 OneWeb, 1 Orbcomm, and 1 Iridium NEXT) were recorded on top of the ElectroScience Laboratory (ESL) at The Ohio State University, Columbus, OH, USA. The receiver presented in [57] was used to process all LEO signals, from which it produced Doppler navigation observables. It is worth mentioning that not all satellites were visible simultaneously, and the signals were recorded as satellites passed overhead. The hardware setup is described in [57]. Fig. 1 illustrates the skyplot of the LEO satellites.

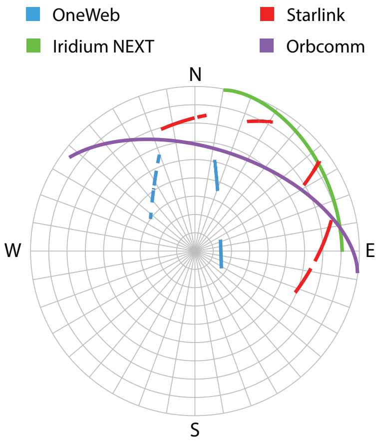


Fig. 5. Skyplot of 4 Starlink, 2 OneWeb, 1 Orbcomm, and 1 Iridium NEXT LEO satellites which were tracked during the experiment.

The Doppler navigation observables were processed through a nonlinear least-squares (NLS) estimator, which estimated the receiver's 3–D position. The NLS was initialized in Irvine, CA, USA, about 3,600 km away from the true receiver position. The NLS's final position estimate converged to within a 2–D error of 5.1 m. Fig. 6 illustrates the LEO satellite trajectories, initial estimate, ground truth receiver position, and final estimate. For additional details about the data processing, NLS formulation, and additional results and analyses, the reader is referred to [57].

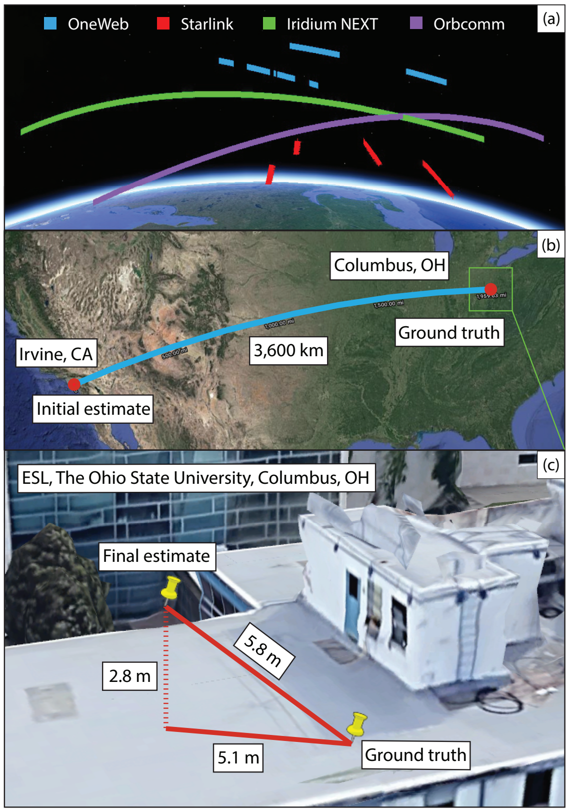
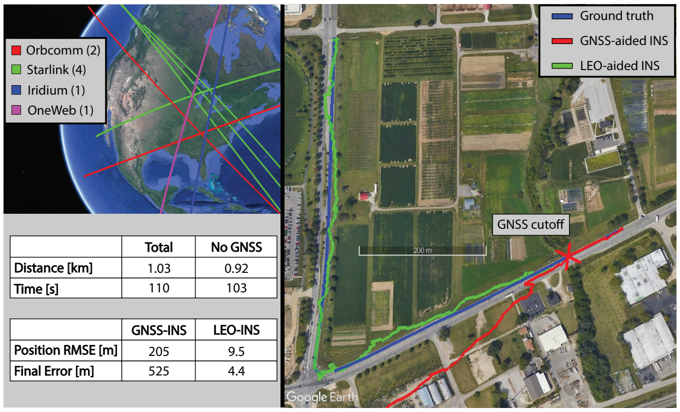


Fig. 6. Positioning results with 4 Starlink, 2 OneWeb, 1 Iridium NEXT, and 1 Orbcomm LEO satellites: (a) LEO satellite trajectories. (b) Initial and final estimated positions. (c) Final errors relative to the receiver's true position.

B. *Mobile Navigation via LEO-Aided DSTAN*

A ground vehicle was equipped with a Septentrio AsteRx SBi3 Pro+integrated GNSS-INS system with an industrial-grade IMU and an altimeter, from which the ground truth was derived. A differential base station with a known position was set up on top of ESL at The Ohio State University campus, about 2.2 km away from the rover (ground vehicle). The ground vehicle traversed a trajectory of 1.03 km in 110 seconds. During the experiment, signals from 8 LEO satellites (4 Starlink, 1 OneWeb, 2 Orbcomm, and 1 Iridium NEXT) were recorded. The receiver presented in [57] was used to process signals collected by the base station and the rover, from which it produced Doppler navigation observables. The vehicle navigated via the DSTAN framework described in [47].

GNSS signals were available for the first 7 seconds of the experiment but were fictitiously cut off for the last 103 seconds, during which the vehicle traveled 0.92 km. The GNSS-INS navigation solution drifted to a final 3-D position error of 525 m and a 3-D position RMSE of 205 m over the true trajectory. The DSTAN LEO-aided INS yielded a final 3-D position error of 4.4 m and a 3-D position RMSE of 9.5 m. Fig. 7 summarizes the experimental results.



	Total	No GNSS
Distance [km]	1.03	0.92
Time [s]	110	103

	GNSS-INS	LEO-INS
Position RMSE [m]	205	9.5
Final Error [m]	525	4.4

Fig. 7. Navigation results with 1 OneWeb, 4 Starlink, 1 Iridium NEXT, and 2 Orbcomm LEO satellites: ground truth trajectory (blue), GNSS-aided INS (red), and DSTAN LEO-aided INS (green).

V. CONCLUSION

This paper summarized the current state-of-the-art with exploiting multi-constellation LEO satellite signals of opportunity for positioning and navigation. Exploiting 6 Starlink, 1 Orbcomm, and 4 Iridium via a cognitive opportunistic navigation receiver is shown to yield a stationary 2–D position error of 6.5 m, starting with an initial estimate about 179 km away. With signals from 3 Starlink, 2 Orbcomm, and 1 Iridium NEXT, a ground vehicle equipped with an industrial-grade IMU traveling for 4.15 km in 150 s (the last 1.82 km in 70 s of which without GNSS) could achieve a 3–D position RMSE of 18.4 m via the LEO-aided STAN framework. Exploiting 4 Starlink, 2 OneWeb, 1 Orbcomm, and 1 Iridium via a blind navigation receiver is shown to yield a stationary 2–D position error of 5.1 m, starting with an initial estimate about 3,600 km away. With signals from 4 Starlink, 1 OneWeb, 2 Orbcomm, and 1 Iridium, a ground vehicle equipped with an industrial-grade IMU traveling for 1.03 km in 110 s (the last 0.92 km in 103 s of which without GNSS) could achieve a 3–D position RMSE of 9.5 m via the LEO-aided DSTAN framework

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REFERENCES

[1] A. Yadav, M. Agarwal, S. Agarwal, and S. Verma, "Internet from space anywhere and anytime - Starlink," in *Proceedings of International Conference on Advancement in Electronics & Communication Engineering*, July 2022, pp. 1–8.

[2] Y. Morton, D. Xu, and Y. Jiao, "Ionospheric scintillation effects on signals transmitted from LEO satellites," in *Proceedings of ION GNSS Conference*, September 2022, pp. 2980–2988.

[3] Y. Yi, J. Johnson, and X. Wang, "Diurnal variations in ocean wind speeds measured by CYGNSS and other satellites," *IEEE Geoscience and Remote Sensing Letters*, vol. 19, pp. 1–5, 2022.

[4] T. Reid, B. Chan, A. Goel, K. Gunning, B. Manning, J. Martin, A. Neish, A. Perkins, and P. Tarantino, "Satellite navigation for the age of autonomy," in *Proceedings of IEEE/ION Position, Location and Navigation Symposium*, 2020, pp. 342–352.

[5] D. Egea-Roca, M. Arizabaleta-Diez, T. Pany, F. Antreich, J. Lppez-Salcedo, M. Paonni, and G. Seco-Granados, "GNSS user technology: State-of-the-art and future trends," *IEEE Access*, vol. 10, pp. 39 939–39 968, 2022.

[6] F. Prol, R. Ferre, Z. Saleem, P. Välisuo, C. Pinell, E. Lohan, M. Elsanhoury, M. Elmusrati, S. Islam, K. Celikbilek, K. Selvan, J. Yliaho, K. Rutledge, A. Ojala, L. Ferranti, J. Praks, M. Bhuiyan, S. Kaasalainen, and H. Kuusniemi, "Position, navigation, and timing (PNT) through low earth orbit (LEO) satellites: A survey on current status, challenges, and opportunities," *IEEE Access*, vol. 10, pp. 83 971–84 002, 2022.

[7] N. Jardak and Q. Jault, "The potential of LEO satellite-based opportunistic navigation for high dynamic applications," *Sensors*, vol. 22, no. 7, pp. 2541–2565, 2022.

[8] T. Janssen, A. Koppert, R. Berkvens, and M. Weyn, "A survey on IoT positioning leveraging LPWAN, GNSS and LEO-PNT," *IEEE Internet of Things Journal*, 2023, accepted.

[9] Z. Kassas, J. Morales, and J. Khalife, "New-age satellite-based navigation – STAN: simultaneous tracking and navigation with LEO satellite signals," *Inside GNSS Magazine*, vol. 14, no. 4, pp. 56–65, 2019.

[10] Q. Wei, X. Chen, and Y. Zhan, "Exploring implicit pilots for precise estimation of LEO satellite downlink Doppler frequency," *IEEE Communications Letters*, vol. 24, no. 10, pp. 2270–2274, 2020.

[11] T. Mortlock and Z. Kassas, "Performance analysis of simultaneous tracking and navigation with LEO satellites," in *Proceedings of ION GNSS Conference*, September 2020, pp. 2416–2429.

[12] M. Psiaki, "Navigation using carrier Doppler shift from a LEO constellation: TRANSIT on steroids," *NAVIGATION, Journal of the Institute of Navigation*, vol. 68, no. 3, pp. 621–641, September 2021.

[13] C. Pinell, "Receiver architectures for positioning with low Earth orbit satellite signals," Master's thesis, Lulea University of Technology, School of Electrical Engineering, Sweden, 2021.

[14] W. Van Uytsel, T. Janssen, R. Halili, and M. Weyn, "Exploring positioning through pseudoranges using low earth Orbit satellites," in *Proceedings of International Conference on P2P, Parallel, Grid, Cloud and Internet Computing*, 2022, pp. 278–287.

[15] M. Hartnett, "Performance assessment of navigation using carrier Doppler measurements from multiple LEO constellations," Master's thesis, Air Force Institute of Technology, Ohio, USA, 2022.

[16] H. More, E. Cianca, and M. Sanctis, "Positioning performance of LEO mega constellations in deep urban canyon environments," in *Proceedings of International Symposium on Wireless Personal Multimedia Communications*, 2022, pp. 256–260.

[17] R. Sabbagh and Z. Kassas, "Observability analysis of receiver localization via pseudorange measurements from a single LEO satellite," *IEEE Control Systems Letters*, vol. 7, no. 3, pp. 571–576, 2023.

[18] H. Kanamori, K. Kobayashi, and N. Kubo, "A map-matching based positioning method using Doppler tracking and estimation by a software-defined receiver for multi-constellation LEO satellites," in *Proceedings of ION International Technical Meeting*, January 2023, pp. 649–663.

[19] T. Reid, A. Neish, T. Walter, and P. Enge, "Broadband LEO constellations for navigation," *NAVIGATION, Journal of the Institute of Navigation*, vol. 65, no. 2, pp. 205–220, 2018.

[20] C. Ardito, J. Morales, J. Khalife, A. Abdallah, and Z. Kassas, "Performance evaluation of navigation using LEO satellite signals with periodically transmitted satellite positions," in *Proceedings of ION International Technical Meeting Conference*, 2019, pp. 306–318.

[21] A. Nardin, F. Dovis, and J. Fraire, "Empowering the tracking performance of LEO-based positioning by means of meta-signals," *IEEE Journal of Radio Frequency Identification*, vol. 5, no. 3, pp. 244–253, 2021.

[22] J. Ji, Y. Liu, W. Chen, D. Wu, H. Lu, and J. Zhang, "A novel signal design and performance analysis in NavCom based on LEO constellation," *Sensors*, vol. 21, no. 23, pp. 8235–8262, December 2021.

[23] S. Bilardi, "A GNSS signal simulator and processor for evaluating acquisition and tracking of GPS-like signals from satellites in LEO," Master's thesis, University of Colorado at Boulder, CO, USA, 2021.

[24] D. Egea-Roca, J. Lopez-Salcedo, G. Seco-Granados, and E. Falletti, "Performance analysis of a multi-slope chirp spread spectrum signal for PNT in a LEO constellation," in *Proceedings of Workshop on Satellite Navigation Technology*, September 2022, pp. 1–9.

[25] P. Iannucci and T. Humphreys, "Fused low-Earth-orbit GNSS," *IEEE Transactions on Aerospace and Electronics Systems*, 2022, accepted.

[26] R. Cassel, D. Scherer, D. Wilburne, J. Hirschauer, and J. Burke, "Impact of improved oscillator stability on LEO-based satellite navigation," in *Proceedings of ION International Technical Meeting*, January 2022, pp. 893–905.

[27] D. Racelis, B. Pervan, and M. Joerger, "Fault-free integrity analysis of mega-constellation-augmented GNSS," in *Proceedings of ION GNSS Conference*, January 2019, pp. 465–484.

[28] M. Li, T. Xu, M. Guan, F. Gao, and N. Jiang, "LEO-constellation-augmented multi-GNSS real-time PPP for rapid re-convergence in harsh environments," *GPS Solutions*, vol. 26, no. 1, pp. 1–12, 2022.

[29] K. Wang, A. El-Mowafy, W. Wang, L. Yang, and X. Yang, "Integrity monitoring of PPP-RTK positioning; part II: LEO augmentation," *Remote Sensing*, vol. 14, no. 7, pp. 1599–1620, March 2022.

[30] K. Wang, J. Liu, H. Su, A. El-Mowafy, and X. Yang, "Real-time LEO satellite orbits based on batch least-squares orbit determination with short-term orbit prediction," *Remote Sensing*, vol. 15, no. 1, pp. 133–153, December 2022.

[31] M. Jiang, H. Qin, C. Zhao, and G. Sun, "LEO Doppler-aided GNSS position estimation," *GPS Solutions*, vol. 26, no. 1, pp. 1–18, 2022.

[32] J. Muyuan, Q. Honglei, C. Zhao, and S. Guiyu, "LEO Doppler-aided GNSS position estimation," *GPS Solutions*, vol. 26, no. 1, pp. 1–18, 2022.

[33] M. Jiang, H. Qin, Y. Su, F. Li, and J. Mao, "A design of differential-low Earth orbit opportunistically enhanced GNSS (D-LoeGNSS) navigation framework," *Remote Sensing*, vol. 15, no. 8, pp. 2136–2158, April 2023.

[34] M. Leng, F. Quitin, W. Tay, C. Cheng, S. Razul, and C. See, "Anchor-aided joint localization and synchronization using SOOP: Theory and experiments," *IEEE Transactions on Wireless Communications*, vol. 15, no. 11, pp. 7670–7685, November 2016.

[35] F. Farhangian and R. Landry, "Multi-constellation software-defined receiver for Doppler positioning with LEO satellites," *Sensors*, vol. 20, no. 20, pp. 5866–5883, October 2020.

[36] U. Singh, M. Shankar, and B. Ottersten, "Opportunistic localization using LEO signals," in *Proceedings of Asilomar Conference on Signals, Systems, and Computers*, 2022, pp. 894–899.

[37] C. Huang, H. Qin, C. Zhao, and H. Liang, "Phase - time method: Accurate Doppler measurement for Iridium NEXT signals," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 58, no. 6, pp. 5954–5962, 2022.

[38] C. Zhao, H. Qin, and Z. Li, "Doppler measurements from multiconstellations in opportunistic navigation," *IEEE Transactions on Instrumentation and Measurement*, vol. 71, pp. 1–9, 2022.

[39] N. Jardak and R. Adam, "Practical use of Starlink downlink tones for positioning," *Sensors*, vol. 23, no. 6, pp. 3234–3253, March 2023.

[40] W. Stock, C. Hofmann, and A. Knopp, "LEO-PNT with Starlink: Development of a burst detection algorithm based on signal measurements," in *Proceedings of International ITG Workshop on Smart Antennas and Conference on Systems, Communications, and Coding*, February 2023, pp. 1–6.

[41] M. Neinavaie and Z. Kassas, "Unveiling Starlink LEO satellite OFDM-like signal structure enabling precise positioning," *IEEE Transactions on Aerospace and Electronic Systems*, 2023, accepted.

[42] T. Reid, T. Walter, P. Enge, D. Lawrence, H. Cobb, G. Gutt, M. O'Conner, and D. Whelan, "Position, navigation, and timing technologies in the 21st century," J. Morton, F. van Diggelen, J. Spilker, Jr., and B. Parkinson, Eds. Wiley-IEEE, 2021, vol. 2, ch. 43: Navigation from low Earth orbit – Part 1: concept, current capability, and future promise, pp. 1359–1379.

[43] Z. Kassas, "Position, navigation, and timing technologies in the 21st century," J. Morton, F. van Diggelen, J. Spilker, Jr., and B. Parkinson, Eds. Wiley-IEEE, 2021, vol. 2, ch. 43: Navigation from low Earth orbit – Part 2: models, implementation, and performance, pp. 1381–1412.

[44] Z. Kassas, M. Neinavaie, J. Khalife, N. Khairallah, J. Haidar-Ahmad, S. Kozhaya, and Z. Shadram, "Enter LEO on the GNSS stage: Navigation with Starlink satellites," *Inside GNSS Magazine*, vol. 16, no. 6, pp. 42–51, 2021.

[45] J. Khalife and Z. Kassas, "Performance-driven design of carrier phase differential navigation frameworks with megaconstellation LEO satellites," *IEEE Transactions on Aerospace and Electronic Systems*, pp. 1–20, 2023, accepted.

[46] C. Zhao, H. Qin, N. Wu, and D. Wang, "Analysis of baseline impact on differential doppler positioning and performance improvement method for LEO opportunistic navigation," *IEEE Transactions on Instrumentation and Measurement*, pp. 1–10, 2023.

[47] J. Saroufim, S. Hayek, and Z. Kassas, "Simultaneous LEO satellite tracking and differential LEO-aided IMU navigation," in *Proceedings of IEEE/ION Position Location and Navigation Symposium*, April 2023, accepted.

[48] Z. Kassas, N. Khairallah, and S. Kozhaya, "Ad astra: Simultaneous tracking and navigation with megaconstellation LEO satellites," *IEEE Aerospace and Electronic Systems Magazine*, 2023, accepted.

[49] D. Shen, J. Lu, G. Chen, E. Blasch, C. Sheaff, M. Pugh, and K. Pham, "Methods of machine learning for space object pattern classification," in *Proceedings of IEEE National Aerospace and Electronics Conference*, 2019, pp. 565–572.

[50] N. Khairallah and Z. Kassas, "Ephemeris closed-loop tracking of LEO satellites with pseudorange and Doppler measurements," in *Proceedings of ION GNSS Conference*, September 2021, pp. 2544–2555.

[51] J. Haidar-Ahmad, N. Khairallah, and Z. Kassas, "A hybrid analytical-machine learning approach for LEO satellite orbit prediction," in *Proceedings of International Conference on Information Fusion*, 2022, pp. 1–7.

[52] R. Deng, H. Qin, H. Li, D. Wang, and H. Lv, "Noncooperative LEO satellite orbit determination based on single pass Doppler measurements," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 59, no. 2, pp. 1096–1106, April 2023.

[53] Z. Yang, H. Liu, C. Qian, B. Shu, L. Zhang, X. Xu, Y. Zhang, and Y. Lou, "Real-time estimation of low Earth orbit (LEO) satellite clock based on ground tracking stations," *Remote Sensing*, vol. 12, no. 12, pp. 2050–2067, June 2020.

[54] N. Khairallah and Z. Kassas, "An interacting multiple model estimator of LEO satellite clocks for improved positioning," in *Proceedings of IEEE Vehicular Technology Conference*, 2022, pp. 1–5.

[55] K. Wang and A. El-Mowafy, "LEO satellite clock analysis and prediction for positioning applications," *Geo-spatial Information Science*, vol. 25, no. 1, pp. 14–33, 2022.

[56] M. Neinavaie, J. Khalife, and Z. Kassas, "Cognitive opportunistic navigation in private networks with 5G signals and beyond," *IEEE Journal of Selected Topics in Signal Processing*, vol. 16, no. 1, pp. 129–143, 2022.

[57] S. Kozhaya, H. Kanj, and Z. Kassas, "Multi-constellation blind beacon estimation, Doppler tracking, and opportunistic positioning with OneWeb, Starlink, Iridium NEXT, and Orbcomm LEO satellites," in *Proceedings of IEEE/ION Position, Location, and Navigation Symposium*, April 2023, accepted.

[58] M. Orabi, J. Khalife, and Z. Kassas, "Opportunistic navigation with Doppler measurements from Iridium Next and Orbcomm LEO satellites," in *Proceedings of IEEE Aerospace Conference*, March 2021, pp. 1–9.

[59] J. Khalife, M. Neinavaie, and Z. Kassas, "The first carrier phase tracking and positioning results with Starlink LEO satellite signals," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 56, no. 2, pp. 1487–1491, April 2022.

[60] J. Khalife, M. Neinavaie, and Z. Kassas, "Navigation with differential carrier phase measurements from megaconstellation LEO satellites," in *Proceedings of IEEE/ION Position, Location, and Navigation Symposium*, April 2020, pp. 1393–1404.

[61] M. Neinavaie, J. Khalife, and Z. Kassas, "Acquisition, Doppler tracking, and positioning with Starlink LEO satellites: First results," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 58, no. 3, pp. 2606–2610, June 2022.