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EDITORIAL

# Navigator Notes

## Editorial Highlights from the Editor-in-Chief

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Welcome to the Spring 2025 issue of *NAVIGATION*. In this issue, we feature articles on a wide range of topics including jamming and spoofing of GNSS signals, navigation using pulsars, high accuracy positioning using a global differential GPS service, and the use of Starlink for positioning, navigation, and timing.

ION promotes the research of journal authors in a variety of ways including video abstracts hosted on the ION website. The latest video abstracts are documented below. You can find the video abstract for any recently published article under the article's supplemental menu item on the journal's website. ION also engages with the PNT community, through its webinar series, to highlight current topics of interest to the community. The most recent webinars are also documented below.

And congratulations to Clark Taylor and Jason Gross who were selected as the winners of the Institute of Navigation's 2024 Samuel M. Burka Award, recognizing outstanding achievement in the preparation of a paper advancing the art and science of positioning, navigation, and timing. Presented at the ION International Technical Meeting in Long Beach, California, back in January, this award recognizes the paper as one of the most significant published in *NAVIGATION* in 2024 and I extend my personal congratulations to the authors.

Article Citation: Taylor, C., & Gross, J. (2024). Factor graphs for navigation applications: A tutorial. *NAVIGATION, 71*(3). https://doi.org/10.33012/navi.653

## VIDEO ABSTRACTS

*Video Abstracts* allow authors to present their research in their own words. This multimedia format communicates the background and context of authors' research in a quick and easy way, elevating research from simple print delivery.

**Video for** "Satellite Ephemeris Parameterization Methods to Support Lunar Positioning, Navigation, and Timing Services"
By Marta Cortinovis, Keidai Iiyama, and Grace Gao (https://navi.ion.org/content/71/4/navi.664/tab-supplemental)

Abstract: Plans to establish a satellite network around the Moon to support communication, position, navigation, and timing services are rapidly evolving. Satellites that are part of this system broadcast their ephemeris as finite parameters to lunar users for user state estimation. In this work, we investigate lunar satellite ephemeris design to identify the optimal parameterization



 

to broadcast to a lunar user. The proposed framework directly approximates the lunar satellite position and velocity in the inertial frame and obtains the conversion parameters necessary for state representation in the lunar fixed frame. The framework leverages signal-in-space-error requirements as constraints in the parameterization process to guide the search for the best ephemeris parameter set. We evaluate the performance of our proposed framework for satellites in a low lunar orbit and an elliptical lunar frozen orbit. The performance of different methods is assessed based on the precision of the ephemeris prediction, fit interval, and message size. We showcase the ability of the developed framework to approximate satellite ephemeris for both orbits to the desired precision by adjusting the fit interval and the number of parameters to broadcast. In particular, we demonstrate that formulations with a standard polynomial basis and a Chebyshev polynomial basis produce feasible solutions for ephemeris approximation at varying epochs in orbits, abiding by signal-in-space-error requirements.

Article Citation: Cortinovis, M., Iiyama, K., & Gao, G. (2024). Satellite ephemeris parameterization methods to support lunar positioning, navigation, and timing services. *NAVIGATION, 71*(4). https://doi.org/10.33012/navi.664

**Video for** "Galileo High Accuracy Service: Tests in Different Operational Conditions"
By Luca Cucchi, Sophie Damy, Ciro Gioia, Beatrice Motella, and Matteo Paonni (https://navi.ion.org/content/71/4/navi.665/tab-supplemental)

Abstract: With corrections transmitted through the E6 signal, the Galileo High Accuracy Service (HAS) provides the information necessary to execute a stand-alone precise point positioning algorithm in real time. Once fully operational, the service aims to deliver an accuracy of 20 cm and 40 cm (at the 95% confidence level) in the horizontal and vertical channels, respectively.

While most of the current literature focuses on analyzing the performance of HAS in static and open-sky signal reception scenarios, this study presents the results of tests conducted in both static and dynamic conditions, including open-sky and urban canyon scenarios. The tests clearly demonstrate that utilizing HAS corrections leads to a significant reduction in positioning error across all tested environments. Furthermore, a specific analysis of HAS message availability in a harsh environment indicates that the corrections obtained from the signal in space are available approximately 95% of the time during dynamic scenario tests.

Article Citation: Cucchi, L., Damy, S., Gioia, C., Motella, B., & Paonni, M. (2024). Galileo High Accuracy Service: Tests in different operational conditions. *NAVIGATION, 71*(4). https://doi.org/10.33012/navi.665

**Video for** "Improving GNSS Positioning Correction Using Deep Reinforcement Learning with an Adaptive Reward Augmentation Method"
By Jianhao Tang, Zhenni Li, Kexian Hou, Peili Li, Haoli Zhao, Qianming Wang, Ming Liu, and Shengli Xie (https://navi.ion.org/content/71/4/navi.667/tab-supplemental)

Abstract: High-precision global navigation satellite system (GNSS) positioning for automatic driving in urban environments remains an unsolved problem

because of the impact of multipath interference and non-line-of-sight reception. Recently, methods based on data-driven deep reinforcement learning (DRL), which are adaptable to nonstationary urban environments, have been used to learn positioning-correction policies without strict assumptions about model parameters. However, the performance of DRL relies heavily on the amount of training data, and high-quality, available GNSS data collected in urban environments are insufficient because of issues such as signal attenuation and large stochastic noise, resulting in poor performance and low training efficiency for DRL. In this paper, we propose a DRL-based positioning correction method with an adaptive reward augmentation method (ARAM) to improve the GNSS positioning accuracy in nonstationary urban environments. To address the problem of insufficient training data in the target domain environment, we leverage sufficient data collected in source domain environments to compensate for insufficient training data, where the source domain environments can be in different locations than the target environment. We then employ ARAM to achieve domain adaptation that adaptively modifies data matching between the source domain and target domain by a simple modification to the reward function, thus improving the performance and training efficiency of DRL. Hence, our novel DRL model can achieve an adaptive dynamic-positioning correction policy for nonstationary urban environments. Moreover, the proposed positioning-correction algorithm can be flexibly combined with different model-based positioning approaches. The proposed method was evaluated using the Google Smartphone Decimeter Challenge data set and the Guangzhou GNSS measurement data set, with results demonstrating that our method can obtain an improvement of approximately 10% in positioning performance over existing model-based methods and 8% over learning-based approaches.

Article Citation: Tang, J., Li, Z., Hou, K., Li, P., Zhao, H., Wang, Q., Liu, M., & Xie, S. (2024). Improving GNSS positioning correction using deep reinforcement learning with an adaptive reward augmentation method. *NAVIGATION, 71*(4). https://doi.org/10.33012/navi.667

**Video for** "Efficient Signal Quality Monitoring of GNSS Signals Disturbed by Evil Waveforms"
By Fernando D. Nunes and Fernando M. G. Sousa (https://navi.ion.org/content/71/4/navi.668/tab-supplemental)

Abstract: Evil waveforms (EWFs) are anomalies in signals transmitted by a global navigation satellite system, provoked by electric malfunctions, that can significantly degrade the accuracy of the receiver's position, velocity, and time solution. In this work, cross-correlation functions of a received signal disturbed by EWF distortion and the locally generated code signal are derived for threat models TM-A, TM-B, and TM-C, with expressions obtained for binary phase shift keying, binary offset carrier (BOC), and composite BOC pilot modulations. Closed-form expressions are offered in terms of sine integral functions for TM-A. A description is presented on how to use these results to assess the performance of EWF detectors through semi-analytic simulation, allowing the detectability and hazard regions to be determined in a computationally efficient way.

Article Citation: Nunes, F. D., & Sousa, F. M. G. (2024). Efficient signal quality monitoring of GNSS signals disturbed by evil waveforms. *NAVIGATION, 71*(4). https://doi.org/10.33012/navi.668

**Video for** "Tightly Coupled Graph Neural Network and Kalman Filter for Smartphone Positioning"
By Adyasha Mohanty and Grace Gao (https://navi.ion.org/content/71/4/navi.670/tab-supplemental)

Abstract: Smartphone positioning based on global navigation satellite systems is crucial for various applications, including navigation, emergency response, and augmented and virtual reality. Despite significant advancements, constraints on size, weight, power consumption, and cost still pose challenges, leading to degraded accuracy in challenging urban settings. To improve smartphone positioning accuracy, we introduce a novel framework that deeply couples a graph neural network (GNN) with a learnable backpropagation Kalman filter. This hybrid approach combines the strengths of both model-based and data-driven methods, enhancing adaptability in complex urban settings. We further augment the measurement modeling capabilities of the GNN with extended features, a novel edge creation technique, and an inductive graph learning framework. Additionally, we implement a unique backpropagation strategy that uses real-time positioning corrections to refine the performance of both the GNN and the learned Kalman filter. We validate our algorithm on real-world data sets collected via smartphone receivers in urban environments and demonstrate improved performance over existing model-based and learning-based approaches.

Article Citation: Mohanty, A., & Gao, G. (2024). Tightly coupled graph neural network and Kalman filter for smartphone positioning. *NAVIGATION, 71*(4). https://doi.org/10.33012/navi.670

**Video for** "Timescale Realization with Linked Platforms for AltPNT"
By Christopher Flood and Penina Axelrad (https://navi.ion.org/content/71/4/navi.669/tab-supplemental)

Abstract: Recognition of the critical importance of positioning, navigation, and timing to all economic sectors is driving the development of diverse alternatives to global navigation satellite systems (GNSSs), termed AltPNT. One promising approach is to leverage the proliferation of small satellite constellations in low Earth orbit (LEO) to deliver GNSS augmentation services. The generation of one-way ranging signals suitable for AltPNT requires stable timing, accurately referenced to a common timescale such as Global Positioning System Time or Coordinated Universal Time. This paper describes a small-scale laboratory demonstration of an approach for cooperatively realizing a local timescale using low-size, weight, and power clocks distributed across multiple platforms, with no dependence on a GNSS. The demonstration is based on four interconnected software-defined radios to represent a four-satellite subset of a LEO constellation. Lab results show how each platform can generate a common timescale, with stability benefiting from all reference clocks.

Article Citation: Flood, C., & Axelrad, P. (2024). Timescale realization with linked platforms for altPNT. *NAVIGATION, 71*(4). https://doi.org/10.33012/navi.669

**Video for** "Feasibility Study of GBAS/INS and RRAIM for Airport Surface Movement Under Low-Visibility Conditions"
By Junesol Song, Carl Milner, and Heekwon No (https://navi.ion.org/content/71/4/navi.673/tab-supplemental)

Abstract: Currently, surface movement, encompassing all operations on the airport surface prior to take-off and after landing, cannot be achieved under low-visibility conditions by an aircraft-guidance-only solution. In addition to surface movement radar and Automatic Dependent Surveillance–Broadcast, pilots also rely on signage, lighting and reports/commands from the airport traffic control tower, which are partly based on visual inspection of the airport, to aid in guidance from the runway to the gate. Therefore, low-visibility conditions caused by meteorological effects can significantly affect the continuity of operations on the airport surface. Global navigation satellite systems are considered to overcome these difficulties by enhancing guidance and situational awareness on the airport surface. This paper explores the feasibility of utilizing a ground-based augmentation system, which is potentially available at the airport, an inertial navigation system, and relative receiver autonomous integrity monitoring to support surface movement operations in low-visibility conditions. The paper provides results assessing the compliance of the proposed solution to accuracy and integrity requirements.

Article Citation: Song, J., Milner, C., & No, H. (2024). Feasibility study of GBAS/INS and RRAIM for airport surface movement under low-visibility conditions. *NAVIGATION, 71*(4). https://doi.org/10.33012/navi.673

**Video for** "Addressing Inaccurate Phase Center Offsets in Precise Orbit Determination for Agile Satellite Missions"
By Kevin Gutsche, Thomas Hobiger, and Stefan Winkler (https://navi.ion.org/content/71/4/navi.671/tab-supplemental)

Abstract: Incorrect offsets between a satellite's center of mass and its global navigation satellite system antenna phase center pose challenges to the precise orbit determination (POD) of many current Earth observation missions. Based on hardware-in-the-loop simulations, this paper demonstrates the more adverse effects on agile satellites, which perform frequent attitude maneuvers around all spacecraft axes. However, findings obtained from an observability analysis and Monte Carlo simulations indicate that rapid attitude changes enable the direct estimation of otherwise unobservable offsets. Application to the POD of agile satellites leads to a consistent and significant performance improvement in the presence of incorrect phase center offsets. Directly estimated corrections for the phase center offset of Sentinel-6A, which performs slews on several occasions, are consistent with values obtained from other studies via independent methods. These results underscore the possibility of estimating the lever arm for both agile and non-agile satellites in dedicated calibration maneuvers.

Article Citation: Gutsche, K., Hobiger, T., & Winkler, S. (2024). Addressing inaccurate phase center offsets in precise orbit determination for agile satellite missions. *NAVIGATION, 71*(4). https://doi.org/10.33012/navi.671

**Video for** "Hybrid Carrier Tracking with Decoupled Local Filters in Multi-Frequency GNSS Receivers"
By Rong Yang, Jihong Huang and Xingqun Zhan (https://navi.ion.org/content/71/4/navi.672/tab-supplemental)

Abstract: The collaborative efforts of multi-frequency receivers have proven to be a significant advantage in the challenging environments of global navigation satellite system carrier tracking. This paper delves into the exploration of multi-carrier

hybrid tracking, employing both phase-locked loop and frequency-locked loop observations to maximize tracking capability. This hybrid approach conducts distributed phase tracking and centralized Doppler frequency tracking within decoupled local filters to accommodate the frequency dispersion and reduce dimensionality. Subsequently, global assimilation is performed to adjust filter weights for performance optimization. Theoretical analysis affirms that this hybrid design can achieve tracking performance close to optimality when compared with classic centralized estimation, significantly outperforming fully distributed approaches. Additionally, simulations of ionospheric scintillation validate the effectiveness of the proposed hybrid carrier tracking design.

Article Citation: Yang, R., Huang, J., & Zhan, X. (2024). Hybrid carrier tracking with decoupled local filters in multi-frequency GNSS receivers. *NAVIGATION, 71*(4). https://doi.org/10.33012/navi.672

**Video for** "GNSS Meta-Signal Tracking Using a Bicomplex Kalman Filter"
By Daniele Borio and Melania Susi (https://navi.ion.org/content/71/4/navi.674/tab-supplemental)

Abstract: Global navigation satellite system (GNSS) signals from different frequencies can be effectively treated as a single entity, characterized by common delays and carrier phases, leading to so-called GNSS meta-signals. A convenient approach for deriving meta-signal acquisition and tracking algorithms has been recently introduced based on bicomplex numbers, which are a bidimensional extension of complex numbers. Bicomplex numbers allow one to represent two signals from different frequencies as a single quantity, providing a compact notation for algorithm development. In this work, an error-state Kalman filter (KF) is developed, and two signals from different frequencies are tracked simultaneously using the bicomplex number paradigm. A triple-loop architecture, in which loop filters are replaced by a single KF, is developed, implemented, and tested using real Galileo alternative binary offset carrier and BeiDou B1I/B1C meta-signals. This analysis clearly shows the advantages of KF tracking for processing GNSS meta-signals with components from different frequencies.

Article Citation: Borio, D., & Susi, M. (2024). GNSS meta-signal tracking using a bicomplex Kalman filter. *NAVIGATION, 71*(4). https://doi.org/10.33012/navi.674

**Video for** "Improving the Prediction of GNSS Satellite Visibility in Urban Canyons Based on a Graph Transformer"
By Shaolong Zheng, Kungan Zeng, Zhenni Li, Qianming Wang, Kan Xie, Ming Liu, and Shengli Xie (https://navi.ion.org/content/71/4/navi.676/tab-supplemental)

Abstract: Signals from global navigation satellite systems (GNSS) in urban areas suffer from serious multipath errors caused by building blockages and reflections. The use of deep neural networks offers great potential for predicting and eliminating complex multipath/non-line-of-sight (NLOS) errors. However, existing methods for predicting the original signals face two remaining challenges. The first challenge is an inability to effectively exploit irregular GNSS measurement data caused by an inconsistent number of visible satellites in different epochs. The second challenge is degradation in the generalization performance of the multipath/NLOS prediction model when using data collected from different locations and periods. To address these challenges, this paper

proposes a novel graph transformer neural network (GTNN) for predicting satellite visibility that effectively learns environment representations from irregular GNSS measurements to both alleviate multipath interference and improve the generalization performance of the multipath prediction model. To learn from irregular GNSS measurements, a sky satellite graph is constructed as input to a graph neural network by using satellites captured in the same epoch, which can represent the spatial relationships between satellites and enable the model to learn satellite-related features sufficiently well. To improve the generalization ability of our multipath prediction model, a multihead attention mechanism is introduced to aggregate satellite node information by computing the correlation between satellites to extract the environment representation around the receiver. Based on the constructed sky satellite graph and the multihead attention mechanism, our novel GTNN for predicting satellite visibility can not only handle irregular GNSS measurements but can also learn an environment representation via graph attention. Comparative experiments were conducted on real-world GNSS measurement data in urban areas, demonstrating that the proposed method can achieve an accuracy exceeding 96% for satellite visibility prediction and obtain better generalization performance than existing multipath prediction methods. Moreover, the attention weights among satellites were visualized to demonstrate the environment representation learned by the GTNN from the sky satellite graph.

Article Citation: Zheng, S., Zeng, K., Li, Z., Wang, Q., Xie, K., Liu, M., & Xie, S. (2024). Improving the prediction of GNSS satellite visibility in urban canyons based on a graph transformer. *NAVIGATION, 71*(4). https://doi.org/10.33012/navi.676

**Video for** "Cooperative Localization for GNSS-Denied Subterranean Navigation: A UAV–UGV Team Approach"
By David Akhihiero, Uthman Olawoye, Shounak Das, and Jason Gross (https://navi.ion.org/content/71/4/navi.677/tab-supplemental)

Abstract: This paper presents a cooperative navigation architecture in a global navigation satellite system (GNSS)-denied subterranean environment using an unmanned ground vehicle (UGV) and unmanned aerial vehicle (UAV) team. The main focus of this design is to prolong the UAV mission time by reducing the UAV payload, sensing, and computational elements. To accomplish this, the UGV handles the mapping of the environment, its own state estimation, and the state estimation of the UAV using the UAV's proprioceptive sensors, a three-dimensional lidar, and an ultra-wideband ranging radio that communicates with a similar radio on the UAV. The UAV is assumed to be instrumented with an inertial measurement unit, stereo camera, and laser altimeter, and the data from these instruments are shared with the UGV over a local network for use in UAV state estimation. This paper presents the architecture for localization of a UAV/UGV team and realizes the implementation using two different nonlinear state estimators. Details and a comparison between an extended Kalman filter and an incremental factor graph optimization implementation are provided. The performance of the presented algorithms is analyzed via experiments conducted in a motion-capture facility.

Article Citation: Akhihiero, D., Olawoye, U., Das, S., & Gross, J. (2024). Cooperative localization for GNSS-denied subterranean navigation: A UAV–UGV team approach. *NAVIGATION, 71*(4). https://doi.org/10.33012/navi.677

## WEBINARS

*ION Webinars* highlight timely and engaging articles published in *NAVIGATION* and other topics of interest to the PNT community in an interactive virtual presentation.

**January 16, 2025 Webinar:** Cooperative Localization for GNSS-Denied Subterranean Navigation: A UAV–UGV Team Approach (https://www.ion.org/publications/webinar-gross.cfm)
By: Jason Gross

Abstract: This paper presents a cooperative navigation architecture in a global navigation satellite system (GNSS)-denied subterranean environment using an unmanned ground vehicle (UGV) and unmanned aerial vehicle (UAV) team. The main focus of this design is to prolong the UAV mission time by reducing the UAV payload, sensing, and computational elements. To accomplish this, the UGV handles the mapping of the environment, its own state estimation, and the state estimation of the UAV using the UAV's proprioceptive sensors, a three-dimensional lidar, and an ultra-wideband ranging radio that communicates with a similar radio on the UAV. The UAV is assumed to be instrumented with an inertial measurement unit, stereo camera, and laser altimeter, and the data from these instruments are shared with the UGV over a local network for use in UAV state estimation. This paper presents the architecture for localization of a UAV/UGV team and realizes the implementation using two different nonlinear state estimators. Details and a comparison between an extended Kalman filter and an incremental factor graph optimization implementation are provided. The performance of the presented algorithms is analyzed via experiments conducted in a motion-capture facility.

Article Citation: Akhihiero, D., Olawoye, U., Das, S., & Gross, J. (2024). Cooperative localization for GNSS-denied subterranean navigation: A UAV–UGV team approach. *NAVIGATION, 71*(4). https://doi.org/10.33012/navi.677

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