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EDITORIAL

Navigator Notes

Editorial Highlights from the Editor-in-Chief

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Welcome to the Winter 2025 issue of *NAVIGATION*. In this issue, we again feature state-of-the-art articles on various topics in positioning and navigation ranging from inertial navigation, magnetic navigation, lidar positioning, the integrity of GNSS including battling interference and spoofing, and much more. Many *NAVIGATION* authors are leading the field in their research areas.

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 webinar is also documented below.

We are pleased to recognize the following authors and papers published that received the greatest number of citations in 2022 and 2023 as calculated as part of the Web of Sciences 2024 Journal Impact Factor report that was published this summer:

MOST CITATIONS:
Hsu, L-T., Huang, F., Ng, H-F., Zhang, G., Zhong, Y., Bai, X., & Wen, W. (2023). Hong Kong UrbanNav: An open-source multisensory dataset for benchmarking urban navigation algorithms. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.602

Gao, G., Kanhere, A., Gupta, S., & Shetty, A. (2022). Improving GNSS positioning using neural-network-based corrections. *NAVIGATION, 69*(4). https://doi.org/10.33012/navi.548

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 "Characterizing and Modeling the BDS-3 Time Group Delay Error for ARAIM"
By Hengwei Zhang, Yiping Jiang, and Zhipeng Wang (https://navi.ion.org/content/72/3/navi.705/tab-supplemental)

Abstract: In the BDS-3 constellation, only the B3I signal is used to compute the broadcast clock offset. However, because advanced receiver autonomous integrity monitoring (ARAIM) uses dual-frequency measurements, the time group delay (TGD) must be considered in BDS-3-based ARAIM applications. The existing BDS-3 error model is therefore not sufficient to describe the actual TGD error encountered by aviation users. Specifically, the estimated signal-in-space error underestimates the actual error, which cannot be bounded by the estimated user range accuracy and nominal bias. This inaccuracy results in a loss of integrity. To avoid this risk, this paper develops a separated Gaussian model to bound the TGD error for BDS-3 in ARAIM. Using a one-year data set, this paper characterizes and bounds the TGD error for different signal combinations. Of the tested combinations, the B1C/B2a signal combination resulted in the smallest standard deviation of 0.78 m and a corresponding bias component of 0.71 m. We suggest that this signal combination be adopted for use in ARAIM.

Article Citation: Zhang, H., Jiang, Y., & Wang, Z. (2025). Characterizing and modeling the BDS-3 time group delay error for ARAIM. *NAVIGATION, 72*(3). https://doi.org/10.33012/navi.705

Video for "Spreading Code Sequence Design via Mixed-Integer Convex Optimization"
By Alan Yang, Tara Mina, and Grace Gao (https://navi.ion.org/content/72/3/navi.706/tab-supplemental)

Abstract: For a satellite navigation system, binary spreading codes with good autocorrelation and cross-correlation properties are critical for ensuring precise synchronization and tracking with minimal intrasystem interference. In this paper, we demonstrate that multiple instances of the spreading code design problem found in the literature may be cast as binary-constrained convex optimization problems. This approach enables new optimization methods that can exploit the convex structure of the problem. We demonstrate this approach using a block coordinate descent (BCD) method, which applies a convexity-exploiting branch-and-bound method to perform the block updates. With minimal tuning, the BCD method was able to identify Global Positioning System codes with better mean-squared correlation performance compared with the Gold codes and codes derived from a recently introduced natural evolution strategy.

Article Citation: Yang, A., Mina, T., & Gao, G. (2025). Spreading code sequence design via mixed-integer convex optimization. *NAVIGATION, 72*(3). https://doi.org/10.33012/navi.706

Video for "Analysis of the Trusted Inertial Terrain-Aided Navigation Measurement Function"
By Tucker Haydon Andy Huang, and Todd E. Humphreys (https://navi.ion.org/content/72/3/navi.707/tab-supplemental)

Abstract: The trusted inertial terrain-aided navigation (TITAN) algorithm leverages an airborne vertical synthetic aperture radar to measure the range to the closest ground points along several prescribed iso-Doppler contours. These TITAN minimum-range, prescribed-Doppler measurements are the result of a constrained nonlinear optimization problem whose optimization function and constraints both depend on the radar position and velocity. Owing to the complexity of this measurement definition, analysis of the TITAN algorithm is lacking in prior work.

This publication offers such an analysis, making the following three contributions: (1) an analytical solution to the TITAN constrained optimization measurement problem, (2) a derivation of the TITAN measurement function Jacobian, and (3) a derivation of the Cramér-Rao lower bound on the estimated position and velocity error covariance. These three contributions are verified via Monte Carlo simulations over synthetic terrain, which further reveal two remarkable properties of the TITAN algorithm: (1) the along-track positioning errors tend to be smaller than the cross-track positioning errors, and (2) the cross-track positioning errors are independent of the terrain roughness.

Article Citation: Haydon, T., Huang, A., & Humphreys, T. E. (2025). Analysis of the trusted inertial terrain-aided navigation measurement function. *NAVIGATION, 72*(3). https://doi.org/10.33012/navi.707

Video for "The Effect of Observation Discontinuities on LEO Real-Time Orbital Prediction Accuracy and Integrity"
By Beixi Chen Kan Wang Ahmed El-Mowafy, and Xuhai Yang (https://navi.ion.org/content/72/3/navi.708/tab-supplemental)

Abstract: Real-time, high-accuracy orbital products for low Earth orbit (LEO) satellites are essential for LEO-augmented real-time positioning, navigation and timing services. In particular, complete and continuous global navigation satellite system (GNSS) observations onboard tracked LEO satellites are necessary to guarantee precise orbit determination (POD) and generate short-term predicted orbits that can be fit with real-time ephemeris parameters. However, in practice, GNSS observations of LEO satellites often suffer from discontinuities due to tracking problems, data transmission problems, or downlinking strategies. Understanding the effect of these observation gaps on orbit accuracy is therefore essential for developing strategies to minimize accuracy degradation in real-time LEO satellite orbits. This study investigates trade-offs between two suites of strategies for addressing multi-hour observation data gaps followed by short segments of tail data during reduced-dynamic POD. The first strategy, EP, involves sacrificing the tail data and extending the prediction time. The second set of strategies retain the tail data but vary the POD strategies: the tested options include maintaining stochastic accelerations as estimable parameters (RP), not estimating stochastic accelerations (CP), or combining the RP-based orbits from the non-gap periods with the CP-based orbits during the gap (BP). Using real GNSS observations from the LEO satellite Sentinel-6A, we evaluated the accuracy and integrity of these strategies for 1-h orbital predictions with assumed gap lengths of 3, 5, 7, and 9 h and tail data lengths set to 15, 30, 45, and 60 min. Results show that the BP strategy achieves the highest prediction accuracy, with mean orbital user range errors (OUREs) of approximately 5.7 and 13.4 cm for a 3-h data gap followed by 60-min and 15-min tails, respectively. In contrast, the EP strategy demonstrates the highest integrity. For a 15-min tail, the 99.9% confidence level of the OURE for the EP strategy reaches approximately 3.1 and 8.7 dm for gap lengths of 3 h and 9 h, respectively. Overall, BP is the preferred strategy for maximizing prediction accuracy, while the EP strategy is preferable for short gaps and tails. The CP strategy provides a balanced approach, maintaining reasonably strong performance for both prediction accuracy and integrity.

Article Citation: Chen, B., Wang, K., El-Mowafy, A., & Yang, X. (2025). The effect of observation discontinuities on LEO real-time orbital prediction accuracy and integrity. *NAVIGATION, 72*(3). https://doi.org/10.33012/navi.708

Video for "Spherical Grid-Based IMU/Lidar Localization and Uncertainty Evaluation Using Signal Quantization"
By Ali Hassani and Mathieu Joerger (https://navi.ion.org/content/72/3/navi.709/tab-supplemental)

Abstract: This paper describes the design, analysis, and experimental evaluation of a spherical grid-based localization algorithm that leverages quantization theory to bound navigation uncertainty. This algorithm integrates data from light detection and ranging (lidar) and inertial measuring units in an iterative extended Kalman filter to estimate the position and orientation of a moving vehicle. An analytical bound is derived from the vehicle's state estimation error, which accounts for both random measurement noise and the loss of localization information caused by gridding. The performance of the proposed approach is analyzed and compared with that of a brute-force spherical grid-based method and a landmark-based method in an indoor environment, whereas an outdoor experiment verifies the practicality of the method in a realistic driving scenario.

Article Citation: Hassani, A., & Joerger, M. (2025). Spherical grid-based IMU/lidar localization and uncertainty evaluation using signal quantization. *NAVIGATION, 72*(3). https://doi.org/10.33012/navi.709

Video for "Single-Satellite Lunar Navigation via Doppler Shift Observables for the NASA Endurance Mission"
By Kaila M. Y. Coimbra, Marta Cortinovis, Tara Mina, and Grace Gao (https://navi.ion.org/content/72/3/navi.710/tab-supplemental)

Abstract: The National Aeronautics and Space Administration (NASA) Endurance rover mission concept is designed to enable the exploration and collection of samples along a 2000-km traverse within the Moon's South Pole-Aitken (SPA) impact basin. Precise geotagging of these samples will be critical to the mission's scientific objectives, which include characterizing the Solar System's chronology and the Moon's geological evolution. Concurrently, the European Space Agency (ESA) and Surrey Satellite Technology Ltd. (SSTL) are partnering to launch the Lunar Pathfinder satellite to provide communication services to lunar surface users, including the NASA Endurance rover. To enable precise absolute localization of the rover throughout its 2000-km traverse, we have investigated the achievable position estimation by opportunistically leveraging the Doppler shift observables from the Lunar Pathfinder's downlink communication signals with no navigation payload.

With only one satellite available, we accumulated Doppler shift measurements over time while the rover was stationary and refined the rover's position estimate through a weighted batch filter framework. Through simulations, we modeled the effects of Doppler shift measurement uncertainty, which includes the frequency error of the rover clock as well as errors due to carrier tracking as a function of the carrier-to-noise ratio C/N_0. The state estimation performance is evaluated at different key locations of the SPA basin under varying degrees of satellite ephemeris uncertainty and clock stability. With this framework of using the Doppler shift as the only navigation observable, we find that the Lunar Pathfinder is able to opportunistically localize the Endurance rover with sub-10-m accuracy, on average, within two orbital periods of the Lunar Pathfinder. To the best of the authors' knowledge, this paper is the first to examine the achievable localization of a lunar surface asset using only a single satellite that is not equipped with a navigation payload.

Article Citation: Coimbra, K. M. Y., Cortinovis, M., Mina, T., & Gao, G. (2025). Single-satellite lunar navigation via Doppler shift observables for the NASA Endurance mission. *NAVIGATION*, *72*(3). https://doi.org/10.33012/navi.710

Video for "Analytical Solution and Satellite Phasing Rules for Designing Dedicated Geosynchronous Orbit Satellite Constellations"
By Soung Sub Lee (https://navi.ion.org/content/72/3/navi.711/tab-supplemental)

Abstract: This study proposes a dedicated closed-form solution and satellite phasing rules for designing a geosynchronous orbit (GSO) constellation. Trajectories of GSO satellites have a characteristic figure-eight shape because their rotation speed is the same as that of the Earth. The GSO has the advantage of providing good coverage performance for local areas. Recently, several countries have begun developing local navigation systems based on the GSO. Various GSO constellation designs are available for an effective regional navigation performance analysis; however, no dedicated GSO constellation solution exists. This study provides a solution for such constellations and proves its practicability through a comparative analysis and evaluation of the geometric dilution-of-precision performance for several cases.

Article Citation: Lee, S. S. (2025). Analytical solution and satellite phasing rules for designing dedicated geosynchronous orbit satellite constellations. *NAVIGATION, 72*(3). https://doi.org/10.33012/navi.711

Video for "Analysis of BDS ARAIM Integrity Support Data Parameters"
By Changjiang Geng, Chenghe Fang, Zhigang Hu, Xiaoli Song, Lei Chen, Zhipeng Wang, and Yilun Cui (https://navi.ion.org/content/72/3/navi.712/tab-supplemental)

Abstract: The realization of the advanced receiver autonomous integrity monitoring (ARAIM) algorithm relies on integrity support data (ISD). To support the use of the BeiDou Navigation Satellite System (BDS) in ARAIM applications, the ISD parameters for BDS are analyzed. Global averages and worst-case signal-in-space ranging errors (SISREs) are computed using data from July 2020 to July 2022. The data cover three open signals: B1I, B1C, and B2a, which are committed for civilian aviation uses. The complementary Gaussian cumulative distribution function is used to bound the SISREs of different signals for all satellites. The results show that the global SISRE values are less than 0.6 m (root mean square) for B1I, B1C, and B2a signals, and the worst-case SISRE can be bounded by a zero-mean Gaussian distribution with a standard deviation of 4.0 m at the 4.0×10^{-5} level. Furthermore, a general discussion of P_{const} and b_{nom} is presented, with some recommendations.

Article Citation: Geng, C., Fang, C., Hu, Z., Song, X., Chen, L., Wang, Z., & Cui, Y. (2025). Analysis of BDS ARAIM integrity support data parameters. *NAVIGATION, 72*(3). https://doi.org/10.33012/navi.712

Video for "Wide-area Multilateration Airspace Surveillance with Unsynchronized Low-Cost ADS-B Receivers Using TDOA Observations"
By Clemens Sonnleitner and Thomas Hobiger (https://navi.ion.org/content/72/3/navi.704/tab-supplemental)

Abstract: This paper proposes and evaluates a novel approach for wide area multilateration (WAM) airspace surveillance based on time difference of arrival (TDOA) navigation. Unlike commercial Automatic Dependent Surveillance-Broadcast (ADS-B)-based WAM solutions, which require high-grade clock synchronization, the framework proposed here achieves airspace surveillance without the need for highly stable clocks or time synchronization between ground stations. In the proposed approach, aircraft 3D positions and velocities and the relative clock offsets of the receivers are estimated consistently using an extended Kalman filter (EKF). The accuracy of the 3D aircraft position estimates was tested using simulated ADS-B messages across a variety of different ground station network configurations.

Article Citation: Sonnleitner, C., & Hobiger, T. (2025). Wide-Area multilateration airspace surveillance with unsynchronized low-cost ADS-B receivers using time difference of arrival observations. *NAVIGATION, 72*(3). https://doi.org/10.33012/navi.704

Video for "Adaptation of One-Way Radiometric Range and Range-Rate Errors to the Lunar Environment"
By Mark Hartigan and E. Glenn Lightsey (https://navi.ion.org/content/72/3/navi.714/tab-supplemental)

Abstract: Several organizations, including NASA and the European Space Agency, have initiated plans for establishing lunar navigation satellite systems (LNSSs). This effort is driven by surging interest in the Moon as a platform for scientific discovery and staging area for future missions beyond Earth orbit. Near-Earth missions benefit from GNSSs, which have been refined over decades and are capable of real-time, sub-meter level positioning. For GNSS systems, the navigation community and managing organizations, such as the U.S. Department of Defense (in the case of GPS), have precisely characterized the error sources inherent in pseudorange and range-rate measurements in Earth's vicinity. Here, we draw parallels between errors in current GNSSs and those expected in future cislunar navigation systems. We identify key differences between the terrestrial and lunar environments and propose methods to accurately quantify the resulting measurement errors. Specifically, we develop techniques for constructing a time-varying error budget for pseudorange and pseudorange-rate measurements near the Moon and then test these techniques using arbitrary system and signal configurations.

Article Citation: Hartigan, M., & Lightsey, E. G. (2025). Adaptation of one-way radiometric range and range-rate errors to the lunar environment. *NAVIGATION, 72*(3). https://doi.org/10.33012/navi.714

Video for "Locating GNSS Interference Sources using ADS-B with Non-linear Least Squares"
By Zixi Liu, Sherman Lo, Juan Blanch, Yu-Hsuan Chen, and Todd Walter (https://navi.ion.org/content/72/3/navi.716/tab-supplemental)

Abstract: Global navigation satellite systems (GNSS) support safety-of-life aviation applications, including precise navigation during aircraft approach and landing. However, signal interference near airports can severely impair operational availability and integrity, and traditional methods for interference detection are generally costly and time-consuming to implement over large areas. In this paper, we develop a novel algorithm that uses Automatic Dependent Surveillance–Broadcast (ADS-B) reports, which are routinely transmitted by aircraft and publicly available, to estimate interference power and the geographic location of a GNSS interference source. We then test the algorithm on recorded ADS-B transmissions from a 2022 interference event at Denver International Airport (KDEN). Results show that the algorithm successfully detects interference and localizes the source within a 0.1-degree error margin in latitude and longitude. Unlike previous interference detection methods, our algorithm also quantifies uncertainty through error bounds and probability heatmaps, enhancing the reliability and interpretability of the results. Overall, this algorithm can help narrow the ground search area and support the physical shutdown of GNSS interference sources.

Article Citation: Liu, Z., Lo, S., Blanch, J., Chen, Y.-H., & Walter, T. (2025). Locating GNSS interference sources using ADS-B with non-linear least squares. *NAVIGATION, 72*(3). https://doi.org/10.33012/navi.716

Video for "A Novel Orbit Determination and Time Synchronization Architecture for a Radio Navigation Satellite Constellation in the Cislunar Environment"
By Luciano Iess, Mauro Di Benedetto, Giovanni Boscagli, Paolo Racioppa, Andrea Sesta, Fabrizio De Marchi, Paolo Cappuccio, Daniele Durante, Serena Molli, Michael K. Plumaris, Pasquale Tartaglia, Agnes Fienga, Nicolas Rambeaux, Fabrizio Santi, Debora Pastina, Nicola Linty, Krzysztof Sosnica, Grzegorz Bury, Radosław Zajdel, Jacopo Belfi, Pietro Giordano, Richard Swinden, and Javier Ventura-Traveset (https://navi.ion.org/content/72/3/navi.713/tab-supplemental)

Abstract: This paper presents a novel concept for orbit determination and time synchronization of a lunar radio navigation system. The proposed approach is based on small ground antennas that simultaneously track the entire constellation using K-band frequency links, implementing the concept of multiple spacecraft per aperture. This configuration ensures sufficient data rates and provides high accuracy in Doppler, range, and single-beam interferometry observables, enabling a precise orbit determination. We assess the achieved time transfer accuracies using both the standard asynchronous two-way satellite time and frequency transfer and a novel time transfer method that leverages onboard code epoch time-stamping and precise spacecraft range information. We propose a structure for the navigation message as well as a reference frame and associated time scale for user positioning. We complete the analysis by estimating the attainable accuracies of the signal-in-space error.

Article Citation: Iess, L., Di Benedetto, M., Boscagli, G., Racioppa, P., Sesta, A., De Marchi, F., Cappuccio, P., Durante, D., Molli, S., Plumaris, M. K., Tartaglia, P., Fienga, A., Rambeaux, N., Santi, F., Pastina, D., Linty, N., Sosnica, K., Bury, G., Zajdel, R., ...Ventura-Traveset, J. (2025). A novel orbit determination and time synchronization architecture for a radio navigation satellite constellation in the cislunar environment. *NAVIGATION, 72*(3). https://doi.org/10.33012/navi.713

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.

September 24, 2025 Webinar: Quantum Sensors for Navigation – From Physics to Field Deployment (https://www.ion.org/publications/webinar-kealy.cfm)
By: Allison Kealy and Andrew Greentree

Abstract: Quantum-enabled navigation is moving beyond the lab and into the real world, promising a new era of resilient positioning solutions. But building effective navigation systems requires more than just innovative sensors—it requires a hybrid and fully integrated approach. In this webinar, we unpack the quantum physics principles behind next-generation gravimeters and magnetometers, highlighting how these sensors differ from classical technologies and why they offer superior performance. We then explore how quantum sensors can be deployed within navigation systems, examining approaches that fuse classical and quantum data, as well as the critical role of maps and matching techniques as complementary “measurements.”

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