



Navigator Notes

Editorial Highlights from the Editor-in-Chief

Dr. Richard B. Langley
Editor of *NAVIGATION*:
Journal of the Institute of Navigation
Email: lang@unb.ca

Welcome to the Winter 2024 issue of *NAVIGATION*. In this issue, we again feature articles on a wide range of topics on positioning, navigation, and timing including navigation underground, in urban canyons, for Earth-orbiting satellites, and even on the Moon. All that and very much more.

At ION's invitation, Clark Taylor and Jason Gross have made available a factor graph tutorial. This tutorial presents the factor graph, a recently introduced estimation framework that is a generalization of the Kalman filter. An approach for constructing a factor graph, with its associated optimization problem and efficient sparse linear algebra formulation, is described. A comparison with Kalman filters is presented, together with examples of the generality of factor graphs. A brief survey of previous applications of factor graphs to navigation problems is also presented. The tutorial can be found at <https://navi.ion.org>:

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

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.

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 "Array-Aided Precise Orbit and Attitude Determination of CubeSats Using GNSS"

By Amir Allahviridi-Zadeh and Ahmed El-Mowafy (<https://navi.ion.org/content/71/3/navi.651/tab-supplemental>)

Abstract: CubeSats hold promise for various applications, but their viability in demanding missions such as future low Earth orbiting position, navigation, and timing (LEO-PNT) systems hinges on higher orbital accuracy and reliable attitude information. To address these challenges, we present an array aided combined

precise orbit and attitude determination model with an optimal solution. In the estimation process, multi- and affine-constrained models are used to precisely determine the attitude, and then, highly precise observations for an antenna array are reconstructed based on fixed ambiguities and a decorrelation step. Validations confirm the significance of integer ambiguities in the model, highlighting the cost-effectiveness of this model compared with star trackers for attitude determination. The reconstructed observations outperform the original observations, leading to improved orbital components, with the three-dimensional root mean square (RMS) equal to 4.1 cm. The observation residuals are smoother, with an RMS of 6 mm, half of that obtained via a single antenna. The developed models offer great potential for CubeSats, advancing their orbit and attitude determination capabilities.

Article Citation: Allahviridi-Zadeh, A., & El-Mowafy, A. (2024). Array-aided precise orbit and attitude determination of CubeSats using GNSS. *NAVIGATION*, 71(3). <https://doi.org/10.33012/navi.651>

Video for “Factor Graphs for Navigation Applications: A Tutorial”

By Clark Taylor and Jason Gross (<https://navi.ion.org/content/71/3/navi.653/tab-supplemental>)

Abstract: This tutorial presents the factor graph, a recently introduced estimation framework that is a generalization of the Kalman filter. An approach for constructing a factor graph, with its associated optimization problem and efficient sparse linear algebra formulation, is described. A comparison with Kalman filters is presented, together with examples of the generality of factor graphs. A brief survey of previous applications of factor graphs to navigation problems is also presented. Source code for the extended Kalman filter comparison and for generating the graphs in this paper is available at <https://github.com/cntaylor/factorGraph2DsatelliteExample>.

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 for “Weiss–Weinstein Bound of Frequency Estimation Error for Very Weak GNSS Signals”

By Xin Zhang, Xingqun Zhan, Jihong Huang, Jiahui Liu, and Yingchao Xiao (<https://navi.ion.org/content/71/3/navi.654/tab-supplemental>)

Abstract: Tightness remains the primary goal in all modern estimation bounds. For very weak signals, tightness is enabled by appropriately selecting the prior probability distribution and bound family. While current bounds in global navigation satellite systems (GNSSs) assess the performance of carrier frequency estimators under Gaussian or uniform assumptions, the circular nature of frequency is overlooked. Of all bounds in the Bayesian framework, the Weiss–Weinstein bound (WWB) stands out because it is free from regularity conditions or restrictions on the prior distribution. Therefore, the WWB is extended for the current frequency estimation problem. A divide-and-conquer type of hyperparameter tuning method is developed to mitigate issues of computational complexity for the WWB family while enhancing tightness. Synthetic results show that for a von Mises prior probability distribution, the WWB provides a bound up to 22.5% tighter than the

Ziv–Zakai bound when the signal-to-noise ratio varies between -3.5 dB and -20 dB, where the GNSS signal is deemed extremely weak.

Article Citation: Zhang, X., Zhan, X., Huang, J., Liu, J., & Xiao, Y. (2024). Weiss–Weinstein bound of frequency estimation error for very weak GNSS signals. *NAVIGATION*, 71(3). <https://doi.org/10.33012/navi.654>

Video for “Authentication Security of Combinatorial Watermarking for GNSS Signal Authentication”

By Jason Anderson, Sherman Lo, and Todd Walter (<https://navi.ion.org/content/71/3/navi.655/tab-supplemental>)

Abstract: Watermarking signal authentication is a technique in which a global navigation satellite system (GNSS) provider cryptographically perturbs the spreading code to allow for limited cryptographic authentication of a signal. Several proposals and studies have been presented or are underway to augment GNSS signals with this capability. This work reintroduces a generalized combinatorial watermarking function that affords a flexible pathway to cryptographically prove the authentication security of a signal with receiver observables under certain assumptions. The security levels are comparable to those of standard cryptographic security (e.g., 128-bit security) and require little or no additional use of the navigation data bandwidth. We show how our methods can be applied to signals of different designs and signal-to-noise ratios. With our receiver processing strategy, one can design a watermarking signal authentication scheme and the accompanying receiver to have high confidence in a signal’s authenticity.

Article Citation: Anderson, J., Lo, S., & Walter, T. (2024). Authentication security of combinatorial watermarking for GNSS signal authentication. *NAVIGATION*, 71(3). <https://doi.org/10.33012/navi.655>

Video for “Kalman Filtering with Uncertain and Asynchronous Measurement Epochs”

By James D. Brouk and Kyle J. DeMars (<https://navi.ion.org/content/71/3/navi.652/tab-supplemental>)

Abstract: This paper develops an asynchronous measurement processing technique for sequential filtering that effectively handles small errors in the measurement sampling epoch within a linearized framework. The derived method relaxes the assumption that sensing systems generate and communicate measurements instantaneously and suggests a linearized method for extracting information from latent measurements via a temporal measurement update that considers uncertainty in the measurement acquisition epoch. To investigate performance, numerical simulations are performed utilizing the consider/neglect extended Kalman filter framework applied to a lunar descent-to-landing scenario in which latent vision-based measurements with uncertain acquisition times are used to navigate the vehicle. Through Monte Carlo simulation and analysis, this paper shows that the presented approach can be used to maintain filter consistency for latent measurements with low measurement-time uncertainties. Furthermore, an error budget and sensitivity analysis are presented to provide insight into the impact of the measurement-time uncertainty on navigation performance.

Article Citation: Brouk, J. D., & DeMars, K. J. (2024). Kalman filtering with uncertain and asynchronous measurement epochs. *NAVIGATION*, 71(3). <https://doi.org/10.33012/navi.652>

Video for “Linear Estimation of Deterministic Accelerometer Errors”

By Julien Burkhard, Aman Sharma, and Jan Skaloud (<https://navi.ion.org/content/71/3/navi.656/tab-supplemental>)

Abstract: The deterministic errors of an accelerometer comprise the prevailing i) bias, ii) scale factor, and iii) non-orthogonality. Together, these errors result in a nonlinear measurement model, which is conventionally solved via an iterative nonlinear least-squares method. In contrast to the conventional approach, we propose a novel method to transform the above nonlinear model into a system of linear equations, resulting in an exact, closed-form solution of the deterministic errors. The developed mathematical formulations are first verified in a simulation setting, followed by a real-time implementation using Robot Operating System for small micro-electromechanical inertial measurement units.

Article Citation: Burkhard, J., Sharma, A., & Skaloud, J. (2024). Linear estimation of deterministic accelerometer errors. *NAVIGATION*, 71(3). <https://doi.org/10.33012/navi.656>

Video for “Distributed Nonlinear Least-Squares Solver for Practical Network Determination”

By Josef Krška and Václav Navrátil (<https://navi.ion.org/content/71/3/navi.658/tab-supplemental>)

Abstract: An integral step in an ultra-wideband localization network installation is determining the positions of the fixed infrastructure nodes, the anchors. This process is time-consuming and usually requires specialized equipment. Additionally, it is difficult to achieve scalability, as any change or addition in the network requires a redetermination of the affected anchors. One can automate this process by utilizing the distance-measuring capabilities of the network infrastructure and employing a distributed position estimation algorithm, such as the consensus subgradient (CSG) algorithm. Yet, the CSG suffers from scalability issues due to high problem dimensionality and data-sharing bottlenecks in practical applications. Consequently, implementation in embedded devices is difficult. In this article, we propose a modification of this algorithm, the neighborhood CSG, which aims toward embedded implementation by local reduction of the problem dimensions without hindering the precision of the original CSG algorithm or its convergence rate.

Article Citation: Krška, J., & Navrátil, V. (2024). Distributed nonlinear least-squares solver for practical network determination. *NAVIGATION*, 71(3). <https://doi.org/10.33012/navi.658>

Video for “High-Precision Time Transfer and Relative Orbital Determination Among LEO Satellites in Real Time”

By Kan Wang, Baoqi Sun, Ahmed El-Mowafy, and Xuhai Yang (<https://navi.ion.org/content/71/3/navi.659/tab-supplemental>)

Abstract: For low-Earth-orbit (LEO) satellites, high-precision clock estimation often depends on high-precision real-time global navigation satellite system

(GNSS) products. Thus, service providers often choose to downlink observation data to the ground to achieve high accuracy. To relieve this burden for future LEO mega-constellations, this study investigates the performance of relative clocks and orbits determined between LEO satellites using the phase common-view (PCV) method. The PCV results are compared with results from three other single-satellite-based clock and orbit determination methods. Using real data from the Gravity Recovery and Climate Experiment (GRACE) Follow-On satellites and three different types of real-time GNSS products, the PCV method can deliver a relative clock precision below 0.2 ns and a relative orbital user range error of approximately 5 cm, even when using the broadcast ephemeris, whereas all three other methods encountered sharp degradations in their results when using degraded real-time GNSS products.

Article Citation: Wang, K., Sun, B., El-Mowafy, A., & Yang, X. (2024). High-precision time transfer and relative orbital determination among LEO satellites in real time. *NAVIGATION*, 71(3). <https://doi.org/10.33012/navi.659>

Video for “Impacts of Global Navigation Satellite System Jamming on Aviation”
By Michael Felux, Patric Fol, Benoit Figuet, Manuel Waltert, and Xavier Olive (<https://navi.ion.org/content/71/3/navi.657/tab-supplemental>)

Abstract: Global navigation satellite systems have enabled significant improvements in aeronautical navigation. However, in recent years, a growing number of interference events have been reported by flight crews. In this paper, we first identify such events using crowd-sourced surveillance data collected between February and December 2022 for three different regions: the Baltic states, eastern Europe bordering the Black Sea, and the eastern Mediterranean. Then, we assess the extent and duration of these events to determine their impact on civil aviation. The analysis shows different characteristics, ranging from isolated events to regular large-scale and recurrent disruptions. Next, we identify aircraft types for the affected flights and evaluate flight plan data with respect to navigation equipment in order to identify flights that rely solely on satellite navigation and that might require assistance in the case of a loss of satellite navigation. Finally, we show the impact of radio frequency interference (RFI) on a selected passenger flight by analyzing automatic dependent surveillance-broadcast data as well as avionics data obtained from the airline’s flight data monitoring department for that specific flight and link the observations to the warnings triggered by the aircraft to alert the flight crew while encountering RFI.

Article Citation: Felux, M., Fol, P., Figuet, B., Waltert, M., & Olive, X. (2024). Impacts of global navigation satellite system jamming on aviation. *NAVIGATION*, 71(3). <https://doi.org/10.33012/navi.657>

Video for “Integrity-Constrained Factor Graph Optimization for GNSS Positioning in Urban Canyons”
By Xiao Xia, Weisong Wen, and Li-Ta Hsu (<https://navi.ion.org/content/71/3/navi.660/tab-supplemental>)

Abstract: Global navigation satellite system (GNSS) integrity monitoring (IM) has been introduced in aviation, but remains challenging for urban scenarios because of limited satellite visibility and strong multipath and non-line-of-sight effects. Consequently, factors such as limited measurement redundancy and inaccurate uncertainty modeling significantly compromise positioning and IM performance.

To alleviate these issues, this paper proposes an integrity-constrained factor graph optimization model for GNSS positioning augmented by switch variables. In contrast to conventional IM methods, this method enhances redundancy through the factor graph structure. Instead of directly excluding measurements, the proposed method reweights the measurements by using switch variables to satisfy a chi-square test constraint within the optimization, ultimately yielding optimal positioning accuracy. Moreover, a proper protection level that conservatively bounds the positioning error can be derived by using the modified weighting matrix under a single-fault assumption. The effectiveness of the proposed method was verified based on data sets collected in open-sky and urban-canyon areas in Hong Kong.

Article Citation: Xia, X., Wen, W., & Hsu, L.-T. (2024). Integrity-Constrained factor graph optimization for GNSS positioning in urban canyons. *NAVIGATION*, 71(3). <https://doi.org/10.33012/navi.660>

Video for “Highly Efficient Real-Time Kinematic-Based Precise Relative Navigation for Autonomous Rendezvous CubeSat”

By Hanjoon Shim and Changdon Kee (<https://navi.ion.org/content/71/3/navi.661/tab-supplemental>)

Abstract: This study addresses the practical challenges associated with real-time kinematic relative navigation for cube satellites (CubeSats) performing rendezvous missions in a low Earth orbit (LEO). Considering the limitations of CubeSats, we propose a method to achieve precise centimeter-level relative navigation using single-frequency Global Positioning System (GPS) measurements. By using GPS visibility and minimizing errors in the LEO, our approach eliminates the need for additional sensors. We employed range-domain differential GPS with a Hatch filter to enhance the pseudorange accuracy. Double-difference integer ambiguities were resolved epoch-by-epoch using the least-squares ambiguity decorrelation adjustment (LAMBDA) technique without filters, to ensure efficiency. The algorithm was applied to CubeSat hardware, integrating cycle-slip detection and CubeSat-tailored ground plane designs. Simulations validated the algorithm’s performance in LEO, and its real-world efficacy was evaluated through ground-based measurements in an open-sky environment. Considering hardware constraints, our method demonstrates the feasibility of achieving centimeter-level relative navigation for CubeSats, effectively and economically addressing a crucial need in autonomous space missions.

Article Citation: Shim, H., & Kee, C. (2024). Highly efficient real-time kinematic-based precise relative navigation for autonomous rendezvous CubeSat. *NAVIGATION*, 71(3). <https://doi.org/10.33012/navi.661>

Video for “Expanding Network RTK Coverage Using an Ionospheric-Free Combination and Kriging for Tropospheric Delay”

By Bu-Gyeom Kim, Donguk Kim, Junesol Song, and Changdon Kee (<https://navi.ion.org/content/71/3/navi.662/tab-supplemental>)

Abstract: Network real-time kinematic (NRTK) coverage is defined as the area inside a station network. In conventional NRTK, the distance between stations is limited to 100 km, thus restricting the coverage of NRTK. In this study, we propose the utilization of an ionospheric-free combination and the application of a Kriging weighting model to mitigate tropospheric delay to extend the coverage of NRTK

through network expansion. A network with station distances exceeding 100 km was constructed, and the residual errors, along with the success-fix rate of integer ambiguities, were analyzed on both sunny and rainy days to confirm the potential for network expansion using the proposed method. The results confirm that the success-fix rate increased by up to 44.3% on rainy days, compared with that of the traditional interpolation method. Furthermore, a high level of performance in integer ambiguity resolution can be maintained within the expanded network, regardless of the weather conditions.

Article Citation: Kim, B. -G., Kim, D., Song, J., & Kee, C. (2024). Expanding network RTK coverage using an ionospheric-free combination and kriging for tropospheric delay. *NAVIGATION*, 71(3). <https://doi.org/10.33012/navi.662>

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.

November 20, 2024 Webinar: Satellite Ephemeris Parameterization Methods to Support Lunar Positioning, Navigation, and Timing Services (<https://www.ion.org/publications/webinar-iiyama.cfm>)

By: Keidai Iiyama

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>

September 4, 2024 Webinar: Authentication Security of Combinatorial Watermarking for GNSS Signal Authentication (<https://www.ion.org/publications/webinar-anderson.cfm>)

By: Jason Anderson

Abstract: Watermarking signal authentication is a technique in which a global navigation satellite system (GNSS) provider cryptographically perturbs the spreading code to allow for limited cryptographic authentication of a signal. Several proposals and studies have been presented or are underway to augment GNSS signals with this capability. This work reintroduces a generalized combinatorial watermarking function that affords a flexible pathway to cryptographically prove the authentication security of a signal with receiver observables under certain assumptions. The security levels are comparable to those of standard cryptographic security (e.g., 128-bit security) and require little or no additional use of the navigation data bandwidth. We show how our methods can be applied to signals of different designs and signal-to-noise ratios. With our receiver processing strategy, one can design a watermarking signal authentication scheme and the accompanying receiver to have high confidence in a signal's authenticity.

Article Citation: Anderson, J., Lo, S., & Walter, T. (2024). Authentication security of combinatorial watermarking for GNSS signal authentication. *NAVIGATION*, 71(3). <https://doi.org/10.33012/navi.655>

How to cite this article: Langley, R. B. (2024). Navigator notes: Editorial Highlights from the Editor-in-Chief. *NAVIGATION*, 71(4). <https://doi.org/10.33012/navi.663>