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EDITORIAL

Navigator Notes

Editorial Highlights from the Editor-in-Chief

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Welcome to the Spring 2024 issue of *NAVIGATION*. In this issue, we feature a review article on GNSS software-defined radio (SDR) covering its history, current developments, and standardization efforts by a world-leading team of SDR experts. We also have the first published article on the derivation of the commonly used GNSS signal-in-space root-mean-square user range error. And we have several articles, among others, related to GNSS integrity as well as articles on GNSS-based remote sensing of the Earth's surface and its ionosphere. Something for everyone!

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 Daniele Borio who was selected as the winner of the Institute of Navigation's 2023 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 2023 and I extend my personal congratulations to the author.

Article Citation: Borio, D. (2023). Bicomplex representation and processing of GNSS signals. *NAVIGATION*, *70*(4). https://doi.org/10.33012/navi.621

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 "Multi-Layered Multi-Constellation Global Navigation Satellite System Interference Mitigation"
By Ciro Gioia and Daniele Borio (https://navi.ion.org/content/70/4/navi.596/tab-supplemental)

Abstract: Several layers of defense can be implemented in a global navigation satellite system (GNSS) receiver to improve its performance in the presence of

interference. These layers include the use of pre-correlation mitigation techniques, post-correlation quality indicators to screen measurements, and fault detection and exclusion (FDE) at the position solution level. This paper provides a characterization of the interactions between these layers of interference mitigation and a measurement quality check. Data collected in the presence of increasing levels of jamming were processed using different interference mitigation techniques, including robust interference mitigation (RIM) and the adaptive notch filter (ANF). A software defined radio (SDR) approach was adopted and measurements were generated by considering five interference-mitigation techniques. Position solutions were then computed using a forward-backward approach for receiver autonomous integrity monitoring (RAIM). Signals from GPS, Galileo, and BeiDou were processed and both single and dual-constellation solutions were analyzed. The analysis revealed that interference mitigation allows the receiver to track a larger number of signals even in the presence of high levels of jamming power. This increased measurement availability was then effectively exploited by RAIM techniques to provide more reliable solutions. Measurements from several constellations further improved the reliable availability of the position solutions.

Article Citation: Gioia, C., & Borio, D. (2023). Multi-layered multi-constellation global navigation satellite system interference mitigation. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.596

Video for "Instantaneous Sub-Meter Level Precise Point Positioning of Low-Cost Smartphones"
By Jiale Wang, Fu Zheng, Yong Hu, Dong Zhang, and Chuang Shi (https://navi.ion.org/content/70/4/navi.597/tab-supplemental)

Abstract: The prevalence of inexpensive global navigation satellite system (GNSS) chips that facilitate the performance of carrier phase measurements has provided hardware that can be used as the foundation for implementing precise point positioning (PPP) of low-cost smartphones. However, because of the atmospheric delays and high measurement noise associated with low-quality patch antennae, the convergence time of smartphone PPP can increase from minutes to even hours. By establishing the Satellite-based Ionospheric Model (SIM) and Real-time Tropospheric Grid Point (RTGP) models, we aim to achieve instantaneous sub-meter level positioning for smartphone PPP. In both kinematic and static experiments, Xiaomi Mi8 and Huawei P40 smartphone signals can converge to sub-meter accuracy in the horizontal direction within one to six seconds when adopting multi-constellation and dual-frequency PPP solutions augmented by precise atmospheric corrections. The atmospheric augmentation PPP method effectively improves the convergence speed and positioning accuracy compared to what can be achieved using the conventional PPP algorithm, thereby satisfying smartphone users' demand for rapid and high-accuracy positioning.

Article Citation: Wang, J., Zheng, F., Hu, Y., Zhang, D., & Shi, C. (2023). Instantaneous sub-meter level precise point positioning of low-cost smartphones. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.597

Video for "Noncoherent Code Discriminator Gains for Global Navigation Satellite System Signal Tracking"
By Ryan S. Cassel (https://navi.ion.org/content/70/4/navi.598/tab-supplemental)

Abstract: Many common discriminators used for code tracking of global navigation satellite system (GNSS) signals are ratios of quadratic forms of the correlation outputs. Here we derive a general expression for the gain of this type of discriminator and show that it depends on the effective carrier-to-noise ratio. We then evaluate this expression for several different code discriminators and GNSS signals, including GPS C/A-code, P-code, L1C, and M-code, Galileo E1 OS, GLONASS L1OF and L2OF, and BeiDou B1I and B2I. We also determine how noise and interference saturate the discriminator (i.e., make its output less sensitive to changes in the input) and the resulting effect on loop bandwidth. The discriminator gains described in this paper compensate for the saturation and ensure that loop bandwidth and code tracking performance can be accurately predicted and controlled over a critical range of effective carrier-to-noise ratios.

Article Citation: Cassel, R. (2023). Noncoherent code discriminator gains for global navigation satellite system signal tracking. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.598

Video for "A Case Study Analysis for Designing a Lunar Navigation Satellite System with Time Transfer from the Earth GPS"
By Sriramya Bhamidipati, Tara Mina, and Grace Gao (https://navi.ion.org/content/70/4/navi.599/tab-supplemental)

Abstract: There is growing interest in designing a future lunar navigation satellite system (LNSS) while utilizing a SmallSat platform. However, many design decisions, e.g., regarding the satellite clock and lunar orbit, are yet to be finalized. In our prior work, we developed an LNSS architecture that leverages intermittently available Earth-GPS signals to compute timing corrections, thereby alleviating the need for a higher-grade onboard clock. In this work, we formulate twenty case studies with different grades of clocks and lunar orbits to analyze the trade-offs in designing a SmallSat-based LNSS with time transfer from the Earth GPS. For each case study, the accuracy of ranging signals is assessed via the lunar user equivalent range error (UERE). Even with lower-grade clocks, the lunar UERE exhibits performance comparable to that of the Earth GPS. Furthermore, variations in the lunar UERE are also examined when the available Earth-GPS measurements are processed at different rates.

Article Citation: Bhamidipati, S., Mina, T., & Gao, G. (2023). A case study analysis for designing a lunar navigation satellite system with time transfer from the Earth GPS. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.599

Video for "Asynchronous Method of Simultaneous Object Position and Orientation Estimation with Two Transmitters"
By Jacek Stefanski and Jaroslaw Sadowski (https://navi.ion.org/content/70/4/navi.601/tab-supplemental)

Abstract: This paper proposes an object location method for all types of applications, including the Internet of Things. The proposed method enables estimations of the position and orientation of an object on a plane or in space, especially during motion, by means of location signals transmitted simultaneously from two transmitters placed on the object at a known distance from each other. A mathematical analysis of the proposed method and Newton's algorithm for solving the system of nonlinear positional equations is presented. Next, an analysis of a

position-dilution-of-precision parameter for the proposed method and a Cramer–Rao lower bound, limiting the accuracy of the method, is presented. Finally, the results of complex simulation studies on the efficiency of the proposed method are described.

Article Citation: Stefanski, J., & Sadowski, J. (2023). Asynchronous method of simultaneous object position and orientation estimation with two transmitters. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.601

Video for "PRN Sequence Estimation with a Self-Calibrating 40-Element Antenna Array"
By Dominik Dötterböck, Thomas Pany, Roman Lesjak, Thomas Prechtl, and Amir Tabatabaei (https://navi.ion.org/content/70/4/navi.600/tab-supplemental)

Abstract: This work explores the use of a low-cost global navigation satellite system (GNSS) antenna array including front-ends and a global navigation satellite system (GNSS) software receiver to receive signals of opportunity (SoO) whose pseudorandom noise (PRN) code is unknown. The front-ends are only loosely synchronized in time and frequency via hardware elements, and precise synchronization or calibration is achieved by using open service global navigation satellite system (GNSS) signals. After calibration, the raw received signals from all antenna elements are added coherently, which allows the pseudorandom noise (PRN) codes of the unknown signals of opportunity (SoO) to be estimated. The pseudorandom noise (PRN) sequences are then fed into a test receiver with a single antenna element that uses the sequences to acquire and track the signals of opportunity (SoO) in a conventional way. The process of chip estimation combined with the use of these sequences in a test receiver is called blind processing. The paper discusses the used algorithms, limitations, the expected performance in the chip error rate (CER), and effective loss of signal power when tracking the signals of opportunity (SoO) in a test receiver. An experimental setup with an array of 40 antenna elements is described, and results from simulated data and from one real Global Positioning System (GPS) M-code signal used as the signals of opportunity (SoO) show the feasibility of this concept. Among the types of global navigation satellite system (GNSS) signals of opportunity (SoO), the GPS M-code is more difficult to estimate than its Galileo or BeiDou counterparts due to its high chipping rate. A chip error rate (CER) of 15.1 % is achieved for the M-code signal. Applications of blind processing include receiver prototyping, signal quality monitoring of the signals of opportunity (SoO), and server-side processing for the purpose of signal authentication.

Article Citation: Dötterböck, D., Pany, T., Lesjak, R., Prechtl, R., & Tabatabaei, A. (2023). PRN sequence estimation with a self-calibrating 40-element antenna array. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.600

Video for "Hong Kong UrbanNav: An Open-Source Multisensory Dataset for Benchmarking Urban Navigation Algorithms"
By Li-Ta Hsu, Feng Huang, Hoi-Fung Ng, Guohao Zhang, Yihan Zhong, Xiwei Bai, and Weisong Wen (https://navi.ion.org/content/70/4/navi.602/tab-supplemental)

Abstract: Accurate positioning in urban canyons remains a challenging problem. To facilitate the research and development of reliable and precise positioning methods using multiple sensors in urban canyons, we built a multisensory dataset, *UrbanNav*, collected in diverse, challenging urban scenarios in Hong Kong.

The dataset provides multi-sensor data, including data from multi-frequency global navigation satellite system (GNSS) receivers, an inertial measurement unit (IMU), multiple light detection and ranging (lidar) units, and cameras. Meanwhile, the ground truth of the positioning (with centimeter-level accuracy) is postprocessed by commercial software from NovAtel using an integrated GNSS real-time kinematic and fiber optics gyroscope inertial system. In this paper, the sensor systems, spatial and temporal calibration, data formats, and scenario descriptions are presented in detail. Meanwhile, the benchmark performance of several existing positioning methods is provided as a baseline. Based on the evaluations, we conclude that GNSS can provide satisfactory results in a middle-class urban canyon if an appropriate receiver and algorithms are applied. Both visual and lidar odometry are satisfactory in deep urban canyons, whereas tunnels are still a major challenge. Multisensory integration with the aid of an IMU is a promising solution for achieving seamless positioning in cities. The dataset in its entirety can be found on GitHub at https://github.com/IPNL-POLYU/UrbanNavDataset.

Article Citation: 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

Video for "Closed-Form Study of Undetected Range Errors Induced by Ionospheric Anomalies for GAST-D GBAS"
By Wang Li and Yiping Jiang (https://navi.ion.org/content/70/4/navi.603/tab-supplemental)

Abstract: In ground-based augmentation system (GBAS) approach service type D (GAST-D), various ionospheric monitors are implemented in both aircraft and ground facilities to detect ionospheric anomalies. Additionally, the largest undetected differential range errors induced by ionospheric anomalies must be examined because these errors are used in geometry screening to identify potentially unsafe satellite geometries. Based on the ionospheric front threat model, a closed-form expression of the largest undetected ionospheric range error has been established for GBAS approach service type C (GAST-C), where only ground ionospheric monitoring is involved. This paper presents a closed-form expression for GAST-D, and both the ionospheric front model and plasma bubble threat model are taken into consideration. Based on exhaustive simulations among all possible ionospheric threat conditions, the expression is determined as a linear function of the relative speed and gradient magnitude of the ionospheric anomaly. Compared with the linear expression of ionospheric errors for GAST-C, the expression for GAST-D demonstrates that the use of additional ionospheric monitors and a smaller time constant for the code-carrier smoothing filter can effectively reduce the largest undetected ionospheric range error.

Article Citation: Li, W., & Jiang, Y. (2023). Closed-form study of undetected range errors induced by ionospheric anomalies for GAST-D GBAS. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.603

Video for "Atom Strapdown: Toward Integrated Quantum Inertial Navigation Systems"
By Benjamin Tennstedt, Ashwin Rajagopalan, Nicolai B. Weddig, Sven Abend, Steffen Schön, and Ernst M. Rasel (https://navi.ion.org/content/70/4/navi.604/tab-supplemental)

Abstract: We present an alternative technique for estimating the response of a cold atom interferometer (CAI). Using data from a conventional inertial measurement unit (IMU) and common strapdown terminology, the position of the atom wave packet is tracked in a newly introduced sensor frame, enabling hybridization of both systems in terms of acceleration and angular rate measurements. The sensor frame allows for an easier mathematical description of the CAI measurement and integration into higher-level navigation systems. The dynamic terms resulting from the transformation of the IMU frame into the CAI sensor frame are evaluated in simulations. The implementation of the method as a prediction model in an extended Kalman filter is explained and demonstrated in realistic simulations, showing improvements of over two orders of magnitude with respect to the conventional IMU strapdown solution. Finally, the implications of these findings for future hybrid quantum navigation systems are discussed.

Article Citation: Tennstedt, B., Rajagopalan, A., Weddig, N. B., Abend, S., Schön, S., & Rasel, E. M. (2023). Atom strapdown: Toward integrated quantum inertial navigation systems. *NAVIGATION, 70(4)*. https://doi.org/10.33012/navi.604

Video for "GEODNET: Global Earth Observation Decentralized Network"
By Mike Horton, David Chen, Yudan Yi, Xiaohua Wen, and James Doebbler (https://navi.ion.org/content/70/4/navi.605/tab-supplemental)

Abstract: This paper explains some design and architecture decisions around the GEODNET network and the GeoDAO decentralized autonomous organization, which aims to create and operate a truly decentralized public GNSS reference sensing network. This paper covers the motivation of the network, the capabilities of current and future reference stations, the blockchain and GEOD token mechanics, and how the network powers applications ranging from climate change monitoring to real-time centimeter-accurate positioning.

Article Citation: Horton, M., Chen, D., Yi, Y., Wen, X., & Doebbler, J. (2023). GEODNET—Global Earth observation decentralized network. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.605

Video for "On GNSS Synchronization Performance Degradation under Interference Scenarios: Bias and Misspecified Cramér-Rao Bounds"
By Lorenzo Ortega, Corentin Lubeigt, Jordi Vilà-Valls, and Eric Chaumette (https://navi.ion.org/content/70/4/navi.606/tab-supplemental)

Abstract: Global navigation satellite systems (GNSSs) play a key role in a plethora of applications, ranging from navigation and timing to Earth observation and space weather characterization. For navigation purposes, interference scenarios are among the most challenging operation conditions, with a clear impact on the maximum likelihood estimates (MLEs) of signal synchronization parameters. While several interference mitigation techniques exist, an approach for theoretically analyzing GNSS MLE performance degradation under interference, which is fundamental for system/receiver design, is lacking. The main goal of this contribution is to provide such analysis, by deriving closed-form expressions of the misspecified Cramér–Rao (MCRB) bound and estimation bias, for a generic GNSS signal corrupted by interference. The proposed bias and MCRB expressions are validated for a linear frequency-modulation chirp signal interference.

Article Citation: Ortega, L., Lubeigt, C., Vilà-Valls, J., & Chaumette, E. (2023). On GNSS synchronization performance degradation under interference scenarios: Bias and misspecified Cramér-Rao bounds. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.606

Video for "An Embedded High-Precision GNSS-Visual-Inertial Multi-Sensor Fusion Suite"
By Cheng Liu, Shuai Xiong, Yongchao Geng, Song Cheng, Fang Hu, Bo Shao, Fang Li, and Jie Zhang (https://navi.ion.org/content/70/4/navi.607/tab-supplemental)

Abstract: Because of the high complementarity between global navigation satellite systems (GNSSs) and visual-inertial odometry (VIO), integrated GNSS-VIO navigation technology has been the subject of increased attention in recent years. In this paper, we propose an embedded high-precision multi-sensor fusion suite that includes a multi-frequency and multi-constellation GNSS module, a consumption-grade inertial measurement unit (IMU), and a grayscale camera. The suite uses an NVIDIA Jetson Xavier NX as the host and develops a field programmable gate array-based controller for hardware time synchronization between heterogeneous sensors. A multi-state constraint Kalman filter is used to generate the tightly-coupled estimation from the camera and the IMU. As a result, the GNSS output is loosely coupled to facilitate the acquisition of the global drift-free estimation. Results from the calibration reveal that the time synchronization accuracy of the suite is better than 30 μs (standard deviation [STD]) and that the projection error of camera-IMU is less than 0.1 pixels (STD); these results highlight the advantage of this hardware time synchronization mechanism. Results from the vehicle-mounted tests reveal reductions in the three-dimensional (3D) positioning error from 8.455 m to 5.751 m (root mean square) on experimental urban roads, which significantly improves the accuracy and continuity of GNSS individual positioning. In underground sites where the satellite signal is completely unavailable, the 3D position error drift of the suite is only 1.58 ‰, which also shows excellent performance.

Article Citation: Liu, C., Xiong, S., Geng, Y., Cheng, S., Hu, F., Shao, B., Li, F., & Zhang, J. (2023). An embedded high-precision GNSS-visual-inertial multi-sensor fusion suite. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.607

Video for "Evaluation of the Benefits of Zero Velocity Update in Decentralized Extended Kalman Filter-Based Cooperative Localization Algorithms for GNSS-Denied Multi-Robot Systems"
By Cagri Kilic, Eduardo Gutierrez, and Jason N. Gross (https://navi.ion.org/content/70/4/navi.608/tab-supplemental)

Abstract: This paper proposes the cooperative use of zero velocity update (ZU) in a decentralized extended Kalman filter (DEKF)-based localization algorithm for multi-robot systems. The filter utilizes inertial measurement unit (IMU), ultra-wideband (UWB), and odometer-based velocity measurements to improve the localization performance of the system in a GNSS-denied environment. In this work, we evaluate the benefits of using ZU in a DEKF-based localization algorithm. The algorithm was tested with real hardware in a video motion capture facility and a robot operating system (ROS)-based simulation environment for unmanned ground vehicles (UGVs). Both simulation and real-world experiments

were performed to determine the effectiveness of using ZU in one robot to reinstate the localization of the others in a multi-robot system. Experimental results from GNSS-denied simulation and real-world environments revealed that using ZU in the DEKF together with simple heuristics significantly improved the three-dimensional localization accuracy.

Article Citation: Kilic, C., Gutierrez, E., & Gross, J. N. (2023). Evaluation of the benefits of zero velocity update in decentralized extended Kalman filter-based cooperative localization algorithms for GNSS-denied multi-robot systems. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.608

Video for "Development and Validation of a Multipath Mitigation Technique Using Multi-Correlator Structures"
By Christian Siebert, Andriy Konovaltsev, and Michael Meurer (https://navi.ion.org/content/70/4/navi.609/tab-supplemental)

Abstract: Multipath propagation is a major source of error in global navigation satellite systems (GNSSs), especially in urban environments. This is because conventional GNSS receivers can provide biased range estimates that lead to positioning errors. In this paper, an Extended Kalman Filter (EKF)-based solution that relies on a multi-correlator structure is proposed to replace the conventional delay locked loop (DLL). The underlying signal model incorporates the radio propagation channel between the satellite and receiver and thus inherently accounts for reflected signal replicas. The algorithm was evaluated with simulations and hardware emulations and a measurement campaign was conducted in road traffic with different multipath environments. Our results revealed that the proposed EKF was very effective against multipath-associated error.

Article Citation: Siebert, C., Konovaltsev, A., & Meurer, M. (2023). Development and validation of a multipath mitigation technique using multi-correlator structures. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.609

Video for "Identifying Aerodynamics of Small Fixed-Wing Drones Using Inertial Measurements for Model-Based Navigation"
By Aman Sharma, Gabriel François Laupré, and Jan Skaloud (https://navi.ion.org/content/70/4/navi.611/tab-supplemental)

Abstract: The success of drone missions is incumbent on an accurate determination of the drone pose and velocity, which are collectively estimated by fusing inertial measurement unit and global navigation satellite system (GNSS) measurements. However, during a GNSS outage, the long-term accuracy of these estimations are far from allowing practical use. In contrast, vehicle dynamic model (VDM)-based navigation has demonstrated significant improvement in autonomous positioning during GNSS outages. This improvement is achieved by incorporating mathematical models of aerodynamic forces/moments in the sensor fusion architecture. Such an approach, however, relies on a knowledge of aerodynamic model parameters, specific to the operating vehicle. We present a novel calibration algorithm to identify these parameters from the flight data of two geometrically different drones. The identified parameters, when used in the VDM framework, show a significant reduction in navigation drift during GNSS outages. Moreover, the obtained results show that the proposed algorithm is independent of the choice of fixed-wing platform and prior knowledge of aerodynamics.

Article Citation: Sharma, A., François Laupré, G., & Skaloud, J. (2023). Identifying aerodynamics of small fixed-wing drones using inertial measurements for model-based navigation. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.611

Video for "A Flexible Ephemeris Representation for GNSS and Alternative PNT Signal Sources Using B-Splines"
By Mikaela Dobbin and Penina Axelrad (https://navi.ion.org/content/70/4/navi.610/tab-supplemental)

Abstract: Most global navigation satellite systems (GNSSs) ephemeris representations require straightforward, albeit specialized algorithms to compute the transmitter position at a time of interest. As potential positioning, navigation, and timing (PNT) signal sources expand beyond medium Earth orbit, these representations must be modified to capture the dynamics of the host platforms. This work introduces the use of B-splines as a flexible framework to represent transmitter ephemerides that are applicable to any orbital or airborne regime and host platform. With this approach, the user equipment implements a simple, generic algorithm to compute transmitter positions from the B-spline representation that require no orbit or platform-specific models. Here we propose a B-spline ephemeris approach in which we compare the required navigation message length and fit accuracy to the legacy global positioning system (GPS) broadcast for use with medium earth orbit transmission. We also demonstrate the applicability of this approach for a PNT satellite in low earth orbit.

Article Citation: Dobbin, M., & Axelrad, P. (2023). A Flexible Ephemeris Representation for GNSS and Alternative PNT Signal Sources Using B-Splines. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.610

Video for "Satellite Constellation Design for a Lunar Navigation and Communication System"
By Sriramya Bhamidipati, Tara Mina, Alana Sanchez, and Grace Gao (https://navi.ion.org/content/70/4/navi.613/tab-supplemental)

Abstract: There has been a growing interest in using small satellites (SmallSats) for a future lunar navigation and communication satellite system (LNCSS). We conceptualize the design of a SmallSat-based LNCSS with Earth-Global Positioning System (GPS) time transfer that provides navigation and communication services near the lunar south pole. A hybrid constellation design is formulated, wherein all satellites provide navigation services while only a fraction are communication-enabled. Using Systems Tool Kit software, we examine various LNCSS case studies based on an elliptical lunar frozen orbit with a lower-grade chip-scale atomic clock. Case studies are evaluated in terms of (1) navigation considerations, including position and timing accuracy, lunar user equivalent ranging error, and dilution of precision, (2) communication considerations, including data volume, availability, and data rate, and (3) SmallSat factors, including cost, size, weight, and power. We performed a trade-off analysis for satisfying the criteria outlined by international space agencies while designing low-cost, low-SWaP lunar constellations.

Article Citation: Bhamidipati, S., Mina, T., Sanchez, A., & Gao, G. (2023). Satellite constellation design for a lunar navigation and communication system. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.613

Video for "Spatiotemporal Deep Learning Network for High-Latitude Ionospheric Phase Scintillation Forecasting"
By Yunxiang Liu, Zhe Yang, Y. Jade Morton, and Ruoyu Li (https://navi.ion.org/content/70/4/navi.615/tab-supplemental)

Abstract: In this paper, we present a spatiotemporal deep learning (STDL) network to conduct binary phase scintillation forecasting at a high-latitude global navigation satellite systems (GNSS) station. Historical measurements from the target and surrounding GNSS stations are utilized. In addition, external features such as solar wind parameters and geomagnetic activity indices are also included. The results show that the STDL network can adaptively incorporate spatiotemporal and external information to achieve the best performance by outperforming a naive method, three conventional machine learning algorithms (logistic regression, gradient boosting decision tree, and fully connected neural network) and a machine learning algorithm known as long short-term memory that incorporates temporal information.

Article Citation: Liu, Y., Yang, Z., Morton, Y. J., & Li, R. (2023). Spatiotemporal deep learning network for high-latitude ionospheric phase scintillation forecasting. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.615

Video for "Navigation Safety Assurance of a KF-Based GNSS/IMU System: Protection Levels Against IMU Failure"
By Jinsil Lee, Minchan Kim, Dongchan Min, Sam Pullen, and Jiyun Lee (https://navi.ion.org/content/70/4/navi.612/tab-supplemental)

Abstract: This study introduces a navigation integrity and continuity algorithm against an inertial measurement unit (IMU) sensor fault within a Kalman filter (KF) that ensures a high level of safety for IMU-integrated safety-critical navigation applications. A representative example of an IMU integrated navigation system is a global navigation satellite system (GNSS)/IMU system. Most previous studies have focused on GNSS faults when evaluating the integrity and continuity of a KF-based GNSS/IMU navigation system, leaving the IMU fault hypothesis unaddressed. Unlike GNSS, which is applied in the measurement update step within the KF, IMU measurements are applied in the state prediction step, which results in different fault propagation characteristics in the user state error compared with those in GNSS. This paper analytically derives the sequential IMU fault impacts on user state errors. Based on this investigation, a KF innovation-based fault detector and protection-level equations are developed, which can safely bound user state errors against sequential IMU fault impacts.

Article Citation: Lee, J., Kim, M., Min, D., Pullen, S. & Lee, J. (2023). Navigation safety assurance of a KF-based GNSS/IMU system: Protection levels against IMU failure. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.612

Video for "Stochastic Reachability-Based GPS Spoofing Detection with Chimera Signal Enhancement"
By Tara Mina, Ashwin Kanhere, Shreyas Kousik, and Grace Gao (https://navi.ion.org/content/70/4/navi.616/tab-supplemental)

Abstract: To protect civilian Global Positioning System (GPS) users from spoofing attacks, the U.S. Air Force Research Lab has proposed the chips-message robust authentication (Chimera) enhancement for the L1C signal. In particular, the

Chimera fast channel allows users to authenticate the received GPS signal once every 1.5 or 6 s, depending on the out-of-band source utilized for receiving the fast channel marker keys. However, for many moving receiver applications, receivers often use much higher GPS measurement rates, at 5–20 Hz.

In this work, we derive a stochastic reachability (SR)-based detector to perform continuous GPS signal verification and state estimation between Chimera authentications. Our SR detector validates the received GPS measurement against any self-contained sensor, such as an inertial measurement unit, in the presence of bounded biases in the sensor error distributions. We demonstrate via Monte Carlo simulations that our detector satisfies a user-defined false alarm requirement during nominal conditions, while successfully detecting a simulated spoofing attack. We further demonstrate that our SR state estimation filter successfully bounds the true state during both authentic and spoofed conditions.

Article Citation: Mina, T., Kanhere, A., Kousik, S., & Gao, G. (2023). Stochastic reachability-based GPS spoofing detection with Chimera signal enhancement. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.616

Video for "Multi-Epoch Kriging-Based 3D Mapping-Aided GNSS and Doppler Measurement Fusion Using Factor Graph Optimization"
By Hoi-Fung Ng, Li-Ta Hsu, and Guohao Zhang (https://navi.ion.org/content/70/4/navi.617/tab-supplemental)

Abstract: Global navigation satellite system (GNSS) signal reflection over buildings degrades positioning performance in urban canyons. Different three-dimensional (3D) mapping-aided (3DMA) GNSS algorithms have been proposed, which utilize 3D building models to aid in positioning. Recently, the candidate-based 3DMA GNSS framework has been applied to examine evenly spaced distributed particles. The particles that best match the observed measurements, that is, with the minimum cost, are identified as the receiver location. However, such particle sampling approaches incur a high computational load and are not robust. In this study, a Kriging-based interpolation method is applied to model the cost function of a 3DMA GNSS based on sampled particles, and the modeled cost function is then integrated with Doppler measurements through factor graph optimization. The regressed model can reduce the computational load by sparsely distributing the particles. Designed experiments with smartphone and commercial-level GNSS receivers demonstrate that the positioning performance can achieve a root mean square error of less than 10 m in Hong Kong and New York City urban canyons.

Article Citation: Ng, H.-F., Hsu, L.-T., & Zhang, G. (2023). Multi-epoch Kriging-based 3D mapping-aided GNSS and Doppler measurement fusion using factor graph optimization. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.617

Video for "RFI Mapped by Spaceborne GNSS-R Data"
By Clara Chew, T. Maximillian Roberts, and Steve Lowe (https://navi.ion.org/content/70/4/navi.618/tab-supplemental)

Abstract: Radio frequency interference (RFI) in global navigation satellite system (GNSS) frequencies can endanger human life and safety by preventing the use of these signals for navigation and positioning, in addition to degrading measurements for science applications. Here, we use data from the Cyclone GNSS (CYGNSS) constellation to map GNSS RFI from 2017 to 2022, identify the location

of several potential sources of RFI, and quantify the duration of transmission. Although our method of RFI detection can only provide a rough approximation of transmitter positions, it is possible that advanced data processing techniques could better pinpoint their locations, once guided by these observations. We find that, since the launch of CYGNSS, GNSS jammers have proliferated across the world and are often associated with the beginnings of geopolitical unrest. Our results agree well with previous studies that have also used satellite observations to map ground-based RFI transmission.

Article Citation: Chew, C., Roberts, T. M., & Lowe, S. (2023). RFI mapped by space-borne GNSS-R data. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.618

Video for "A Novel Co-Calibration Method for a Dual Heterogeneous Redundant Marine INS"
By Jiarui Cui, Wenqi Wu, Tiefeng Ma, Maosong Wang, and Chengjun Ji (https://navi.ion.org/content/70/4/navi.620/tab-supplemental)

Abstract: This paper focuses on a heterogeneous redundant inertial navigation system (INS) that consists of one three-axis rotation-modulation fiber optic gyroscope (FOG) INS and one strapdown ring laser gyroscope (RLG) INS. A novel co-calibration method is proposed to estimate the FOG scale factor instability and RLG bias instability error in real time, in which the geometric constraints of the FOG-INS rotating axis are deployed to establish the observation equation without external reference information. In addition, the proposed method has a global navigation capability, which is achieved by using the normal vector of the earth ellipsoid and the state transformation extended Kalman filter to predict positioning errors. An output position error compensation method is used without disturbing the original INSs. Simulation and physical experiment results show that the positioning error of the heterogeneous redundant marine INS is reduced by more than 30% over 300 h of navigation.

Article Citation: Cui, J., Wu, W., Ma, T., Wang, M., & Ji, C. (2023). A novel co-calibration method for a dual heterogeneous redundant marine INS. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.620

Video for "Bicomplex Representation and Processing of GNSS Signals"
By Daniele Borio (https://navi.ion.org/content/70/4/navi.621/tab-supplemental)

Abstract: Generalized binary offset carrier (BOC) modulations and global navigation satellite system (GNSS) meta-signals require advanced processing algorithms to overcome problems associated with their multi-peaked correlation functions. In this paper, bicomplex numbers are introduced for GNSS signal representation and for algorithm development. Bicomplex numbers generalize complex numbers and are characterized by four real components. These numbers have the potential to represent multicomponent signals, such as GNSS meta-signals, leading to a compact notation that allows effective derivations and algorithm development. Moreover, bicomplex numbers allow one to express a meta-signal as the product of a code, a carrier, and a subcarrier component: this representation leads to acquisition and tracking algorithms that are capable of effectively processing GNSS meta-signals, thus solving the code ambiguity problem. Theoretical developments are demonstrated using real data collected using software-defined radio front-ends for the Galileo alternative BOC modulation and the BeiDou B1I/B1C meta-signal.

Article Citation: Borio, D. (2023). Bicomplex representation and processing of GNSS signals. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.621

Video for "Learning GNSS Positioning Corrections for Smartphones Using Graph Convolution Neural Networks"
By Adyasha Mohanty and Grace Gao (https://navi.ion.org/content/70/4/navi.622/tab-supplemental)

Abstract: Smartphone receivers comprise approximately 1.5 billion global navigation satellite system receivers currently manufactured worldwide. Smartphone receivers provide measurements with lower signal levels and higher noise than commercial receivers. Because of constraints on size, weight, power consumption, and cost, it is challenging to achieve accurate positioning with these receivers, particularly in urban environments. Traditionally, Global Positioning System measurements are processed via model-based approaches, such as weighted least-squares and Kalman filtering approaches. While model-based approaches can provide meter-level positioning accuracy in a postprocessing manner, these approaches require strong assumptions on the corresponding noise models and require manual tuning of parameters such as covariances. In contrast, learning-based approaches have been proposed that make fewer assumptions about the data structure and can accurately model environment-specific errors. However, these approaches provide lower accuracy than model-based methods and are sensitive to initialization. In this paper, we propose a hybrid framework for learning position correction, which corresponds to the offset between the true receiver position and the estimated position. For a learning-based approach, we propose a graph convolution neural network (GCNN) that can learn different graph structures with multi-constellation and multi-frequency signals. For better initialization of the GCNN, we use a Kalman filter to estimate a coarse receiver position. We then use this coarse receiver position to condition the input features to the graph. We test our proposed approach on real-world data sets from the Google Smartphone Decimeter Challenge and show improved positioning performance over model-based methods such as the weighted least-squares and Kalman filter methods.

Article Citation: Mohanty, A., & Gao, G. (2023). Learning GNSS positioning corrections for smartphones using graph convolution neural networks. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.622

Video for "Analytical and Empirical Navigation Safety Evaluation of a Tightly Integrated Lidar/IMU Using Return-Light Intensity"
By Ali Hassani and Mathieu Joerger (https://navi.ion.org/content/70/4/navi.623/tab-supplemental)

Abstract: This paper describes the design, analysis, and experimental evaluation of a new landmark-based localization method that integrates light detection and ranging (lidar) with an inertial measurement unit (IMU). We develop a tight IMU/lidar integration scheme that exploits the complementary properties of the two sensors to facilitate safety risk evaluation. Lidar localization updates limit the IMU error drift over time while IMU data improve lidar position and orientation (or pose) prediction, thereby reducing the risk of incorrectly associating perceived features with mapped landmarks. In addition, lidar return-light intensity measurements are incorporated to better distinguish landmarks and to further reduce the risk of incorrect associations. We analyze the integrity performance of the localization

algorithm using an automated testbed that generates analytical and empirical pose estimation error distributions.

Article Citation: Hassani, A., & Joerger, M. (2023). Analytical and empirical navigation safety evaluation of a tightly integrated lidar/IMU using return-light intensity. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.623

Video for "Privacy-Preserving Cooperative GNSS Positioning"
By Guillermo Hernandez, Gerald LaMountain, and Pau Closas (https://navi.ion.org/content/70/4/navi.625/tab-supplemental)

Abstract: The issue of user privacy in the context of collaborative positioning is addressed in this work, wherein information is passed between and processed by multiple cooperative agents, with the goal of achieving high levels of positioning accuracy. In particular, this paper discusses three privacy-preserving schemes in the context of differential global navigation satellite system (GNSS)-based and GNSS-based cooperative positioning methods. The discussed architectures provide the same positioning results, while yielding different levels of privacy to the cooperative users. These architectures also involve increased complexity as privacy grows and as non-encrypted, encrypted, and homomorphically encrypted solutions are implemented. The latter scheme is the most computationally demanding; however, it provides the highest level of privacy by employing homomorphic encryption, whereby addition and multiplication operations may be performed on encrypted data to produce encrypted outputs, without revealing information about the collaborative agent's location. The proposed privacy-preserving cooperative position schemes are shown to provide the same results as their non-privacy-preserving counterparts, while providing privacy guarantees. Based on this analysis, some of the proposed solutions can be considered for real-time applications, while homomorphic encryption is a valid solution for latency-tolerant applications. Advances in computing power will increase their overall usability in the near future.

Article Citation: Hernandez, G., LaMountain, G., & Closas, P. (2023). Privacy-preserving cooperative GNSS positioning. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.625

Video for "Performance Analysis of a RTK Vector Phase-Locked Loop Architecture for GPS Signal Tracking in Degraded Environments"
By Scott M. Martin (https://navi.ion.org/content/70/4/navi.626/tab-supplemental)

Abstract: This paper investigates the application of a vector tracking approach to carrier phase tracking for improved tracking in degraded signal environments. In contrast to many vector-based carrier phase tracking approaches, the algorithms described in this paper do not rely on local loop filters to maintain phase lock. A relative position vector estimate, fixed-integer carrier ambiguities, and measurements from the base station are used to drive the carrier replica. To test carrier phase tracking approaches, Monte Carlo simulations were performed to compare the performance of a real-time kinematic (RTK) vector phase-locked loop (VPLL) approach with the performance obtained by scalar tracking. In these simulations, the RTK-VPLL maintains phase lock at carrier-to-noise-density ratios 4 to 7 dB-Hz lower than the scalar tracking receiver. The proposed algorithms were tested using live sky data, and the RTK-VPLL performance was compared with

the performance of a commercial Global Positioning System receiver. Significant reductions in carrier cycle slips and loss of lock were observed in moderate-foliage environments.

Article Citation: Martin, S. M. (2023). Performance analysis of a RTK vector phase-locked loop architecture for GPS signal tracking in degraded environments. *NAVIGATION, 70*(4). https://navi.ion.org/content/70/4/navi.626

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.

February 28, 2024 Webinar: Identifying Aerodynamics of Small Fixed-Wing Drones Using Inertial Measurements for Model-Based Navigation (https://www.ion.org/publications/webinar-sharma.cfm)
By: Aman Sharma

Abstract: The success of drone missions is incumbent on an accurate determination of the drone pose and velocity, which are collectively estimated by fusing inertial measurement unit and global navigation satellite system (GNSS) measurements. However, during a GNSS outage, the long-term accuracy of these estimations are far from allowing practical use. In contrast, vehicle dynamic model (VDM)-based navigation has demonstrated significant improvement in autonomous positioning during GNSS outages. This improvement is achieved by incorporating mathematical models of aerodynamic forces/moments in the sensor fusion architecture. Such an approach, however, relies on a knowledge of aerodynamic model parameters, specific to the operating vehicle. We present a novel calibration algorithm to identify these parameters from the flight data of two geometrically different drones. The identified parameters, when used in the VDM framework, show a significant reduction in navigation drift during GNSS outages. Moreover, the obtained results show that the proposed algorithm is independent of the choice of fixed-wing platform and prior knowledge of aerodynamics.

Article Citation: Sharma, A., Laupré, G. F., & Skaloud, J. (2023). Identifying aerodynamics of small fixed-wing drones using inertial measurements for model-based navigation. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.611

January 31, 2024 Webinar: GEODNET: Global Earth Observation Decentralized Network (https://www.ion.org/publications/webinar-horton.cfm)
By: Mike Horton

Abstract: This paper explains some design and architecture decisions around the GEODNET network and the GeoDAO decentralized autonomous organization, which aims to create and operate a truly decentralized public GNSS reference sensing network. This paper covers the motivation of the network, the capabilities of current and future reference stations, the blockchain and GEOD token mechanics, and how the network powers applications ranging from climate change monitoring to real-time centimeter-accurate positioning.

Article Citation: Horton, M., Chen, D., Yi, Y., Wen, X., & Doebbler, J. (2023). GEODNET—Global Earth observation decentralized network. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.605

December 6, 2023 Webinar: RFI Mapped by Spaceborne GNSS-R Data (https://www.ion.org/publications/webinar-chew.cfm)
By: Clara Chew

Abstract: Radio frequency interference (RFI) in global navigation satellite system (GNSS) frequencies can endanger human life and safety by preventing the use of these signals for navigation and positioning, in addition to degrading measurements for science applications. Here, we use data from the Cyclone GNSS (CYGNSS) constellation to map GNSS RFI from 2017 to 2022, identify the location of several potential sources of RFI, and quantify the duration of transmission. Although our method of RFI detection can only provide a rough approximation of transmitter positions, it is possible that advanced data processing techniques could better pinpoint their locations, once guided by these observations. We find that, since the launch of CYGNSS, GNSS jammers have proliferated across the world and are often associated with the beginnings of geopolitical unrest. Our results agree well with previous studies that have also used satellite observations to map ground-based RFI transmission.

Article Citation: Chew, C., Roberts, T. M., & Lowe, S. (2023). RFI mapped by spaceborne GNSS-R data. *NAVIGATION, 70*(4). https://doi.org/10.33012/navi.618

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