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EDITORIAL

Navigator Notes

Editorial Highlights from the Editor-in-Chief

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Welcome to the Summer 2024 issue of *NAVIGATION*. A hot topic in our PNT research community these days is the development of techniques to counter jamming and spoofing of global navigation satellite systems. While much of this work is classified, some of it appears in the open literature. And in this issue of *NAVIGATION*, we have several articles on the topic. We also have articles on the natural degradation of GNSS signals caused by the ionosphere, the problem of multipath, the use of GNSS to navigate other satellites, and a lot more.

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 "Characterizing Perspective Error in Voxel-Based Lidar Scan Matching" By Jason H. Rife and Matthew McDermott (https://navi.ion.org/content/71/1/navi.627/tab-supplemental)

Abstract: This paper quantifies an error source that limits the accuracy of lidar scan matching, particularly for voxel-based methods. Lidar scan matching, which is used in dead reckoning (also known as *lidar odometry*) and mapping, computes the rotation and translation that best align a pair of point clouds. Perspective errors occur when a scene is viewed from different angles, with different surfaces becoming visible or occluded from each viewpoint. To explain perspective anomalies observed in data, this paper models perspective errors for two objects representative of urban landscapes: a cylindrical column and a dual-wall corner. For each object, we provide an analytical model of the perspective error for voxel-based lidar scan matching. We then analyze how perspective errors accumulate as a lidar-equipped vehicle moves past these objects.

Article Citation: Rife, J. H., & McDermott, M. (2024). Characterizing perspective error in voxel-based lidar scan matching. *NAVIGATION, 71*(1). https://doi.org/10.33012/navi.627

Video for "Surface Reflectivity Variations of Global Navigation Satellite System Signals from a Mixed Ice and Water Surface"
By Roohollah Parvizi, Shahrukh Khan, Alison F. Banwell, and Seebany Datta-Barua (https://navi.ion.org/content/71/1/navi.614/tab-supplemental)

Abstract: This paper presents estimates of surface reflectivity (SR) over time of global navigation satellite system (GNSS) signals scattered from a partially frozen lake surface. A portable ground-based GNSS reflectometry sensor system that collects both scattered Global Positioning System L1 signals and independent validation data (lidar and camera) was deployed on the Lake Michigan waterfront in Chicago at a time when the lake surface was a mixture of ice and water. Lidar surface scans were merged with camera images and mapped, along with estimated reflection zones. For three satellites whose reflection points scan across ice and water over time, the relative SR and mean red intensity (differentiating ice from water) of camera pixels inside the first Fresnel zone were computed and shown to be correlated. This system concept will be used in the future for more complete mapping of phase changes of snow and ice in the cryosphere.

Article Citation: Parvizi, R., Khan, S., Banwell, A., & Datta-Barua, S. (2024). Surface reflectivity variations of global navigation satellite system signals from a mixed ice and water surface. *NAVIGATION, 71*(1). https://doi.org/10.33012/navi.614

Video for "Optimal INS Monitor for GNSS Spoofer Tracking Error Detection"
By Birendra Kujur, Samer Khanafseh, and Boris Pervan (https://navi.ion.org/content/71/1/navi.629/tab-supplemental)

Abstract: In this article, we describe a new method for detecting global navigation satellite system (GNSS) spoofing using an inertial navigation system. We specifically address the most difficult-to-detect scenario, in which a spoofer replicates the authentic GNSS signal with only additive errors due to the spoofer's uncertainty in knowledge of the target's position. We derive an optimal monitor to detect the anomalous temporal structure of the spoofed measurements caused by the spoofer's target tracking errors. This new monitor uses accumulated Kalman filter innovations projected into the position state domain. We demonstrate how the monitor window length can be set to achieve any required missed detection probability, and we evaluate the performance of the monitor for both white and colored tracking error. Finally, we present a complementary solution separation monitoring concept to detect rapid-onset spoofing and to achieve protection levels in real time.

Article Citation: Kujur, B., Khanafseh, S., & Pervan, B. (2024). Optimal INS monitor for GNSS spoofer tracking error detection. *NAVIGATION, 71*(1). https://doi.org/10.33012/navi.629

Video for "Effect of User Antenna Group Delay Variation Error on Advanced RAIM"
By Eugene Bang, Mihaela-Simona Circiu, Stefano Caizzone, Markus Rippl, and Omar Garcia Crespillo (https://navi.ion.org/content/71/1/navi.624/tab-supplemental)

Abstract: This study investigates the impact of antenna group delay variation (AGDV)-induced error on advanced receiver autonomous integrity monitoring. We model the AGDV error contribution not only as a measurement bias but also as a random process sigma term in protection-level computations by using AGDV errors analyzed within the European Dual Frequency Multipath Model for Aviation (DUFMAN) project. We also apply the new multipath and AGDV error models developed for aviation use to assess the availability of localizer performance with vertical guidance down to 200 feet. The results show that the fraction of users with ≥99.5% availability increases by approximately 5% when the newly derived DUFMAN models are used. In contrast, considering the AGDV effect alone as the worst-case bias has a weaker impact at the current user range accuracy standard.

Article Citation: Bang, E., Circiu, M.-S., Caizzone, S., Rippl, M., & Garcia Crespillo, O. (2024). Effect of user antenna group delay variation error on advanced RAIM. *NAVIGATION, 71*(1). https://doi.org/10.33012/navi.624

Video for "A Simple and Effective Approach to Real-Time Ionospheric Monitoring at Low Latitudes and its Applicability to GBAS"
By Leonardo Marini-Pereira, Alison de Oliveira Moraes, and Sam Pullen (https://navi.ion.org/content/71/1/navi.619/tab-supplemental)

Abstract: This paper proposes a strategy for improving ionospheric detection of threatening conditions, motivated by issues with ground-based augmentation systems (GBASs) at low latitudes. A methodology is developed for a real-time alerting system that monitors the ionosphere state using surrounding ground stations and sends alerts to differential global navigation satellite systems services when threatening conditions are detected. The method is based on time-step gradients and data gap analysis to detect ionospheric disturbances and to declare periods for affected satellite signals to be unavailable. Validation was performed with real data using the largest observed gradients from the Brazilian ionospheric threat model. The results demonstrate that the method is effective, detecting the vast majority of previously known threatening gradients. An availability assessment was also performed to assess for a loss of availability resulting from the implementation of this technique. Applications of the developed technique include the improvement of low-latitude nighttime GBAS availability.

Article Citation: Marini-Pereira, L., de Oliveira Moraes, A., & Pullen, S. (2024). A simple and effective approach to real-time ionospheric monitoring at low latitudes and its applicability to GBAS. *NAVIGATION, 71*(1). https://doi.org/10.33012/navi.619

Video for "GNSS Software-Defined Radio: History, Current Developments, and Standardization Efforts"
By Thomas Pany, Dennis Akos, Javier Arribas, M. Zahidul H. Bhuiyan, Pau Closas, Fabio Dovis, Ignacio Fernandez-Hernandez, Carles Fernández–Prades, Sanjeev Gunawardena, Todd Humphreys, Zaher M. Kassas, José A. López Salcedo, Mario Nicola, Mark L. Psiaki, Alexander Rügamer, Young-Jin Song, and Jong-Hoon Won (https://navi.ion.org/content/71/1/navi.628/tab-supplemental)

Abstract: Taking the work conducted by the global navigation satellite system (GNSS) software-defined radio (SDR) working group during the last decade as a seed, this contribution summarizes, for the first time, the history of GNSS SDR

development. This report highlights selected SDR implementations and achievements that are available to the public or that influenced the general development of SDR. Aspects related to the standardization process of intermediate-frequency sample data and metadata are discussed, and an update of the Institute of Navigation SDR Standard is proposed. This work focuses on GNSS SDR implementations in general-purpose processors and leaves aside developments conducted on field programmable gate array and application-specific integrated circuit platforms. Data collection systems (*i.e.*, front-ends) have always been of paramount importance for GNSS SDRs and are thus partly covered in this work. This report represents the knowledge of the authors but is not meant as a complete description of SDR history.

Article Citation: Pany, T., Akos, D., Arribas, J., Bhuiyan, M. Z. H., Closas, P., Dovis, F., Fernandez-Hernandez, I., Fernández-Prades, C., Gunawardena, S., Humphreys, T., Kassas, Z., López-Salcedo, J. A., Nicola, M., Psiaki, M. L., Rügamer, A., Song, Y-J., & Won, J-H. (2024). GNSS software-defined radio: History, current developments, and standardization efforts. *NAVIGATION, 71*(1). https://doi.org/10.33012/navi.628

Video for "Fault-Free Integrity of Urban Driverless Vehicle Navigation with Multi-Sensor Integration: A Case Study in Downtown Chicago"
By Kana Nagai, Matthew Spenko, Ron Henderson, and Boris Pervan (https://navi.ion.org/content/71/1/navi.631/tab-supplemental)

Abstract: This paper investigates how global navigation satellite systems (GNSSs) and inertial navigation systems (INSs), when appropriately augmented by ranging from local landmarks, can safely navigate vehicles through a real-world urban environment. We begin by considering safety requirements for driverless vehicles under fault-free assumptions and developing measurement models for multi-sensor integrated navigation systems using an extended Kalman filter. The critical elements of urban navigation are then discussed, including individual INS noise parameter specifications, vehicle speed, and the effect of velocity updates. Covariance analyses performed along a 9-km-long urban transect in downtown Chicago show that velocity updates measured by wheel speed sensors, vehicle kinematic constraints, and zero-velocity updates can extend navigation continuity by bridging intermittent GNSS signal availability. However, position reference updates at intervals between 15 and 35 m, based on light detection and ranging data from local landmarks in our case, are needed to achieve full navigation availability through the transect.

Article Citation: Nagai, K., Spenko, M., Henderson, R., & Pervan, B. (2024). Fault-free integrity of urban driverless vehicle navigation with multi-sensor integration: A case study in downtown Chicago. *NAVIGATION, 71*(1). https://doi.org/10.33012/navi.631

Video for "Robust Determination of Smartphone Heading by Mitigation of Magnetic Anomalies"
By Andreas Ettlinger, Andreas Wieser, and Hans Neuner (https://navi.ion.org/content/71/1/navi.632/tab-supplemental)

Abstract: We introduce an algorithm that provides robust three-dimensional orientation of a smartphone for pedestrian indoor localization. The algorithm focuses on integration of the magnetometer and a reformulated observation model such

that the influence of magnetic anomalies is mitigated. The methodological novelty of this approach lies in the use of an extended Kalman filter (EKF), based on a state vector that contains only the slow-varying systematic deviation components of the magnetometer. We apply a statistical test to the EKF residuals to detect the presence of magnetic anomalies and update the absolute heading when beneficial conditions prevail. Otherwise, the heading is propagated based on gyroscope observations. We investigate the properties of the proposed algorithm by using simulated smartphone sensor observations with different scenarios of systematic deviations. In experiments with very accurate ground truth, the proposed algorithm achieves a root mean square error of 17.4° for the computed heading, outperforming state-of-the-art algorithms by at least 40%.

Article Citation: Ettlinger, A., Wieser, A., & Neuner, H. (2024). Robust determination of smartphone heading by mitigation of magnetic anomalies. *NAVIGATION, 71*(1). https://doi.org/10.33012/navi.632

Video for "An Analytical Derivation of the Signal-in-Space Root-Mean-Square User Range Error"
By Brent Renfro, Jason Drotar, Austin Finn, Miquela Stein, Emery Reed, and Eduardo Villalba (https://navi.ion.org/content/71/1/navi.630/tab-supplemental)

Abstract: The concept of the signal-in-space (SIS) root-mean-square (RMS) user range error (URE) is used to evaluate the performance of multiple global navigation satellite systems (GNSSs); however, a complete analytical derivation has not been published. This article describes the instantaneous SIS URE and the instantaneous SIS RMS URE, explains the role of the instantaneous SIS RMS URE in evaluating the statistical accuracy of GNSS signals, and provides an analytical derivation of the instantaneous SIS RMS URE. This derivation is then compared to the equations found in various papers and performance standards to illustrate how the equations, although appearing different, actually measure the same quantity with differing constraints.

Article Citation: Renfro, B., Drotar, J., Finn, A., Stein, M., Reed, E., & Villalba, E. (2024). An analytical derivation of the signal-in-space root-mean-square user range error. *NAVIGATION, 71*(1). https://doi.org/10.33012/navi.630

Video for "Visual Semantic Context and Efficient Map-Based Rotation-Invariant Estimation of Position and Heading"
By Junwoo Park, Sungjoong Kim, Kyungwoo Hong, and Hyochoong Bang (https://navi.ion.org/content/71/1/navi.634/tab-supplemental)

Abstract: This paper proposes a visual map-based position and heading estimation system that is invariant to image rotation and consistent over time, which is achieved by exploiting the radial and azimuthal distributions of semantic segments. To characterize the specific position and heading, a novel concept termed "visual semantic context" is applied, which collects semantics in a polar-coordinated fashion in collaboration with measures of discrepancy. The system then matches visual semantic contexts: one from a semantically segmented aerial image aided by deep learning technology and others from a semantics-labeled database. Two-stage minimization alleviates the expensive computation of an exhaustive search. The first stage marginalizes the heading and coarsely searches for positions. At the same time, the Kolmogorov–Smirnov test significantly reduces the search domain by

rejecting unlikely candidates, and the second stage refines the estimates. Numerical experiments show that the proposed algorithm fixes the position and heading, is invariant to image rotation, and is also robust to imprecise scale information.

Article Citation: Park, J., Kim, S., Hong, K., & Bang, H. (2024). Visual semantic context and efficient map-based rotation-invariant estimation of position and heading. *NAVIGATION, 71*(1). https://doi.org/10.33012/navi.634

Video for Formulation and Characterization of One-Way Radiometric Tracking with the Iris Radio Using a Chip-Scale Atomic Clock
By Todd Ely, Zaid Towfic, and Dana Sorensen (https://navi.ion.org/content/71/1/navi.633/tab-supplemental)

Abstract: The Iris software radio has been updated to collect one-way Doppler and range data for potential use with deep space autonomous navigation. One-way radiometric data have found limited use because a typical radio oscillator is not sufficiently stable for use in navigation. However, Iris has been paired with a chip-scale atomic clock (CSAC) via an input signal of one pulse per second. With superior stability relative to a typical oscillator, the CSAC has the potential to provide onboard tracking data with sufficient accuracy to support a small satellite mission with modest navigation requirements. In this paper, we develop models of the Iris radio one-way Doppler and range data and analyze their performance in lab testing prior to a future inflight test on NASA's CAPSTONE mission to the Moon. The test results confirm theoretical predictions for range precision measured between 0.38 m and 2.21 m with a range rate of 11 mm/s at 60 s.

Article Citation: Ely, T., Towfic, Z., & Sorensen, D. (2024). Formulation and characterization of one-way radiometric tracking with the Iris radio using a chip-scale atomic clock. *NAVIGATION, 71*(1). https://doi.org/10.33012/navi.633

Video for Precise Positioning and Timekeeping in a Lunar Orbit via Terrestrial GPS Time-Differenced Carrier-Phase Measurements
By Keidai Iiyama, Sriramya Bhamidipati, and Grace Gao (https://navi.ion.org/content/71/1/navi.635/tab-supplemental)

Abstract: There is a growing interest in the use of legacy terrestrial Global Positioning System (GPS) signals to determine the precise positioning and timing onboard a lunar satellite. Unlike prior works that utilize pseudoranges with meter-level accuracy, we propose a precise positioning and timekeeping technique that leverages carrier-phase measurements with millimeter-level accuracy (when integer ambiguities are correctly fixed). We design an extended Kalman filter framework that harnesses the intermittently available terrestrial GPS time-differenced carrier-phase (TDCP) values and gravitational accelerations predicted by the orbital filter. To estimate the process noise covariance, we implement an adaptive state noise compensation algorithm that adapts to the challenging lunar environment with weak gravity and strong third-body perturbations. Additionally, we perform measurement residual analysis to discard TDCP measurements corrupted by cycle slips and increased measurement noise. We present Monte-Carlo simulations of a lunar satellite in an elliptical lunar frozen orbit and quasi-frozen low lunar orbit, wherein we showcase higher positioning and timing accuracy as compared with the pseudorange-only navigation solution.

Article Citation: Iiyama, K., Bhamidipati, S., & Gao, G. (2024). Precise positioning and timekeeping in a lunar orbit via terrestrial GPS time-differenced carrier-phase measurements. *NAVIGATION, 71*(1). https://doi.org/10.33012/navi.635

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.

May 1, 2024 Webinar: Hong Kong UrbanNav: An Open-Source Multisensory Dataset for Benchmarking Urban Navigation Algorithms (https://www.ion.org/publications/webinar-hsu-2.cfm)
By: Li-Ta Hsu

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

April 3, 2024 Webinar: Fault-Free Integrity of Urban Driverless Vehicle Navigation with Multi-Sensor Integration: A Case Study in Downtown Chicago (https://www.ion.org/publications/webinar-nagai.cfm)
By: Kana Nagai

Abstract: This paper investigates how global navigation satellite systems (GNSSs) and inertial navigation systems (INSs), when appropriately augmented by ranging from local landmarks, can safely navigate vehicles through a real-world urban environment. We begin by considering safety requirements for driverless vehicles under fault-free assumptions and developing measurement models for

multi-sensor integrated navigation systems using an extended Kalman filter. The critical elements of urban navigation are then discussed, including individual INS noise parameter specifications, vehicle speed, and the effect of velocity updates. Covariance analyses performed along a 9-km-long urban transect in downtown Chicago show that velocity updates measured by wheel speed sensors, vehicle kinematic constraints, and zero-velocity updates can extend navigation continuity by bridging intermittent GNSS signal availability. However, position reference updates at intervals between 15 and 35 m, based on light detection and ranging data from local landmarks in our case, are needed to achieve full navigation availability through the transect.

Article Citation: Nagai, K., Spenko, M., Henderson, R., & Pervan, B. (2024). Fault-free integrity of urban driverless vehicle navigation with multi-sensor integration: A case study in downtown Chicago. *NAVIGATION, 71*(1). https://doi.org/10.33012/navi.631

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