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EDITORIAL

Navigator Notes

Editorial Highlights from the Editor-in-Chief

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Welcome to the Spring 2022 issue of *NAVIGATION* – our first issue since transitioning to an open access journal at the beginning of the year. As I mentioned in "Navigator Notes" in the Winter 2021 issue, all journal articles from now on will be available for download without charge. And Institute of Navigation members will be able to download complete issues. Consult the ION website at https://navi.ion.org for details.

In this issue, we again feature articles on a wide range of topics including detection of GPS satellite oscillator anomalies, vision localization, and GNSS spoofing. We are also featuring an article on the design of a lunar navigation satellite system as well as a comprehensive article on how the Wide Area Augmentation System monitors the state of the ionosphere to protect users from ionospheric disturbances.

ION will continue promoting the research of journal authors through video abstracts hosted on the ION website. In fact, a video abstract will become compulsory for publishing in *NAVIGATION*. The latest video abstracts are documented below. 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 we announce the ION 2021 Samuel M. Burka Award winner.

2021 SAMUEL M. BURKA AWARD WINNER

The Samuel M. Burka Award, sponsored by the Institute of Navigation, recognizes outstanding achievement in the preparation of papers advancing the art and science of positioning, navigation, and timing. It is given in memory of Dr. Samuel M. Burka, a dedicated public servant, who devoted a long and distinguished career to the research and development of air navigation equipment and reviewing technical material for official publications.

The award is presented to the following author for his article, "Navigation using carrier Doppler shift from a LEO constellation: TRANSIT on steroids," published in the Fall 2021 issue of *NAVIGATION*.

Dr. Mark L. Psiaki is the Kevin Crofton Faculty Chair of Aerospace and Ocean Engineering at Virginia Tech. He is also Professor Emeritus of Mechanical and Aerospace Engineering at Cornell University, where he taught for 30 years. His research interests are in the areas of GNSS signal processing, applications, and resilience; spacecraft attitude and orbit determination;

remote sensing; and general estimation, filtering, and detection. Dr. Psiaki is a Fellow of the ION and the American Institute of Aeronautics and Astronautics. He is the ION's 2021 Kepler Award winner and the recipient of ION's 2013 Tycho Brahe Award and the 2005 Samuel M. Burka Award. He is also the AIAA's 2022 Mechanics and Control of Flight Award winner. Dr. Psiaki received a BA in physics as well as MA and PhD degrees in mechanical and aerospace engineering from Princeton University.

Abstract: A new global navigation concept is studied that relies on carrier Doppler shift measurements from a large LEO constellation. This system could provide an alternative to pseudorange-based GNSS. The concept uses a high-fidelity model of received carrier Doppler shift. This model is used in a point-solution batch filter that simultaneously estimates eight unknowns: the three position vector components, receiver clock offset, three velocity vector components, and receiver clock offset rate. The filter uses eight or more measured Doppler shifts in its least-squares fit. A generalized geometric dilution of precision (GDOP) analysis indicates that absolute position accuracies on the order of 1–5 meters and absolute velocity accuracies on the order of 0.01 m/sec to 0.05 m/sec may be achievable if the range-rate precision of the Doppler shift measurements is 0.01 m/sec. These accuracies are comparable to current pseudorange-based GNSS. Clock offset accuracy is on the order of 0.0001 to 0.0010 sec 1-sigma.

Article Citation: Psiaki, ML. Navigation using carrier Doppler shift from a LEO constellation: TRANSIT on steroids. *NAVIGATION*. 2021; 68: 621–641. https://doi.org/10.1002/navi.438

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 "Urban positioning: 3D mapping-aided GNSS using dual-frequency pseudorange measurements from smartphones"
By Hoi-Fung Ng, Guohao Zhang, Yiran Luo, and Li-Ta Hsu
(https://www.ion.org/publications/abstract.cfm?articleID=102931)

Abstract: A smartphone with a highly sensitive antenna receiving numerous unhealthy measurements suffers from non-line-of-sight (NLOS) reception and multipath effects. 3D mapping-aided (3DMA) GNSS has been proven to be effective in urban environments. However, the multipath effect remains challenging for urban positioning. In nature, the new GNSS civilian L5-band signal with a shorter chip length shows a much better resistance to multipath than the conventional L1-band signal. Therefore, this study integrated the multi-constellation L5-band measurements into 3DMA GNSS to improve the positioning performance in urban canyons, namely the L1-L5 3DMA GNSS. Furthermore, this study compares different approaches on the receiver clock biases estimation for 3DMA GNSS. Finally, the integration of different 3DMA GNSSs is presented. The experiments conducted using smartphone data show that the L1-L5 3DMA GNSS is available for a better position solution than the 3DMA GNSS with L1-band only, thereby achieving a positioning accuracy within 10 m on average.

Article Citation: Ng, H-F, Zhang, G, Luo, Y, Hsu, L-T. Urban positioning: 3D mapping-aided GNSS using dual-frequency pseudorange measurements from smartphones. *NAVIGATION*. 2021; 68: 727–749. https://doi.org/10.1002/navi.448

Video for "Study of structures of the sporadic E layer by using dense GNSS network observations"
By Susumu Saito, Keisuke Hosokawa, Jun Sakai, and Ichiro Tomizawa
(https://www.ion.org/publications/abstract.cfm?articleID=102937)

Abstract: The sporadic E (Es) layer has been known to introduce long-range propagation of aeronautical very high frequency (VHF) navigation beyond the radio horizon and cause potential interference on the navigation system. This study utilizes a rate of total electron content (TEC) index (ROTI) map with dense Global Navigation Satellite System (GNSS) observations for effective Es layer detection. The daytime Es layer shows a well-defined frontal structure when ROTI values are mapped at the typical Es layer height (100 km). A methodology of detecting and characterizing the Es layer frontal structure without manual operation is developed by utilizing the Hough transform. The front direction and drift velocity are successfully derived. Sub-structures in the Es layer front are revealed by analysis using the characteristics of the frontal structure and TEC variation. The developed method is suitable for an automated real-time Es-layer monitoring system in a wide area.

Article Citation: Saito, S, Hosokawa, K. Study of structures of the sporadic E layer by using dense GNSS network observations. *NAVIGATION*. 2021; 68: 751–758. https://doi.org/10.1002/navi.454

Video for "PPP/PPP-RTK open formats: Overview, comparison, and proposal for an interoperable message"
By Rui Hirokawa, Ignacio Fernández-Hernández, and Simon Reynolds
(https://www.ion.org/publications/abstract.cfm?articleID=102935)

Abstract: This paper presents and reviews the main existing open specifications for PPP/PPP-RTK services, including satellite navigation providers (QZSS, Galileo, BeiDou, GLONASS) and other industrial or scientific initiatives (RTCM, SAPCORDA, 3GPP, IGS). To structure the comparison, we adapted PPP/PPP-RTK services to the well-known OSI model and defined them according to their properties in the OSI communication layers. We show how the proposed formats relate to the current standards, mainly RTCM SSR and CSSR, and what their differences and similarities are in terms of transmitted corrections and bandwidth. We compare the efficiency of the existing formats in two scenarios: a global PPP scenario with multi-GNSS corrections, and a regional PPP-RTK scenario, also multi-GNSS and including ionospheric corrections. We propose an interoperable format that can be an extension to CSSR and allows efficient transmission of corrections for both global-scale MEO-based PPP as well as nationwide IGSO/GEO-based PPP-RTK.

Article Citation: Hirokawa, R, Fernández-Hernández, I, Reynolds, S. PPP/PPP-RTK open formats: Overview, comparison, and proposal for an interoperable message. *NAVIGATION*. 2021; 68: 759–778. https://doi.org/10.1002/navi.452

Video for "Advanced and versatile signal conditioning for GNSS receivers using the high-rate DFT-based data manipulator (HDDM)"
By Johannes Rossouw van der Merwe, Fabio Garzia, Alexander Rügamer, and Wolfgang Felber
(https://www.ion.org/publications/abstract.cfm?articleID=102929)

Abstract: Proper signal conditioning is crucial for reliable Global Navigation Satellite System (GNSS) navigation. Signal conditioning includes correcting receiver front-end distortions, shaping noise, removing interferences, and altering the received signal. The high-rate DFT-based data manipulator (HDDM) is a versatile signal processing architecture based on the Discrete Fourier Transform (DFT). In this article, the HDDM is theoretically modeled, analyzed, and evaluated. Some applications are presented, including interference mitigation, spectrum reconstruction, overlay signal design, altering signal modulations, and signal equalization. Additionally, the complexity of one concrete hardware implementation is investigated. The HDDM has shown excellent results with interference mitigation, and it can simultaneously achieve other signal conditioning tasks. Processing several tasks with the same nested architecture provides a significant processing benefit compared to discrete processing architectures. It emphasizes the benefits of a single architecture to simultaneously address several signal condition tasks, as opposed to separate structures requiring significantly more processing or poorer synergy.

Article Citation: van der Merwe, JR, Garzia, F, Rügamer, A, Felber, W. Advanced and versatile signal conditioning for GNSS receivers using the high-rate DFT-based data manipulator (HDDM). *NAVIGATION*. 2021; 68: 779–797. https://doi.org/10.1002/navi.441

Video for "Improved high-precision GNSS navigation with a passive hydrogen maser"
By Thomas Krawinkel and Steffen Schön
(https://www.ion.org/publications/abstract.cfm?articleID=102930)

Abstract: Receiver clock modeling (RCM) based on code observations requires a chip-scale atomic clock to improve the PVT solution. When using carrier phase observations, a more stable oscillator like a passive hydrogen maser (PHM) is necessary. We applied a PHM in an automotive experiment of about 80 minutes in an urban environment recording 10-Hz multi-GNSS data. Modeling the clock process noise in a linearized Kalman filter according to the spectral behavior of the PHM (i.e., RCM), improves position and velocity regarding precision and accuracy by 15% and 57%, respectively, as well as reliability by 30%. In situations with sparse, geometrically unfavorable observations, RCM prevents large position drifts. The convergence time of the carrier-phase ambiguities is not affected. Conclusively, precision, accuracy, and reliability in kinematic precise point positioning can be improved by using an oscillator like a PHM. Future advancements in clock technology should make this approach more feasible for ordinary use cases.

Article Citation: Krawinkel, T, Schön, S. Improved high-precision GNSS navigation with a passive hydrogen maser. *NAVIGATION*. 2021; 68: 799–814. https://doi.org/10.1002/navi.444

Video for "Positioning with medium frequency R-Mode"
By Lars Grundhöfer, Filippo Giacomo Rizzi, Stefan Gewies, Michael Hoppe, Jesper Bäckstedt, Marek Dziewicki, and Giovanni Del Galdo
(https://www.ion.org/publications/abstract.cfm?articleID=102933)

Abstract: R-Mode is a terrestrial navigation system under development for the maritime domain that provides backup in case of a GNSS outage. This paper describes the first test results for real-time positioning on board a ship using medium frequency R-Mode signals. The estimation and positioning algorithms used are described in detail and it is shown how they are integrated into the R-Mode receiver developed by the German Aerospace Center. Moreover, during two daytime experiments with lower and higher dynamic movements of a ship in the Baltic Sea, we were able to achieve a 95% horizontal positioning accuracy of better than 12 m in the center of three R-Mode transmitters. This demonstrates the first time that the medium frequency R-Mode has provided positioning at sea.

Article Citation: Grundhöfer, L, Rizzi, FG, Gewies, S, Hoppe, M, Bäckstedt, J, Dziewicki, M, Del Galdo, G. Positioning with medium frequency R-Mode. *NAVIGATION*. 2021; 68: 829–841. https://doi.org/10.1002/navi.450

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 7, 2022 Webinar: First results from three years of GNSS interference monitoring from low Earth orbit
By Dr. Todd E. Humphreys and Dr. Lakshay Narula
(https://www.ion.org/publications/webinar-humphreys.cfm)

Abstract: Observation of terrestrial GNSS interference (jamming and spoofing) from low Earth orbit (LEO) is a uniquely effective technique for characterizing the scope, strength, and structure of interference and for estimating transmitter locations. Such details are useful for situational awareness, interference deterrence, and the development of interference-hardened GNSS receivers. This paper presents the results of a three-year study of global interference, with emphasis on a particularly powerful interference source active in Syria since 2017. It then explores the implications of such interference for GNSS receiver operation and design.

Article Citation: Murrian, MJ, Narula, L, Iannucci, PA, Budzien, S, O'Hanlon, BW, Psiaki, ML, Humphreys, TE. First results from three years of GNSS interference monitoring from low Earth orbit. *NAVIGATION*. 2021; 68: 673–685. https://doi.org/10.1002/navi.449

December 14, 2021 Webinar: Navigation using carrier Doppler shift from a LEO constellation: TRANSIT on steroids
By Mark L. Psiaki
(https://www.ion.org/publications/webinar-psiaki.cfm)

Abstract: A new global navigation concept is studied that relies on carrier Doppler shift measurements from a large LEO constellation. This system could provide an alternative to pseudorange-based GNSS. The concept uses a high-fidelity model of received carrier Doppler shift. This model is used in a point-solution batch filter that simultaneously estimates eight unknowns: three position vector components, the receiver clock offset, three velocity vector components, and the receiver clock offset rate. The filter uses eight or more measured Doppler shifts in its least-squares fit. A generalized geometric dilution of precision (GDOP) analysis indicates that absolute position accuracies on the order of 1–5 meters and absolute velocity accuracies on the order of 0.01 m/sec to 0.05 m/sec may be achievable if the range-rate precision of the Doppler shift measurements is 0.01 m/sec. These accuracies are comparable to current pseudorange-based GNSS. Clock offset accuracy is on the order of 0.0001 to 0.0010 sec 1-sigma.

Article Citation: Psiaki, ML. Navigation using carrier Doppler shift from a LEO constellation: TRANSIT on steroids. *NAVIGATION*. 2021; 68: 621–641. https://doi.org/10.1002/navi.438

November 11, 2021 Webinar: Data-driven protection levels for camera and 3D map-based safe urban localization
By Shubh Gupta
(https://www.ion.org/publications/webinar-gupta.cfm)

Abstract: Reliably assessing the error in an estimated vehicle position is integral for ensuring the vehicle's safety in urban environments. Many existing approaches use GNSS measurements to characterize protection levels (PLs) as probabilistic upper bounds on position error. However, GNSS signals might be reflected or blocked in urban environments, and thus additional sensor modalities need to be considered to determine PLs. In this paper, we propose an approach for computing PLs by matching camera image measurements to a lidar-based 3D map of the environment. We specify a Gaussian mixture model probability distribution of position error using deep neural-network-based data-driven models and statistical outlier weighting techniques. From the probability distribution, we compute PL by evaluating the position error bound using numerical line-search methods. Through experimental validation with real-world data, we demonstrate that the PLs computed from our method are reliable bounds on the position error in urban environments.

Article Citation: Gupta, S, Gao, G. Data-driven protection levels for camera and 3D map-based safe urban localization. *NAVIGATION*. 2021; 68: 643–660. https://doi.org/10.1002/navi.445

October 28, 2021 Webinar: Air data fault detection and isolation for small UAS using integrity monitoring framework
By Kerry Sun
(https://www.ion.org/publications/webinar-sun.cfm)

Abstract: A fault detection and isolation (FDI) algorithm is developed to protect against water-blockage (WB) pitot tube failure in the safety-critical air data system (ADS) used on small unmanned aircraft systems (UAS). The algorithm utilizes two identical synthetic air data systems (SADS) as the basis for state estimation. Each SADS works independently with a pitot tube while sharing an IMU and GNSS receiver. The fault detection is designed using the integrity monitoring framework, and the isolation is obtained via independent fault detection channels. The ADS

requirements are established, and the WB failure mode is analyzed based on real faulty air data. A new residual-based test statistic is introduced, and the link among the test statistic, observability matrix, and minimal detectable error (MDE) are examined. Finally, a flight data set with a known water-blockage fault signature is used to assess the algorithm's performance in terms of the air data protection levels and alert limits.

Article Citation: Sun, K. Gebre-Egziabher, D. Air data fault detection and isolation for small UAS using integrity monitoring framework. *NAVIGATION*. 2021; 68, 577–600. https://doi.org/10.1002/navi.440

October 18, 2021 Webinar: How insect brains perform dead reckoning
By Dr. Barbara Webb
(https://www.ion.org/publications/webinar-webb.cfm)

Background: Insects such as bees and ants are known to use dead reckoning to return in a 'bee-line' to their nest after excursions of more than a kilometer. Recent anatomical and neurophysiological investigations have now established the underlying brain circuits that enable this behavior. These can be shown to carry out the required geometric operations when replicated as detailed computational models and tested on robots.

September 14, 2021 Webinar: Performance assessment of GNSS diffraction models in urban areas
By Guohao Zhang and Dr. Li-Ta Hsu
(https://www.ion.org/publications/webinar-zhang.cfm)

Abstract: The GNSS performance is significantly degraded in urban canyons because of the signal interferences caused by buildings. Besides the multipath and non-line-of-sight (NLOS) receptions, the diffraction effect frequently occurs in urban canyons, which will severely attenuate the signal strength when the satellite line-of-sight (LOS) transmitting path is close to the building edge. It is essential to evaluate the performance of current diffraction models for GNSS before applying mitigation. The detailed steps of applying the knife-edge model and the uniform geometrical theory of diffraction (UTD) model on GNSS are given, including the C/N_0 and pseudorange simulation of the diffracted signal. The performances of both models are assessed using real data from two typical urban scenarios. The result shows the UTD can adequately model the GNSS diffraction effect even in a complicated urban area. Compared with the knife-edge model, the UTD achieves better modeling accuracy, whereas it requires higher computational loads.

Article Citation: Zhang, G, Hsu, L-T. Performance assessment of GNSS diffraction models in urban areas. *NAVIGATION*. 2021; 68(2): 369–389. https://doi.org/10.1002/navi.417

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