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EDITORIAL

# Navigator Notes

## Editorial Highlights from the Editor-in-Chief

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

Welcome to the Spring 2023 issue of *NAVIGATION*. In this issue, we feature articles on positioning and navigation in a wide range of situations and environments from open-pit mines to Earth-orbiting spacecraft.

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 Elisa Gallon, Mathieu Joerger, and Boris Pervan who were selected as the winners of the Institute of Navigation's 2022 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 their paper as one of the most significant published in *NAVIGATION* in 2022 and I extend my personal congratulations to the authors.

Article Citation: Gallon, E., Joerger, M., & Pervan, B. (2022). Robust modeling of GNSS orbit and clock error dynamics. *NAVIGATION, 69*(4). https://doi.org/10.33012/navi.539

### 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** "Robust Modeling of GNSS Orbit and Clock Error Dynamics"
By Elisa Gallon, Mathieu Joerger, and Boris Pervan
(https://navi.ion.org/content/69/4/navi.539/tab-supplemental)

Abstract: In this paper, we develop new stochastic orbit and clock error models for positioning, fault detection, and integrity monitoring over time. GPS and Galileo orbit and clock data are evaluated and ranging errors are analyzed and modeled over time. This work is intended for time-sequential safety-critical navigation systems including global navigation satellite systems (GNSSs) integrated with inertial navigation systems (INSs) and Kalman filter implementations of Advanced Receiver Autonomous Integrity Monitoring (ARAIM).

Article Citation: Gallon, E., Joerger, M., & Pervan, B. (2022). Robust modeling of GNSS orbit and clock error dynamics. *NAVIGATION, 69*(4). https://doi.org/10.33012/navi.539

**Video for** "A Method to Determine Secondary Codes and Carrier Phases of Short Snapshot Signals"
By Xiao Liu, Pau Closas, Adrià Gusi-Amigó, Adria Rovira-Garcia, and Jaume Sanz
(https://navi.ion.org/content/69/4/navi.541/tab-supplemental)

Abstract: Recently, the snapshot real-time kinematic (SRTK) technique was demonstrated, which aims at achieving high accuracy navigation solutions with a very short signal collection. The main challenge in implementing SRTK is the generation of valid carrier-phase measurements, which relies on a data bit ambiguity (DBA) resolution process. For pilot signals, this step is equivalent to the correct selection of secondary code indexes (SCIs) from the ambiguous sets obtained from a multi-hypotheses (MH) acquisition process. Currently, SCI ambiguities are solved independently for each satellite. However, this method is ineffective when the snapshot signal is relatively short. In order to tackle this problem, this article proposes a new method that makes use of assistance data and processes information from all satellites to jointly solve the DBA issue. This new method is shown to be more effective in determining the correct SCI and enabling valid snapshot carrier-phase measurements, largely expanding the scope of high-accuracy snapshot positioning.

Article Citation: Liu, X., Closas, P., Gusi-Amigó, A., Rovira-Garcia, A., & Sanz, J. (2022). A method to determine secondary codes and carrier phases of short snapshot signals. *NAVIGATION, 69*(4). https://doi.org/10.33012/navi.541

**Video for** "High-Precision Positioning Using Plane-Constrained RTK Method in Urban Environments"
By Chen Zhuang, Hongbo Zhao, Yuli He, Shan Hu, Wenquan Feng, and Bing Hou
(https://navi.ion.org/content/69/4/navi.540/tab-supplemental)

Abstract: High-precision positioning methods have drawn great attention in recent years due to the rapid development of smart vehicles as well as automatics driving technology. The real-time kinematic (RTK) technique is a mature tool to achieve centimeter-level positioning accuracy in open-sky areas. However, the users who drive under dense urban conditions are always confronted with harsh global navigation satellite system (GNSS) environments. Skyscrapers and overpasses block the signals and reduce the number of visible satellites, making it difficult to achieve continuous and precise positioning. Considering that the road is relatively smooth in most urban areas, vehicles are expected to travel on the same plane when they are close to each other. The road plane information is a promising candidate to enhance the performance of the RTK method in constrained environments. In this paper, we propose a plane-constrained RTK (PCRTK) method using the positioning information from cooperative vehicles. In a vehicle-to-vehicle (V2V) network, the positions of cooperative vehicles are used to fit a road plane for the target vehicle. The parameters of the plane fitting are treated as new measurements to enhance the performance of the float estimator. The relationship between the plane parameters and the state of the estimator is derived in our study. To validate the performance of the proposed method, several experiments with a four-vehicle fleet were carried out in open-sky areas and dense urban areas in Beijing, China. Simulations and experimental results show that the proposed method can take advantage of the plane constraint and obtain more accurate positioning results compared to the traditional RTK method.

Article Citation: Zhuang, C., Zhao, H., He, Y., Hu, S., Feng, W., & Hou, B. (2022). High-precision positioning using plane-constrained RTK method in urban environments. *NAVIGATION, 69*(4). https://doi.org/10.33012/navi.540

**Video for** "Measurement Error Detection for Stereo Visual Odometry Integrity"
By Yuanwen Fu, Shizhuang Wang, Yawei Zhai, Xingqun Zhan, and Xin Zhang
(https://navi.ion.org/content/69/4/navi.542/tab-supplemental)

Abstract: Integrity, a safety-of-life framework from civil aviation for satellite navigation, is greatly under-explored in visual navigation. A new two-factor approach to rejecting measurement outliers is proposed for navigation integrity in stereo visual odometry (VO). In contrast to other treatments using reprojection error as measurement residuals, our choice of landmark matching error inherently connects navigation solutions and integrity monitoring. We propose two methods to detect large measurement residuals that cannot otherwise be identified by existing outlier rejection methods in state-of-the-art VO pipelines. By rejecting these outliers, measurement residuals can be bounded by the distribution overbounding method that provides fundamental inputs for integrity computations. We evaluate our methods using an open-source data set. Overbounding performance is improved in terms of tightness, computational efficiency, and most important of all, scenario tolerance. This could be a good starting point for developing future integrity monitoring algorithms for visual navigation and in particular, stereo VO.

Article Citation: Fu, Y., Wang, S., Zhai, Y., Zhan, X., & Zhang, X. (2022). Measurement error detection for stereo visual odometry integrity. *NAVIGATION, 69*(4). https://doi.org/10.33012/navi.542

**Video for** "Multi-Frequency Simulation of Ionospheric Scintillation Using a Phase-Screen Model"
By Fernando D. Nunes, Fernando M. G. Sousa, and José M. V. Marçal
(https://navi.ion.org/content/69/4/navi.545/tab-supplemental)

Abstract: A fast Monte-Carlo technique to simulate equatorial ionospheric scintillation on global navigation satellite system signals is proposed. The algorithm uses a single-layer phase-screen model of the ionosphere and the scintillation is expressed as a Huygens-Fresnel integral (HFI). By assuming a specially-tailored random phase screen, the HFI can be expressed in closed form as a combination of Fresnel integrals. We statistically characterize the amplitude and phase computed by the HFI for different values of the scintillation index S4. Results for the L1, L2, and L5 bands were obtained and compared with real data, showing good agreement. Some of the advantages of the proposed technique are: (a) the amplitude and phase of the scintillation process are simultaneously obtained; (b) arbitrarily long ionospheric scintillation time series with pre-defined stationary characteristics are synthesized; and (c) several scintillation time series corresponding to different carrier frequencies are generated using a common phase-screen model.

Article Citation: Nunes, F. D., Sousa, F. M. G., & Marçal, J. M. V. (2022). Multi-frequency simulation of ionospheric scintillation using a phase-screen model. *NAVIGATION, 69*(4). https://doi.org/10.33012/navi.545

**Video for** "Navigation and Ionosphere Characterization Using High-Frequency Signals: A Performance Analysis"
By Yoav Baumgarten, Mark L. Psiaki, and David L. Hysell
(https://navi.ion.org/content/69/4/navi.546/tab-supplemental)

Abstract: The performance of a proposed high-frequency (HF) navigation concept is analyzed using simulated data. The method relies on pseudorange and beat carrier-phase measurements of signals that propagate in the ionosphere along curved trajectories, where signals are refracted back downwards from the ionosphere. It has been demonstrated that the location of a receiver can be determined if several signals, broadcast from beacons at different locations, are received and processed at a user receiver. A challenge of determining exact signal paths is the uncertainty in the ionosphere's electron density distribution. This is addressed by a batch filter that simultaneously estimates the receiver position along with corrections to a parametric model of the ionosphere. A previous paper developed the theory and batch filter for this concept. The present study examines its potential performance. Total horizontal position errors on the order of tens to hundreds of meters are achieved, depending on the case's characteristics.

Article Citation: Baumgarten, Y., Psiaki, M. L., & Hysell, D. L. (2022). Navigation and ionosphere characterization using high-frequency signals: A performance analysis. *NAVIGATION, 69*(4). https://doi.org/10.33012/navi.546

**Video for** "Real-Time Precise GPS Orbit and Clock Estimation With a Quasi-Orbit-Fixed Solar Radiation Pressure Model"
By Peizhao Liu and Junping Chen
(https://navi.ion.org/content/69/4/navi.549/tab-supplemental)

Abstract: Real-time precise global navigation satellite system (GNSS) orbit and clock products play a key role for real-time GNSS-based applications, both in the scientific and industrial communities. Different from the typical two-step procedure to generate orbit and clock solutions separately, we estimate the real-time orbit and clock products simultaneously using a Kalman filter. For this purpose, we developed a GNSS data processing software that can run in pseudo-real-time mode with RINEX files and is ready to run in real-time mode once given the real-time observation stream. Meanwhile, a quasi-orbit-fixed solar radiation pressure (SRP) model is developed. In order to verify the performance of the software and the new SRP model, several experiments with a global network of 60 tracking stations over a time span of three months were conducted to generate real-time Global Positioning System (GPS) orbit and clock products. Then, the results were assessed in terms of accuracy and efficiency, both critical for real-time precise GNSS applications. Compared to the International GNSS Service (IGS) final orbits, the real-time GPS orbit accuracy was 2.82 cm, 5.45 cm, and 5.47 cm in the radial, along-track, and cross-track components, respectively. The precision of the clock product in terms of standard deviation (STD) value was about 0.1 ns. Moreover, the average execution time per epoch was usually less than 1.0 s, which ensures the high efficiency of the processing.

Article Citation: Liu, P., & Chen, J. (2022). Real-time precise GPS orbit and clock estimation with a quasi-orbit-fixed solar radiation pressure model. *NAVIGATION, 69*(4). https://doi.org/10.33012/navi.549

**Video for** "Resilience Monitoring for Multi-Filter All-Source Navigation Framework With Assurance"
By Jonathon S. Gipson and Robert C. Leishman
(https://navi.ion.org/content/69/4/navi.550/tab-supplemental)

Abstract: The Autonomous and Resilient Management of All-source Sensors (ARMAS) framework monitors residual-space test statistics across unique sensor-exclusion banks of filters (known as subfilters) to provide a resilient, fault-resistant all-source navigation architecture with assurance. A critical assumption of this architecture, demonstrated in this paper, is fully overlapping state observability across all subfilters. All-source sensors, particularly those that only provide partial state information (altimeters, TDoA, AOB, etc.), do not intrinsically meet this requirement. This paper presents a novel method to monitor real-time overlapping position state observability and introduces an observability bank within the ARMAS framework, known as stable observability monitoring (SOM). SOM uses a monitoring-epoch stability analysis to provide an intrinsic awareness to ARMAS of the capabilities of the fault detection and exclusion (FDE) functionality. We define the ability to maintain consistent all-source FDE to recover failed sensors as navigation resilience. A resilient FDE capability is one that is aware of when it requires more sensor information to protect the consistency of the FDE and integrity functions from corruption. SOM is the first demonstration of such a system for all-source sensors that the authors are aware of. A multi-agent 3D environment simulating both GNSS and position and velocity alternative navigation sensors was created and individual GNSS pseudorange sensor anomalies are utilized to demonstrate the capabilities of the novel algorithm. This paper demonstrates that SOM seamlessly integrates within the ARMAS framework, provides timely prompts to augment new sensor information from other agents, and indicates when framework stability and preservation of all-source navigation integrity are achieved.

Article Citation: Gipson, J. S., & Leishman, R., C. (2022). Resilience monitoring for multi-filter all-source navigation framework with assurance. *NAVIGATION, 69*(4). https://doi.org/10.33012/navi.550

**Video for** "Commercial GNSS Radio Occultation on Aerial Platforms With Off-The-Shelf Receivers"
By Bryan C. Chan, Ashish Goel, Jonathan Kosh, Tyler G. R. Reid, Corey R. Snyder, Paul M. Tarantino, Saraswati Soedarmadji, Widyadewi Soedarmadji, Kevin Nelson, Feiqin Xie, and Michael Vergalla
(https://navi.ion.org/content/69/4/navi.544/tab-supplemental)

Abstract: In recent decades, GNSS radio occultation (RO) soundings have proven to be an invaluable input to global weather forecasting. The success of government programs such as COSMIC is now complemented by commercial low-cost cubesats. The result is access to more than 10,000 soundings per day. We examine aerial platforms for commercial GNSS-RO, specifically high-altitude balloons and commercial aviation. Meteorological balloons (radiosondes) are deployed daily in over 900 locations globally. Adding GNSS-RO capability to radiosondes would expand capability and enable local area monitoring. Commercial aviation offers scale with more than 100,000 flights daily. A barrier to entry for the inclusion of GNSS-RO sensors is cost and complexity, as GNSS-RO traditionally requires highly specialized equipment. This paper describes a low-cost and scalable approach to aerial GNSS-RO based on commercial-off-the-shelf (COTS) GNSS receivers. We present hardware prototypes and data processing techniques that demonstrate technical feasibility through the results from several flight testing campaigns.

Article Citation: Chan, B. C., Goel, A., Kosh, J., Reid, T. G. R., Snyder, C. R., Tarantino, P. M., Soedarmadji, S., Soedarmadji, W., Nelson, K., Xie, F., & Vergalla, M. (2022). Commercial GNSS radio occultation on aerial platforms with off-the-shelf receivers. *NAVIGATION, 69*(4). https://doi.org/10.33012/navi.544

**Video for** "Set-Valued Shadow Matching Using Zonotopes for 3D-Map-Aided GNSS Localization"
By Sriramya Bhamidipati, Shreyas Kousik, and Grace Gao
(https://navi.ion.org/content/69/4/navi.547/tab-supplemental)

Abstract: Unlike many urban localization methods that return point-valued estimates, a set-valued representation enables robustness by ensuring that a continuum of possible positions obeys safety constraints. One strategy with the potential for set-valued estimation is GNSS-based shadow matching (SM) in which one uses a three-dimensional (3D) map to compute GNSS shadows (where line-of-sight is blocked). However, SM requires a point-valued grid for computational tractability, with accuracy limited by grid resolution. We propose zonotope shadow matching (ZSM) for set-valued 3D-map-aided GNSS localization. ZSM represents buildings and GNSS shadows using constrained zonotopes, a convex polytope representation that enables propagating set-valued estimates using fast vector concatenation operations. Starting from a coarse set-valued position, ZSM refines the estimate depending on the receiver being inside or outside each shadow as judged by received carrier-to-noise density. We demonstrate our algorithm's performance using simulated experiments on a simple 3D example map and on a dense 3D map of San Francisco.

Article Citation: Bhamidipati, S., Kousik, S., & Gao, G. (2022). Set-valued shadow matching using zonotopes for 3D-map-aided GNSS localization. *NAVIGATION, 69*(4). https://doi.org/10.33012/navi.547

**Video for** "Improving GNSS Positioning Using Neural-Network-Based Corrections"
By Ashwin V. Kanhere, Shubh Gupta, Akshay Shetty, and Grace Gao
(https://navi.ion.org/content/69/4/navi.548/tab-supplemental)

Abstract: Deep neural networks (DNNs) are a promising tool for global navigation satellite system (GNSS) positioning in the presence of multipath and non-line-of-sight errors, owing to their ability to model complex errors using data. However, developing a DNN for GNSS positioning presents various challenges, such as (a) poor numerical conditioning caused by large variations in measurements and position values across the globe, (b) varying number and order within the set of measurements due to changing satellite visibility, and (c) overfitting to available data. In this work, we address the aforementioned challenges and propose an approach for GNSS positioning by applying DNN-based corrections to an initial position guess. Our DNN learns to output the position correction using

the set of pseudorange residuals and satellite line-of-sight vectors as inputs. The limited variation in these input and output values improves the numerical conditioning for our DNN. We design our DNN architecture to combine information from the available GNSS measurements, which vary both in number and order, by leveraging recent advancements in set-based deep learning methods. Furthermore, we present a data augmentation strategy to reduce overfitting in the DNN by randomizing the initial position guesses. We, first, perform simulations and show an improvement in the initial positioning error when our DNN-based corrections are applied. After this, we demonstrate that our approach outperforms a weighted least squares (WLS) baseline on real-world data. Our implementation is available at github.com/Stanford-NavLab/deep_gnss.

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

**Video for** "Signal Quality Monitoring Based on Chip Domain Observables: Theory, Design, and Implementation"
By Xiang Wang, Xiaowei Cui, Gang Liu, Kefan Wei, and Mingquan Lu
(https://navi.ion.org/content/69/4/navi.543/tab-supplemental)

Abstract: Signal quality monitoring (SQM) is a technique utilized by satellite- and ground-based augmentation systems (SBAS/GBAS) to detect potential hazardous deformations in signals and better protect integrity for safety-critical users. The next generation of SBASs will incorporate dual-frequency multi-constellation (DFMC) techniques, for which SQM is particularly important since signal deformations might be the largest source of uncertainty in ranging error after first-order ionospheric delays are eliminated. However, the performance bounds of the traditional multi-correlator-based SQM technique face some challenges because of the raised requirement on detection sensitivity by dual-frequency ionosphere-free measurements and multiple modulation modes of civilian signals from multi-constellation techniques. To mitigate the challenges and improve overall performance, SQM based on chip domain observables (CDOs) is emerging, but has not yet been systematically studied. We propose a design methodology for CDO-based SQM, consisting of derivations and corresponding massive simulations. Correctness and effectiveness are assessed to confirm the methodology, and a simplification process by checking the sensitivity of CDOs is demonstrated in terms of implementation.

Article Citation: Wang, X., Cui, X., Liu, G., Wei, K., & Lu, M. (2022). Signal quality monitoring based on chip domain observables: theory, design, and implementation. *NAVIGATION, 69*(4). https://doi.org/10.33012/navi.543

## 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 15, 2023 Webinar**: Resilience Monitoring for Multi-Filter All-Source Navigation Framework With Assurance
By Jonathan S. Gipson
(https://www.ion.org/publications/webinar-gipson.cfm)

Abstract: The Autonomous and Resilient Management of All-source Sensors (ARMAS) framework monitors residual-space test statistics across unique sensor-exclusion banks of filters (known as subfilters) to provide a resilient, fault-resistant all-source navigation architecture with assurance. A critical assumption of this architecture, demonstrated in this paper, is fully overlapping state observability across all subfilters. All-source sensors, particularly those that only provide partial state information (altimeters, TDoA, AOB, etc.), do not intrinsically meet this requirement. This paper presents a novel method to monitor real-time overlapping position state observability and introduces an observability bank within the ARMAS framework, known as stable observability monitoring (SOM). SOM uses a monitoring-epoch stability analysis to provide an intrinsic awareness to ARMAS of the capabilities of the fault detection and exclusion (FDE) functionality. We define the ability to maintain consistent all-source FDE to recover failed sensors as navigation resilience. A resilient FDE capability is one that is aware of when it requires more sensor information to protect the consistency of the FDE and integrity functions from corruption. SOM is the first demonstration of such a system for all-source sensors that the authors are aware of. A multi-agent 3D environment simulating both GNSS and position and velocity alternative navigation sensors was created and individual GNSS pseudorange sensor anomalies are utilized to demonstrate the capabilities of the novel algorithm. This paper demonstrates that SOM seamlessly integrates within the ARMAS framework, provides timely prompts to augment new sensor information from other agents, and indicates when framework stability and preservation of all-source navigation integrity are achieved.

Article Citation: Gipson, J. S., & Leishman, R. C. (2022). Resilience monitoring for multi-filter all-source navigation framework with assurance. NAVIGATION, *69*(4). https://doi.org/10.33012/navi.550

**January 12, 2023 Webinar**: Commercial GNSS Radio Occultation on Aerial Platforms with Off-the-Shelf Receivers
By Bryan Chan
(https://www.ion.org/publications/webinar-chan.cfm)

Abstract: In recent decades, GNSS radio occultation (RO) soundings have proven to be an invaluable input to global weather forecasting. The success of government programs such as COSMIC is now complemented by commercial low-cost cubesats. The result is access to more than 10,000 soundings per day. We examine aerial platforms for commercial GNSS-RO, specifically high-altitude balloons and commercial aviation. Meteorological balloons (radiosondes) are deployed daily in over 900 locations globally. Adding GNSS-RO capability to radiosondes would expand capability and enable local area monitoring. Commercial aviation offers scale with more than 100,000 flights daily. A barrier to entry for the inclusion of GNSS-RO sensors is cost and complexity, as GNSS-RO traditionally requires highly specialized equipment. This paper describes a low-cost and scalable approach to aerial GNSS-RO based on commercial-off-the-shelf (COTS) GNSS receivers. We present hardware prototypes and data processing techniques that demonstrate technical feasibility through the results from several flight-testing campaigns.

Article Citation: Chan, B. C., Goel, A., Kosh, J., Reid, T. G. R., Snyder, C. R., Tarantino, P. M., Soedarmadji, S., Soedarmadji, W., Nelson, K., Xie, F., & Vergallo, M. (2022). Commercial GNSS radio occultation on aerial platforms with off-the-shelf receivers. *NAVIGATION, 69*(4). https://doi.org/10.33012/navi.544

**December 8, 2022 Webinar**: Detecting GNSS Jamming and Spoofing on Android Devices
By Dennis Akos
(https://www.ion.org/publications/webinar-akos.cfm)

Abstract: Global navigation satellite system (GNSS) location engines on Android devices provide location and navigation utility to billions of people worldwide. However, these location engines currently have very limited protection from threats to their position, navigation, and time (PNT) solutions. External sources of radio frequency interference (RFI) can render PNT information unusable. Even worse, false signals or spoofing can provide a false PNT solution to Android devices. To mitigate this, four detection methods were developed and evaluated using native location parameters within Android: Comparing the GNSS and network locations, checking the Android mock location flag, comparing the GNSS and Android system times, and observing the automatic gain control (AGC) and carrier-to-noise density (C/N0) signal metrics. These methods provide a powerful means to significantly increase the robustness of the Android GNSS-based PNT solution and are implemented in the GNSSAlarm Android application to demonstrate real-time jamming and spoofing detection.

Article Citation: Spens, N., Lee, D.-K., Nedelkov, F., & Akos, D. (2022). Detecting GNSS jamming and spoofing on Android devices. *NAVIGATION, 69*(3). https://doi.org/10.33012/navi.537

**November 15, 2022 Webinar:** Characterization and Performance Assessment of BeiDou-2 and BeiDou-3 Satellite Group Delays
By Oliver Montenbruck
(https://www.ion.org/publications/webinar-Montenbruck.cfm)

Abstract: Based on one year of data, a comprehensive assessment of broadcast group delays and differential code biases (DCBs) from network solutions is presented for all open BeiDou signals. Daily DCB estimates exhibit a precision of 0.1 ns, which also places a limit on long-term variations of the satellite group delays. On the other hand, the estimated DCBs show a notable dependence on the employed receivers, which causes inconsistencies at the few-nanosecond level between BeiDou-2 and BeiDou-3 satellites. Systematic satellite-specific offsets can likewise be identified in broadcast group delay values and clock offsets. These constitute the dominant contribution of the signal-in-space range error (SISRE) budget and are a limiting factor for single point positioning and timing. Use of the modernized B1C/B2a signals is therefore recommended instead of B1I/B3I. This offers a SISRE reduction from about 0.6 m to 0.45 m and also improves the consistency of precise clock and bias products derived from heterogeneous receiver networks.

Article Citation: Montenbruck, O., Steigenberger, P., Wang, N., & Hauschild, A. (2022). Characterization and performance assessment of BeiDou-2 and BeiDou-3 satellite group delays. *NAVIGATION, 69*(3). https://doi.org/10.33012/navi.526

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