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EDITORIAL

Navigator Notes

Editorial Highlights from the Editor-in-Chief

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Welcome to the Summer 2023 issue of *NAVIGATION*. In this issue, we feature several articles on GNSS precise point positioning or PPP including its augmentation by additional sensors, articles on optimizing position estimation in environments with significant multipath, on the uncertainties in Coordinated Universal Time, on improving real-time ionospheric delay prediction, and much, much more.

On the journal's website, navi.ion.org, we have listed some recent articles we think might be of particular interest under the "Top Topics" heading. Check them out.

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 "Decentralized Connectivity Maintenance for Multi-Robot Systems Under Motion and Sensing Uncertainties"
By Akshay Shetty, Timmy Hussain, and Grace Gao
(https://navi.ion.org/content/70/1/navi.552/tab-supplemental)

Abstract: Communication connectivity is desirable for the safe and efficient operation of multi-robot systems. While decentralized algorithms for connectivity maintenance have been explored in recent literature, the majority of these works do not account for robot motion and sensing uncertainties. These uncertainties are inherent in practical robots and result in robots deviating from their desired positions which could potentially result in a loss of connectivity. In this paper, we present a decentralized connectivity maintenance algorithm accounting for robot motion and sensing uncertainties (DCMU). We, first, propose a novel weighted graph definition for the multi-robot system that accounts for the aforementioned uncertainties along with realistic connectivity constraints such as line-of-sight connectivity and collision avoidance. We, then, design a decentralized gradient-based controller for connectivity maintenance with which we derive the gradients of the

weighted graph edge weights required for computing the control. Finally, we perform multiple simulations to validate the connectivity maintenance performance of our DCMU algorithm under robot motion and sensing uncertainties, showing an improvement compared to previous work.

Article Citation: Shetty, A., Hussain, T., & Gao, G. (2023). Decentralized connectivity maintenance for multi-robot systems under motion and sensing uncertainties. *NAVIGATION*, *70*(1). https://doi.org/10.33012/navi.552

Video for "Preliminary Analysis of BDS-3 Performance for ARAIM"
By Hengwei Zhang, Yiping Jiang, and Ling Yang
(https://navi.ion.org/content/70/1/navi.553/tab-supplemental)

Abstract: To support the operation of advanced receiver autonomous integrity monitoring (ARAIM), an integrity support message indicating a minimum performance level of satellite constellation is required for aircraft navigation. With BDS-3 providing worldwide service since July 2020, it is desirable to undertake a detailed study on its signal-in-space range error characteristics and prior fault probabilities for ARAIM. The latest accuracy criteria released by the China Satellite Navigation Office in May 2021 is validated by the 27 MEO and IGSO satellites in orbit from July 2020 to June 2021, in which 10 single satellite faults were identified and analyzed in detail with no constellation fault found. Based on this one-year data, the probability of single satellite faults and constellation faults can be initially set as 8×10^{-5} and 1×10^{-3}, respectively, for BDS-3 in ARAIM.

Article Citation: Zhang, H., Jiang, Y., & Yang, L. (2023). Preliminary analysis of BDS-3 performance for ARAIM. *NAVIGATION*, *70*(1). https://doi.org/10.33012/navi.553

Video for "Euclidean Distance Matrix-Based Rapid Fault Detection and Exclusion"
By Derek Knowles and Grace Gao
(https://navi.ion.org/content/70/1/navi.555/tab-supplemental)

Abstract: Faulty signals from global navigation satellite systems (GNSSs) often lead to erroneous position estimates. A variety of fault detection and exclusion (FDE) methods have been proposed in prior research to both detect and exclude faulty measurements. This paper introduces a new technique for the FDE of GNSS measurements using Euclidean distance matrices. After a brief introduction to Euclidean distance matrices, both the detection and exclusion strategy is explained in detail. Euclidean distance matrix-based FDE is verified in two separate real-world data sets and proven to accurately detect and exclude GNSS faults on an average of 1.4-times faster than residual-based FDE and 70-times faster than solution separation FDE.

Article Citation: Knowles, D., & Gao, G. (2023). Euclidean distance matrix-based rapid fault detection and exclusion. *NAVIGATION*, *70*(1). https://doi.org/10.33012/navi.555

Video for "Adaptive Alignment for Low-Cost INS in ECEF Frame Under Large Initial Attitude Errors"
By Kedong Wang, Wei Gao, Xiaohan Xu, and Jinling Wang
(https://navi.ion.org/content/70/1/navi.554/tab-supplemental)

Abstract: A new two-stage alignment on a moving base is proposed for a low-cost inertial navigation system with the aid of a Global Positioning System (GPS) receiver in the Earth-centered, Earth-fixed (ECEF) frame under large initial attitude errors. Both the state and measurement equations are derived using the additive quaternion error model in the ECEF frame for alignment without the need for level adjustment. The nonlinear velocity error equations in both the coarse and the fine stages are linearized further. An improved strong tracking filter is proposed for the coarse stage to converge quickly with large initial attitude errors. After the attitude errors converge to smaller values in the coarse stage, a standard Kalman filter is implemented for the fine stage. Experiments demonstrate that attitude error can converge quickly with the proposed adaptive alignment method.

Article Citation: Wang, K., Gao, W., Xu, X., & Wang, J. (2023). Adaptive alignment for low-cost INS in ECEF frame under large initial attitude errors. *NAVIGATION*, *70*(1). https://doi.org/10.33012/navi.554

Video for "Simultaneous Localization and Calibration (SLAC) Methods for a Train-Mounted Magnetometer"
By Benjamin Siebler, Andreas Lehner, Stephan Sand, and Uwe D. Hanebeck
(https://navi.ion.org/content/70/1/navi.557/tab-supplemental)

Abstract: Magnetic field localization is based on the fact that the Earth's magnetic field is distorted in the vicinity of ferromagnetic objects. When ferromagnetic objects are in fixed positions, the distortions are also fixed and, thus, contain location information. In our prior work, we proposed a simultaneous localization and calibration (SLAC) algorithm based on a Rao-Blackwellized particle filter that enables magnetic train localization using only uncalibrated magnetometer measurements. In this paper, a lower-complexity version of the SLAC algorithm is proposed that only estimates a subset of calibration parameters. An evaluation compares the full and reduced SLAC approach to a particle filter in which the magnetometer is pre-calibrated with a fixed set of parameters. The results show a clear advantage for both SLAC approaches and that the SLAC algorithm with a reduced set of calibration parameters achieves the same performance as the one with a full set of parameters.

Article Citation: Siebler, B., Lehner, A., Sand, S., & Hanebeck, U. D. (2023). Simultaneous localization and calibration (SLAC) methods for a train-mounted magnetometer. *NAVIGATION*, *70*(1). https://doi.org/10.33012/navi.557

Video for "Enabling RTK Positioning Under Jamming: Mitigation of Carrier-Phase Distortions Induced by Blind Spatial Filtering"
By Tobias Bamberg, Andriy Konovaltsev, and Michael Meurer
(https://navi.ion.org/content/70/1/navi.556/tab-supplemental)

Abstract: New GNSS applications demand resilience against radio interference and high position accuracy. Separately, these demands can be fulfilled by multi-antenna systems using spatial filtering and carrier-phase positioning algorithms like real-time kinematic (RTK), respectively. However, combining these approaches encounters a severe issue: The spatial filtering induces a phase offset into the measured carrier phase leading to a loss of position accuracy. This paper presents a new approach to compensate for the phase offset in a blind manner, (i.e., without knowing the antenna array radiation pattern or the direction of arrival of the signals).

The proposed approach is experimentally validated in two jamming scenarios. One includes a jammer with increasing power and the other includes a moving jammer. The results demonstrate that the approach successfully compensates for the phase offset and, hence, allows for the combined use of RTK positioning and spatial filtering even under jamming.

Article Citation: Bamberg, T., Konovaltsev, A., & Meurer, M. (2023). Enabling RTK positioning under jamming: Mitigation of carrier-phase distortions induced by blind spatial filtering. *NAVIGATION*, *70*(1). https://doi.org/10.33012/navi.556

Video for "Reconstructing GNSS Meta-Signal Observations Using Sideband Measurements"
By Daniele Borio and Ciro Gioia
(https://navi.ion.org/content/70/1/navi.558/tab-supplemental)

Abstract: Global navigation satellite systems (GNSSs) provide several signals on different frequencies: Two or more components can be processed jointly as a meta-signal. Despite significant effort devoted to developing effective techniques for meta-signal processing, limited research has been conducted to characterize meta-signal measurements. In this work, the observations obtained by processing a GNSS meta-signal are characterized and fundamental relationships between GNSS meta-signal and dual-frequency measurement combinations are derived.

We show that subcarrier phase observations can be estimated as the wide-lane linear combination of the carrier phases obtained from the two original sideband components. Moreover, meta-signal code measurements can be reconstructed from the pseudoranges and carrier phases of the original components. Thus, meta-signal pseudoranges are mixed code and carrier observations. The experimental results confirm the validity of the theoretical formulas that can be used to reconstruct meta-signal measurements from dual-frequency observations.

Article Citation: Borio, D., & Gioia, C., (2023). Reconstructing GNSS meta-signal observations using sideband measurements. *NAVIGATION*, *70*(1). https://doi.org/10.33012/navi.558

Video for "Low-Cost Inertial Aiding for Deep-Urban Tightly Coupled Multi-Antenna Precise GNSS"
By James E. Yoder and Todd E. Humphreys
(https://navi.ion.org/content/70/1/navi.561/tab-supplemental)

Abstract: A vehicular pose estimation technique is presented that tightly couples multi-antenna carrier-phase differential GNSS (CDGNSS) with a low-cost MEMS inertial sensor and vehicle dynamic constraints. This work is the first to explore the use of consumer-grade inertial sensors for tightly coupled urban CDGNSS, and first to explore the tightly coupled combination of multi-antenna CDGNSS and inertial sensing (of any quality) for urban navigation. An unscented linearization permits ambiguity resolution using traditional integer least-squares while both implicitly enforcing known-baseline-length constraints and exploiting the multi-baseline problem's inter-baseline correlations. A novel false fix detection and recovery technique is developed to mitigate the effect of conditioning the filter state on incorrect integers. When evaluated on the publicly available TEX-CUP

urban positioning data set, the proposed technique achieves, with consumer- and industrial-grade inertial sensors, respectively, a 96.6% and 97.5% integer fix availability, and a 12.0-cm and 10.1-cm overall (fix and float) 95th percentile horizontal positioning error.

Article Citation: Yoder, J. E., & Humphreys, T. E. (2023). Low-cost inertial aiding for deep-urban tightly coupled multi-antenna precise GNSS. *NAVIGATION*, *70*(1). https://doi.org/10.33012/navi.561

Video for "Speed Sensor-Aided Navigation Filter for Robust Localization in GNSS-Denied Mining Environments"
By David Benz, Jan-Jöran Gehrt, René Zweigel, and Dirk Abel
(https://navi.ion.org/content/70/1/navi.566/tab-supplemental)

Abstract: The automation of mining haulage vehicles has great potential in terms of safety and economy. The performance of autonomous vehicles depends largely on highly accurate vehicle state information. Deep mines are especially challenging, as satellite-based localization methods are reaching their limits. Therefore, we introduce a new navigation filter concept for the precise and robust localization of the haulage fleet that can handle temporary GNSS interruptions in deep open-pit mines. The multi-sensor navigation filter utilizes an inertial measurement unit and is aided by GNSS. We introduce a new optical speed sensor update within the tightly coupled unscented Kalman filter. The speed sensor measures the slip-free two-dimensional speed above ground. The filter was validated with an articulated dumper in a gravel pit. The new filter achieved a mean position error of 0.24 m during a test drive of 190 s with a simulated GNSS outage of 90 s.

Article Citation: Benz, D., Gehrt, J.-J., Zweigel, R., & Abel, D. (2023). Speed sensor-aided navigation filter for robust localization in GNSS-denied mining environments. *NAVIGATION*, *70*(1). https://doi.org/10.33012/navi.566

Video for "Improved GPS-Based Single-Frequency Orbit Determination for the CYGNSS Spacecraft Using GipsyX"
By Alex V. Conrad, Penina Axelrad, Bruce Haines, Cinzia Zuffada, and Andrew O'Brien
(https://navi.ion.org/content/70/1/navi.565/tab-supplemental)

Abstract: This paper presents methods for the precise orbit determination (POD) of a satellite in the CYGNSS constellation based on available single-frequency GPS code and carrier measurements. The contributions include the development and evaluation of procedures for single-frequency POD with GipsyX, improvement of CYGNSS orbit knowledge, and an assessment of its final accuracy. Ionospheric effects are mitigated using the GRAPHIC processing method, and spacecraft multipath effects are calibrated with an azimuth/elevation-dependent antenna calibration map. The method is demonstrated using comparable data from the GRACE mission, from which we infer the expected accuracy of the CYGNSS results. Processing more than 170 days of data from each mission, a 1σ CYGNSS orbit accuracy of 2.8 cm radial, 2.4 cm cross-track, and 6 cm in-track is demonstrated. We expect that achieving this level of performance will expand the set of future scientific investigations that can be undertaken using satellites equipped with single-frequency GNSS.

Article Citation: Conrad, A. V., Axelrad, P., Haines, B., Zuffada, C., & O'Brien, A. (2023). Improved GPS-based single-frequency orbit determination for the CYGNSS spacecraft using GipsyX. *NAVIGATION*, *70*(1). https://doi.org/10.33012/navi.565

Video for "Detection of GPS C/A Code Self-Interference: Monitor Overview and Applicability"
By Jessica Belzer and Frank van Graas
(https://navi.ion.org/content/70/1/navi.559/tab-supplemental)

Abstract: Self-interference can cause large errors of up to tens of meters on the GPS C/A code pseudorange measurement. Although the probability of an occurrence of large self-interference errors is small, to enable the use of C/A code phase measurements in high accuracy or safety-of-life applications, a detection or mitigation method is needed. A stressful case of self-interference is modeled on a GPS hardware simulator to investigate monitor performance using real signal results. A summary of contributions in this paper follows. Self-interference pseudorange error characteristics within and mitigation requirements for the Ground Based Augmentation System (GBAS) Approach Service Type D (GAST-D) environment are identified. Existing monitors are evaluated for their response to self-interference and their ability to detect the error based on the GAST-D environment. This includes the potential for misidentification of the error. A novel Frequency Domain Cross-Correlation (FDCC) detector is proposed that can uniquely identify self-interference error with no siting constraints.

Article Citation: Belzer, J., & van Graas, F. (2023). Detection of GPS C/A code self-interference: Monitor overview and applicability. *NAVIGATION*, *70*(1). https://doi.org/10.33012/navi.559

Video for "Radio-Frequency Interference Considerations for Utility of the Galileo E6 Signal Based on Long-Term Monitoring by ARFIDAAS"
By Aiden Morrison, Nadezda Sokolova, Nicolai Gerrard, Anders Rødningsby, Christian Rost, and Laura Ruotsalainen
(https://navi.ion.org/content/70/1/navi.560/tab-supplemental)

Abstract: The extent to which navigation signals in the E6 band may be impacted by shared spectrum allocations might be underappreciated. This paper presents top-level observations from a multi-year international radio frequency interference (RFI) monitoring project covering all L-band global navigation satellite system (GNSS) signals with specific focus on the challenges facing the E6 band. The context of this paper is the assumption that most users will be non-authorized and have access to only the open data-bearing signal component and not the encrypted pilot of the E6 Galileo signal. In virtually all locations where the Advanced RFI Detection, Analysis, and Alerting System (ARFIDAAS) monitoring stations were deployed, frequent disruption of the E6 band from systems such as radar installations or other authorized users of the spectrum was observed. In the presented paper, an effort is made to put the observations in the context of the expected use cases of the E6 signal.

Article Citation: Morrison, A., Sokolova, N., Gerrard, N., Rødningsby, A., Rost, C., & Ruotsalainen, L. (2023). Radio-frequency interference considerations for utility of the Galileo E6 signal based on long-term monitoring by ARFIDAAS. *NAVIGATION*, *70*(1). https://doi.org/10.33012/navi.560

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.

March 9, 2023 Webinar: Signal Quality Monitoring Based on Chip Domain Observables: Theory, Design, and Implementation
By Xiaowei Cui and Mingquan Lu
(https://www.ion.org/publications/webinar-lu.cfm)

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://navi.ion.org/content/69/4/navi.543

February 27, 2023 Webinar: Navigating the Suez Canal
By Morgan McManus
(https://www.ion.org/publications/webinar-suez.cfm)

Abstract: The Suez Canal that links the Mediterranean Sea and the Red Sea allows shipping crews to shave days off their shipping time. Without access to the Suez Canal, ships would need to navigate 3,000 additional nautical miles around the dangerous Cape of Good Hope at the southern tip of Africa and enter the Mediterranean Sea through the Strait of Gibraltar, adding 10 - 15 days to the voyage.

More than 22,000 ships passed through the Suez Canal in 2022 alone, making it the second busiest maritime choke point next to the Strait of Hormuz. But navigating a ship through the canal is fraught with high risks and unique challenges.

Navigating the canal became a source of attention after a giant container ship recently got stuck while navigating through the canal and blocking traffic for six days, preventing an estimated $9.6 billion of goods to pass and causing a significant disruption to the global supply chain.

So, what are the challenges pilots face with traversing the narrow canal with giant container ships? High winds, sandstorms, loss of visibility, tides, geo-political issues, and high-pressure commercial demands to name a few. What instruments are used to mitigate the risks? What navigation technologies are used to ensure success?

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