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EDITORIAL

Navigator Notes

Editorial Highlights from the Editor-in-Chief

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Journal of the Institute of Navigation
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Welcome to the Winter 2023 issue of *NAVIGATION*. It's a jam-packed issue, with 28 articles reporting on significant advances in PNT research. The recent increase in the number of articles per issue is due, in large part, to our attempts to speed up the review process of submitted articles; and for accepted articles to be quickly formatted and distributed on the *NAVIGATION* website (https://navi.ion.org/) as soon as possible for online viewing. We continue to maintain high standards for publication in the journal.

This issue's articles cover some of the most exciting and relevant PNT research being carried out in academia, government research institutes, and industry covering topics such as improved smartphone positioning, lunar navigation, quantum inertial navigation, alternative PNT sources, ionospheric effects, and improved GNSS positioning in degraded signal environments. But all of the articles reflect novelty in their respective topic — a hallmark of the journal.

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 "A Consistent Regional Vertical Ionospheric Model and Application in PPP-RTK Under Sparse Networks"
By Sijie Lyu, Yan Xiang, Tiantian Tang, Ling Pei, Wenxian Yu, and Trieu-Kien Truong (https://navi.ion.org/content/70/3/navi.568/tab-supplemental)

Abstract: Ionospheric augmentation is one of the most important dependences of PPP-RTK. Because of the dispersive features of the ionosphere, the ionospheric information is usually coupled with satellite- and receiver-related biases. This will pose a hidden trouble of inconsistent ionospheric corrections if different numbers of reference stations are involved in calculation. In this paper, we aimed at introducing a consistent regional vertical ionospheric model (RVIM) by estimating receiver

biases. We first presented the inconsistent ionospheric corrections under sparse networks. Then the RVIM is compared with the International GNSS Service final global ionospheric map (GIM) product, and the average of differences between them is 1.13 TECU. Furthermore, the slant ionospheric corrections were employed as a reference to evaluate both RVIM and GIM. The mean RMS values are 1.48 and 2.23 TECU for the RVIM and GIM, respectively. Finally, we applied the RVIM into PPP-RTK. Results indicate that the PPP-RTK with RVIM constraints achieves improvements in horizontal errors, vertical errors, and convergence time by 43.45, 29.3, and 22.6% under the 68% confidence level, compared with the conventional PPP-AR.

Article Citation: Lyu, S., Xiang, Y., Tang, T., Pei, L., Yu, W., & Truong, T. -K. (2023). A consistent regional vertical ionospheric model and application in PPP-RTK under sparse networks. *NAVIGATION, 70*(3). https://doi.org/10.33012/navi.568

Video for "GPS Spoofing Mitigation and Timing Risk Analysis in Networked Phasor Measurement Units via Stochastic Reachability"
By Sriramya Bhamidipati and Grace Gao (https://navi.ion.org/content/70/3/navi.574/tab-supplemental)

Abstract: To address phasor measurement unit (PMU) vulnerability to spoofing, we propose the use of a set-valued state estimation technique known as stochastic reachability (SR)-based distributed Kalman filter (DKF) that computes secure Global Positioning System (GPS) timing across a network of receivers. Utilizing SR, we estimate not only GPS time but also its stochastic reachable set, which is parameterized by probabilistic zonotope (p-zonotope). While requiring known measurement error bounds in only non-spoofed conditions, we designed a two-tiered approach. We first performed measurement-level spoofing mitigation via deviation of a measurement innovation from its expected p-Zonotope. We then performed state-level timing risk analysis via a determination of the intersection probability of the estimated p-Zonotope with an unsafe set that violates IEEE C37.118.1a-2014 standards. Finally, we validated our SR-DKF algorithm by subjecting it to a simulated receiver network to coordinate signal-level spoofing. We demonstrate improved timing accuracy and successful spoofing mitigation via the use of our SR-DKF algorithm. We also validated the robustness of the estimated timing risk as the number of receivers were varied.

Article Citation: Bhamidipati, S., & Gao, G. (2023). GPS spoofing mitigation and timing risk analysis in networked phasor measurement units via stochastic reachability. *NAVIGATION, 70*(3). https://doi.org/10.33012/navi.574

Video for "RTK-Quality Positioning with Global Precise Point Positioning Corrections"
By Nacer Naciri and Sunil Bisnath (https://navi.ion.org/content/70/3/navi.575/tab-supplemental)

Abstract: Global navigation satellite system (GNSS) precise point positioning (PPP) has potential as an alternative or replacement for real-time kinematic (RTK) processing. In this work, we reached for RTK levels of performance without the need for local information through PPP (i.e., centimeter-level positioning that was reached near-instantaneously). This work makes use of information currently available from processing signals from Global Positioning System (GPS), Galileo, BeiDou-2/3, and

GLONASS by fixing ambiguities for the first three constellations on all available frequencies. This processing was done using a four-frequency, four-constellation uncombined decoupled clock model (DCM) that has been expanded as part of this work. The results were tested on 1448 global datasets and showed that instantaneous convergence on average to 2.5 cm error can be achieved for 81% of the stations. These findings were reinforced by the results of epoch-by-epoch processing, as an average of 80% of all single epochs converged below 2.5 cm error at 1σ, as opposed to less than the 0.5% typically observed for classic PPP.

Article Citation: Naciri, N., & Bisnath, S. (2023). RTK-quality positioning with global precise point positioning corrections. *NAVIGATION, 70*(3). https://doi.org/10.33012/navi.575

Video for "Galileo Open Service Navigation Message Authentication: Preparation Phase and Drivers for Future Service Provision"
By Martin Götzelmann, Evelyn Köller, Ignacio Viciano-Semper, Dirk Oskam, Elias Gkougkas, and Javier Simon (https://navi.ion.org/content/70/3/navi.572/tab-supplemental)

Abstract: While Galileo approaches Full Operational Capability and is close to completion of the deployed satellite constellation, a portfolio of new Galileo service features is under development and validation. The Galileo Open Service (OS) is planned to be enhanced with the provision of Navigation Message Authentication (NMA). In November 2020, the Galileo satellites started broadcasting OSNMA test data for an internal preparation phase of seven months duration. The objective of this test period was to determine and select the OSNMA test signal configuration for a subsequent 'public observation phase.'

The paper presents the main outcomes of the preparation phase for a set of defined OSNMA performance parameters. Airbus is supporting the Galileo service provider, the European Union Agency for the Space Programme (EUSPA), both in Galileo service definition and in planning and execution of OSNMA test activities, which have been performed during this preparation phase.

Article Citation: Götzelmann, M., Köller, E., Viciano-Semper, I., Oskam, D., Gkougkas, E., & Simon, J. (2023). Galileo Open Service navigation message authentication: Preparation phase and drivers for future service provision. *NAVIGATION, 70*(3). https://doi.org/10.33012/navi.572

Video for "Conservative Estimation of Inertial Sensor Errors Using Allan Variance Data"
By Kyle A. Lethander and Clark N. Taylor (https://navi.ion.org/content/70/3/navi.563/tab-supplemental)

Abstract: To understand the error sources present in inertial sensors, both the white (time-invariant) and correlated noise sources must be properly characterized. To understand both sources, the standard approach (IEEE standards 647-2006, 952-2020) is to compute the Allan variance of the noise and then use human-based interpretation of linear trends to estimate the separate noise sources present in a sensor. Recent work has sought to overcome the graphical nature and visual-inspection basis of this approach leading to more accurate noise estimates. However, when using noise characterization in a filter, it is important that the

noise estimates be not only accurate but also conservative, i.e., that the estimated noise parameters overbound truth. In this paper, we propose a novel method for automatically estimating conservative noise parameters using the Allan variance. Results of using this method to characterize a low-cost MEMS IMU (Analog Devices ADIS16470) are presented, demonstrating the efficacy of the proposed approach.

Article Citation: Lethander, K. A., & Taylor, C. N. (2023). Conservative estimation of inertial sensor error using Allan variance data. *NAVIGATION, 70*(3). https://doi.org/10.33012/navi.563

Video for "Regional Ionosphere Delay Models Based on CORS Data and Machine Learning"
By Randa Natras, Andreas Goss, Dzana Halilovic, Nina Magnet, Medzida Mulic, Michael Schmidt, and Robert Weber (https://navi.ion.org/content/70/3/navi.577/tab-supplemental)

Abstract: The ionospheric refraction of GNSS signals can have an impact on positioning accuracy, especially in cases of single-frequency observations. Ionosphere models that are broadcasted by the satellite systems (e.g., Klobuchar, NeQuick-G) do not include enough details to permit them to correct single-frequency observations with sufficient accuracy. To address this issue, regional ionosphere models (RIMs) have been developed in several countries in the western Balkans based on dense continuous operating reference stations (CORS) observations. Subsequently, a RIM for the western Balkans was built using an artificial neural network that combined regional ionosphere parameters estimated from the CORS data with spatiotemporal (latitude, longitude, hour of day), solar (F10.7) and geomagnetic (Kp, Dst) parameters. The RIMs were tested at the solar maximum (March 2014), a geomagnetic storm (March 2015), and the solar minimum (March 2018). The new RIMs mimic the integrated electron density much more effectively than the Klobuchar model. Furthermore, RIMs significantly reduce the ionospheric effects on single-frequency positioning, indicating their necessity for use in positioning applications.

Article Citation: Natras, R., Goss, A., Halilovic, D., Magnet, N., Mulic, M., Schmidt, M., & Weber, R. (2023). Regional ionosphere delay models based on CORS data and machine learning. *NAVIGATION, 70*(3). https://doi.org/10.33012/navi.577

Video for "Autonomous Lunar L1 Halo Orbit Navigation Using Optical Measurements to a Lunar Landmark"
By Mark B. Hinga and Dale A. Williams (https://navi.ion.org/content/70/3/navi.586/tab-supplemental)

Abstract: Autonomous cislunar spacecraft navigation is critical to mission success as communication to ground stations and access to Global Positioning System (GPS) signals could be lost. However, if the satellite has a camera of sufficient quality, geometric line-of-sight (unit vector) measurements can be made to known lunar landmarks (e.g., Tycho Crater) to provide observations that enable autonomous estimation of the position and velocity of the spacecraft. In this study, an improved batch Gaussian initial orbit determination (IOD) differential corrector (DC) algorithm, based on the approximated values of the two-body f and g series, is applied to initialize a (non-conic based) circular restricted three body problem (CR3BP) extended Kalman filter (EKF) navigator. This navigator collects geometric

line-of-sight unit vector (angle only) measurements to a known location on the Moon to sequentially estimate the position and velocity of an observer spacecraft flying on an approximate southern L1 Halo orbit.

In this study, it was found that the best approach is to initialize the CR3BP EKF (navigator) using the solution from the batch DC filter with at least 10 measurements taken against the perceived centroid of Tycho Crater. Thereafter, it is best to continue the navigator with subsequent measurements taken against the same center coordinates of the Tycho Crater, where these coordinates are now expressed in the CR3BP rotating frame. For successful conic-based batch filter initialization and long-term CR3BP EKF convergence, it was found that the cadence for all optical measurements should be taken at 10 minutes for a simulated measurement noise of 0.1° one sigma uncertainty about the line-of-sight measurement unit vector.

Article Citation: Hinga, M B., & Williams, D A. (2023). Autonomous lunar L1 halo orbit navigation using optical measurements to a lunar landmark. *NAVIGATION, 70*(3). https://doi.org/10.33012/navi.586

Video for "3D Vision Aided GNSS Real-Time Kinematic Positioning for Autonomous Systems in Urban Canyons"
By Weisong Wen, Xiwei Bai, and Li-Ta Hsu (https://navi.ion.org/content/70/3/navi.590/tab-supplemental)

Abstract: In this paper, a three-dimensional vision-aided method is proposed to improve global navigation satellite system (GNSS) real-time kinematic (RTK) positioning. To mitigate the impact of reflected non-line-of-sight (NLOS) reception, a sky-pointing camera with a deep neural network was employed to exclude these measurements. However, NLOS exclusion results in distorted satellite geometry. To fill this gap, complementarity between the low-lying visual landmarks and the healthy but high-elevation satellite measurements was explored to improve the geometric constraints. Specifically, inertial measurement units, visual landmarks captured by a forward-looking camera, and healthy GNSS measurements were tightly integrated via sliding window optimization to estimate the GNSS-RTK float solution. The integer ambiguities and the fixed GNSS-RTK solution were then resolved. The effectiveness of the proposed method was verified using several challenging data sets collected in urban canyons in Hong Kong.

Article Citation: Wen, W., Bai, X., & Hsu, L. (2023). 3D Vision aided GNSS real-time kinematic positioning for autonomous systems in urban canyons. *NAVIGATION, 70*(3). https://doi.org/10.33012/navi.590

Video for "A Baseband MLE for Snapshot GNSS Receiver Using Super-Long-Coherent Correlation in a Fractional Fourier Domain"
By Yiran Luo, Li-Ta Hsu, and Naser El-Sheimy (https://navi.ion.org/content/70/3/navi.588/tab-supplemental)

Abstract: Low-cost global navigation satellite system and Global Positioning System (GPS) receivers require reliable baseband processing to guarantee accurate positioning. However, classic baseband performance is limited in challenging cases due to the characteristics of traditional loop filters. Accordingly, a snapshot baseband maximum likelihood estimator (MLE) using super-long coherent integration (S-LCI) in a fractional Fourier domain (FrFD) is proposed to upgrade the

traditional frequency/phase/delay lock loop tracking algorithms. First, applying the S-LCI correlation in an FrFD increases the accuracy of a weak and dynamic signal estimation. Tolerance of the initial guess error in the snapshot baseband processing is then relaxed by the MLE. Finally, a gradient descent algorithm accelerates the convergence of signal estimation. Moreover, we derive the Cramer-Rao lower bound for the proposed MLE. Both numerical simulations and real-world experiments based on this GPS receiver prototype verify the effectiveness of its high-accuracy estimations of weak signals, strong tolerance for large initial guess errors, and prompt responses to converging.

Article Citation: Luo, Y., Hsu, L., & El-Sheimy, N. (2023). A baseband MLE for snapshot GNSS receiver using super-long-coherent correlation in a fractional Fourier domain. *NAVIGATION, 70*(3). https://doi.org/10.33012/navi.588

Video for "Decimeter Positioning in an Urban Environment Through a Scalable Optical-Wireless Network"
By Christian Tiberius, Gerard Janssen, Jeroen Koelemeij, Erik Dierikx, Cherif Diouf, and Han Dun (https://navi.ion.org/content/70/3/navi.589/tab-supplemental)

Abstract: This paper presents a terrestrial networked positioning system that obtains a reliable time reference from a national time scale realization and distributes it in a prototype to six roadside base stations through a fiber-optic Gigabit Ethernet network. Wireless wideband signals are transmitted by the base stations, thereby enabling positioning by a mobile receiver with an accuracy of one decimeter in a multipath urban environment. The scalability and compatibility of this system with existing telecommunication-network technologies paves the way for wide-area global navigation satellite system-independent back-up systems for timing and positioning with improved coverage and performance. The results presented in this paper are based on research carried out within the scope of a project funded by the Dutch Research Council (NWO, project 13970).

Article Citation: Tiberius, C., Janssen, G., Koelemeij, J., Dierikx, E., Diouf, C., & Dun, H. (2023). Decimeter positioning in an urban environment through a scalable optical-wireless network. *NAVIGATION, 70*(3). https://doi.org/10.33012/navi.589

Video for "Space-Time Adaptive Processing as a Solution for Mitigating Interference Using Spatially-Distributed Antenna Arrays"
By Marius Brachvogel, Michael Niestroj, Michael Meurer, Syed N. Hasnain, Ralf Stephan, and Matthias A. Hein (https://navi.ion.org/content/70/3/navi.592/tab-supplemental)

Abstract: Antenna arrays and spatial processing techniques are among the most effective countermeasures against interference. Here, we demonstrate a new array concept consisting of spatially-distributed subarrays that are small enough to fit inside the non-metallic parts of an automobile. This will facilitate concealed installation of these devices in bumpers or side mirrors, which is a strict requirement of the industry and preferred by the customers. Using beamforming algorithms, this array was proven to be robust against jammers in the L1 band. The large distances between the individual antenna elements resulted in a non-negligible baseband delay that violated the narrowband assumption and increased with bandwidth. Hence, this paper demonstrates the influence of a jammer in the L5 band. Space-time adaptive processing that allows for compensation of the delays

was introduced and analyzed. Improvements in interference mitigation capabilities were assessed and compared to those of pure spatial state-of-the-art implementation. Real-life measurement data was used to ensure realistic results.

Article Citation: Brachvogel, M., Niestroj, M., Meurer, M., Hasnain, S., Stephan, R., & Hein, M. (2023). Space-time adaptive processing as a solution for mitigating interference using spatially-distributed antenna arrays. *NAVIGATION, 70*(3). https://doi.org/10.33012/navi.592

Video for "Mitigation of Global Navigation Satellite System Cycle Slips Due to Scintillation Using Radio Backpropagation"
By Brian Breitsch and Jade Morton (https://navi.ion.org/content/70/3/navi.593/tab-supplemental)

Abstract: Measurements of signals from satellites from global navigation satellite systems are an important tool not only for precision navigation and timing applications, but also for various scientific and remote-sensing applications such as ionosphere monitoring and atmosphere probing using radio occultation. When traveling through turbulent patches of the Earth's ionosphere, these signals can experience scintillation, which is characterized by rapid fluctuations in the amplitude and phase of the received signal. In addition to these fluctuations, the signal can undergo phase transitions that induce cycle slips in the resulting phase measurement. When left uncorrected, cycle slips can lead to large errors in positioning and remote-sensing applications. In this work, we determine how backpropagation based on a single-phase screen model of the ionosphere can help to limit the occurrence of these cycle slips. This approach is applicable for batch post-processing of measurements. Furthermore, our results when applying the method to both simulations and real-life data suggest that backpropagation can correct many of the cycle slips that are generated during severe scintillation.

Article Citation: Breitsch, B. & Morton, J. (2023). Mitigation of GNSS cycle slips due to scintillation using radio backpropagation. *NAVIGATION, 70*(3). https://doi.org/10.33012/navi.593

Video for "Global Navigation Satellite System Channel Coding Structures for Fast Acquisition Signals in Harsh Environment Conditions"
By Lorenzo Ortega and Charly Poulliat (https://navi.ion.org/content/70/3/navi.585/tab-supplemental)

Abstract: In this article, we present the design of a new navigation message system that includes an error-correcting scheme. This design exploits the "carousel" nature of the broadcast navigation message and facilitates (i) a reduction in the time to first fix (TTFF) and (ii) enhanced error-correcting performance under both favorable and challenging channel conditions. We show here that this combination design requires error-correcting schemes characterized by maximum distance separable (MDS) and full diversity properties. Error-correcting Root low density parity check (Root-LDPC) codes operate efficiently to block various channels and thus can permit efficient and rapid recovery of information over potentially non-ergodic channels. Finally, to ensure appropriate data demodulation in harsh environmental conditions, we propose the use of root-LDPC codes endowed with a nested property which will permit them to adjust the channel coding rate depending on the number of information blocks received. The proposed error-correcting

combination design was then simulated and compared with the well-known GPS L1C subframe 2 using several different transmission scenarios. The results of these simulations revealed some enhancement of the error-correcting performance and reductions in TTFF in several specific situations.

Article Citation: Ortega, L., & Poulliat, C. (2023). Global navigation satellite system channel coding structures for rapid signal acquisition in harsh environmental conditions. *NAVIGATION, 70*(3). https://doi.org/10.33012/navi.585

Video for "SBAS Protection Levels with Gauss-Markov K-Factors for Any Integrity Target"
By Julie Antic, Odile Maliet, and Sébastian Trilles (https://navi.ion.org/content/70/3/navi.594/tab-supplemental)

Abstract: According to aviation minimum operational performance standards (MOPS), protection levels for satellite-based augmentation systems (SBASs) are to be computed as the product of the estimated standard deviation of errors and a scaling, or K-factor. MOPS recognized that K-factors were originally chosen to be consistent with certain assumptions that may not hold under all conditions. Considering the limited applicability of aviation-based K-factors, it will be important to identify a more rigorous method for deriving new SBAS applications for road, rail, or maritime use. Here we describe an innovative method applicable to any integrity risk (e.g., at 10^{-7} for aviation or 10^{-5} for maritime applications) and time interval T (e.g., 150 seconds to 1 hour for aviation or 3 hours for maritime use). This new method relies on rigorous probability justification. No restrictive assumptions are needed for the time correlation pattern of the errors. The method is easy-to-implement and applicable to any type of integrity risk or time interval T.

Article Citation: Antic, J., Maliet, O., Trilles, S. (2023). SBAS protection levels with Gauss-Markov k-factors for any integrity target. *NAVIGATION, 70*(3). https://doi.org/10.33012/navi.594

Video for "Authentication of Satellite-Based Augmentation Systems with Over-the-Air Rekeying Schemes"
By Jason Anderson, Sherman Lo, Andrew Neish, and Todd Walter (https://navi.ion.org/content/70/3/navi.595/tab-supplemental)

Abstract: Here we delineate a complete satellite-based augmentation system (SBAS) authentication scheme, including over-the-air rekeying (OTAR), that uses the elliptic curve digital signature algorithm (ECDSA) and timed efficient stream loss-tolerant authentication (TESLA) without the quadrature (Q) channel. This scheme appends two new message types to the SBAS scheduler without overburdening the message schedule. We have taken special care to ensure that our scheme (1) meets the appropriate security requirements needed to prevent and deter spoofing; (2) is compatible with existing cryptographic standards; (3) is flexible, expandable, and future-proof to different cryptographic and implementation schemes; and (4) is backward compatible with legacy receivers. The scheme accommodates a diverse set of features, including authenticating core-constellation ephemerides. We discuss the SBAS provider and receiver machine state and its startup, including its use by aircraft that traverse differing SBAS coverage areas. We tested our scheme with existing SBAS simulation and analysis tools and found that it had negligible effects on current SBAS availability and continuity requirements.

Article Citation: Anderson, J., Lo, S., Neish, A., & Walter, T. (2023). Authentication of satellite-based augmentation systems with over-the-air rekeying schemes. *NAVIGATION, 70*(3). https://doi.org/10.33012/navi.595

Video for "Extending the Real-Time Kinematics Survey Method to Global Navigation Satellite System-Denied Areas Using a Low-Cost Inertial-Aided Positioning Pole"
By Changxin Lai, Ruonan Guo, Qijin Chen, and Xiaoji Niu (https://navi.ion.org/content/70/3/navi.584/tab-supplemental)

Abstract: The global navigation satellite system (GNSS) real-time kinematics (RTK) survey method cannot be used in GNSS-denied areas largely due to signal blockage. In this work, we aim to extend high-precision RTK positioning capability to GNSS-denied areas via post-processing using an inertial-aided positioning pole that contains an inexpensive inertial measurement unit (IMU) chip and an RTK receiver. The positioning accuracy can be maintained at an acceptable level by using the pole as a walking stick with the pole periodically landing on the ground. Because the pole tip velocity is zero when it maintains contact with solid ground, lever-arm compensated zero-velocity updates (LA-ZUPTs) can be used to suppress errors in the inertial navigation system (INS) in GNSS-denied areas. Experimental results reveal that this method can be used to bridge up to a 60-meter GNSS gap to maintain sub-decimeter-level survey accuracy.

Article Citation: Lai, C., Guo, R., Chen, Q., & Niu, X. (2023). Extending the real-time kinematics survey method to global navigation satellite system-denied areas using a low-cost inertial-aided positioning pole. NAVIGATION, 70(3). https://doi.org/10.33012/navi.584

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.

November 1, 2023 Webinar: Decimeter Positioning in an Urban Environment Through a Scalable Optical-Wireless Network (https://www.ion.org/publications/webinar-tiberius.cfm)
By: Christian Tiberius

Abstract: This paper presents a terrestrial networked positioning system that obtains a reliable time reference from a national time scale realization and distributes it in a prototype to six roadside base stations through a fiber-optic Gigabit Ethernet network. Wireless wideband signals are transmitted by the base stations, thereby enabling positioning by a mobile receiver with an accuracy of one decimeter in a multipath urban environment. The scalability and compatibility of this system with existing telecommunication-network technologies paves the way for wide-area global navigation satellite system-independent back-up systems for timing and positioning with improved coverage and performance. The results presented in this paper are based on research carried out within the scope of a project funded by the Dutch Research Council (NWO, project 13970).

Article Citation: Tiberius, C., Janssen, G., Koelemeij, J., Dierikx, E., Diouf, C., & Dun, H. (2023). Decimeter positioning in an urban environment through a scalable optical-wireless network. *NAVIGATION, 70*(3). https://doi.org/10.33012/navi.589

September 27, 2023 Webinar: Autonomous Lunar L1 Halo Orbit Navigation Using Optical Measurements to a Lunar Landmark (https://www.ion.org/publications/webinar-hinga.cfm)
By: Mark B. Hinga

Abstract: Autonomous cislunar spacecraft navigation is critical to mission success as communication to ground stations and access to Global Positioning System (GPS) signals could be lost. However, if the satellite has a camera of sufficient quality, geometric line-of-sight (unit vector) measurements can be made to known lunar landmarks (e.g., Tycho Crater) to provide observations that enable autonomous estimation of the position and velocity of the spacecraft. In this study, an improved batch gaussian initial orbit determination (IOD) differential corrector (DC) algorithm, based on the approximated values of the two-body f and g series, is applied to initialize a (non-conic based) circular restricted three body problem (CR3BP) extended Kalman filter (EKF) navigator. This navigator collects geometric line-of-sight unit vector (angle only) measurements to a known location on the Moon to sequentially estimate the position and velocity of an observer spacecraft flying on an approximate southern L1 Halo orbit. In this study, it was found that the best approach is to initialize the CR3BP EKF (navigator) using the solution from the batch DC filter with at least 10 measurements taken against the perceived centroid of Tycho Crater. Thereafter, it is best to continue the navigator with subsequent measurements taken against the same center coordinates of the Tycho Crater, where these coordinates are now expressed in the CR3BP rotating frame. For successful conic-based batch filter initialization and long-term CR3BP EKF convergence, it was found that the cadence for all optical measurements should be taken at 10 minutes for a simulated measurement noise of 0.1° one sigma uncertainty about the line-of-sight measurement unit vector.

Article Citation: Hinga, M B., & Williams, D A. (2023). Autonomous lunar L1 halo orbit navigation using optical measurements to a lunar landmark. *NAVIGATION, 70*(3). https://doi.org/10.33012/navi.586

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