ION
INSTITUTE OF NAVIGATION

Quarterly Newsletter

MEETING IN THE "MILE-HIGH" CITY

ION GNSS+ 2022 Gathers for its 35th International Meeting

ION is expecting to welcome many of its international attendees to Denver, Colorado, this September for its ION GNSS+ international technical meeting taking place September 20–23 at the Hyatt Regency Denver, located adjacent to the Colorado Convention Center.

The Final Frontier, Under the Sea or Mars?

The plenary session will feature two speakers who will each explore navigational extremes – under the Earth's seas and on the surface of the planet Mars.

Josh Broussard, Ocean Infinity's Chief Technology Officer, will share with the group how this marine robotics company deploys their autonomous robots (typically in fleet formation operating down
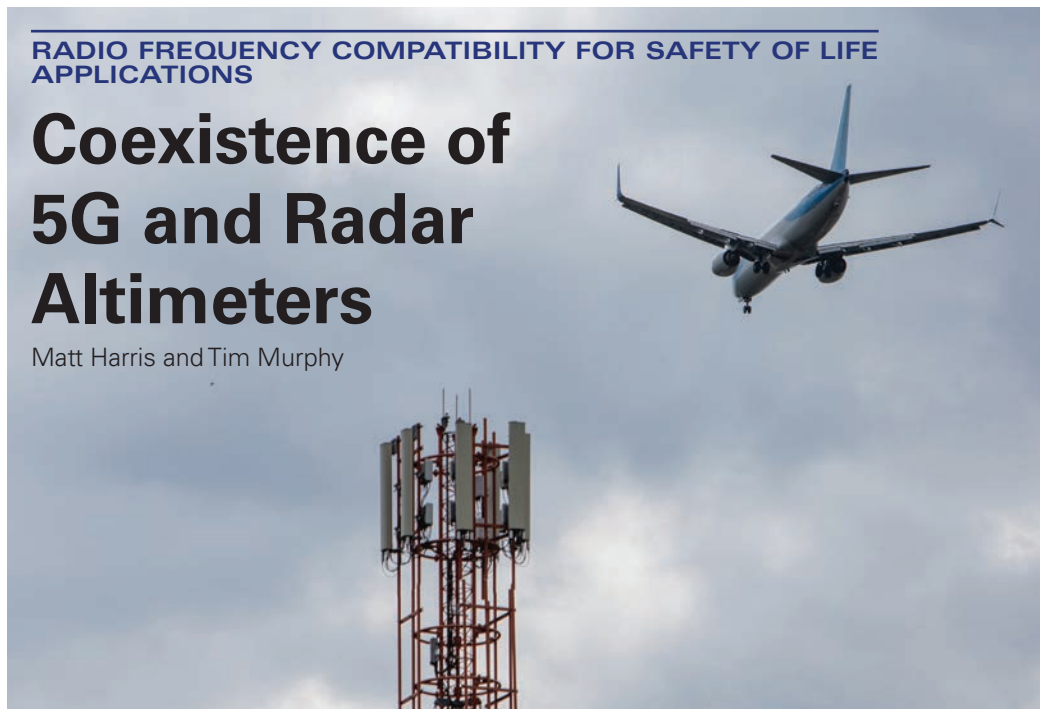

RADIO FREQUENCY COMPATIBILITY FOR SAFETY OF LIFE APPLICATIONS

Coexistence of 5G and Radar Altimeters

Matt Harris and Tim Murphy

Fifth-generation (5G) cellular technologies are being deployed in multiple frequency bands in order to deliver greatly enhanced data services. The prospects to leverage these 5G technologies for positioning, navigation, and timing (PNT) are great including use as a datalink channel for differential GNSS systems, through use of Assisted GPS for indoor positioning and finally for the potential to track new 5G signals as signals of opportunity that can be used in determining a user's position. However, there is a potential problem with one specific aspect of 5G deployment that has been getting a lot of press coverage: the potential for 5G in the mid-band (i.e., 3 to 4 GHz) to interfere with radio altimeters used by airplanes.

This is yet another instance of what is now becoming a familiar story: some bandwidth that was previously used for satellite communications gets repurposed and very high-power transmitters are deployed at frequencies near where a sensitive navigation system is operating. The legacy navigation receivers were not designed for the new RF environment and the accuracy, integrity, and continuity of those systems may be degraded. Due to multiple failures in multiple branches of the government, this problem was allowed to fester until it came to a head toward the end of 2021. To preserve safety, the FAA was prepared to enact severe restrictions on operations that could have had crippling economic impacts on the aviation industry. The 11th hour negotiations led by the White House resulted in the cellular companies agreeing to defer some aspects of

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The Institute of Navigation
8551 Rixlew Lane, Suite 360
Manassas, Virginia 20109

NASA's GPS Advisory Board

I recently attended the bi-annual meeting of the NASA-sponsored GPS advisory board.

Background

The "National Space-Based PNT Advisory Board" (PNTAB) advises the US government on GPS. The board comprises GPS experts from outside the US government, chaired by Admiral Thad Allen (USCG, ret.). See www.gps.gov/governance/advisory/. Six subcommittees focus on various aspects of GPS, including strategy, education, and international engagement.

Current Issues

A major strategy has been "PTA": Protect, Toughen, and Augment GPS– especially with regards to protecting the spectrum and promoting the use of directional antennas to prevent jamming and spoofing. Steered beam antennas are a common technology worldwide; they can virtually eliminate GPS jamming and spoofing threats. Unfortunately, there are outdated, but still active, ITAR (International in Arms Regulation) rules which practically prevent the manufacture and use of steerable antennas in the USA. The PNTAB vice-chair, Brad Parkinson, along with the subcommittee on PTA, chaired by John Betz, lead the advocacy for updating these counter-productive ITAR rules.

Previous ION President, Jade Morton, chairs the subcommittee on Education and Science Innovation (ESI). Several ION community leaders are members of the ESI subcommittee, including Penina Axelrad, Dorota Grejner-Brzezinska, and Terry Moore. The subcommittee is focused on US STEM and future PNT workforce education and training, and bringing awareness of PNT/GNSS scientific applications to the general public. A recent open letter authored by a group of academics and former US government employees highlighted the crisis in the field of geodesy where the number of US geodesists is decreasing at an alarming rate. The ESI subcommittee's goal is to understand different needs, levels of gaps, and size of workforce in PNT-related industry, government, and academia and advocate for the need to invest in the future of US PNT education and training.

> A major strategy has been "PTA": Protect, Toughen, and Augment GPS. Especially with regards to protecting the spectrum, and promoting the use of directional antennas to prevent jamming and spoofing.

Emerging Capabilities of GPS

I chair a subcommittee focused on the emerging capabilities of GPS. Our current work is on creating a GPS service, such as the Galileo High Accuracy Service (HAS) and similar services of QZSS and BeiDou. The Galileo HAS provides corrections to the satellite orbit and clock errors, and corrections for ionospheric delays delivered via the internet. The proposed GPS service would provide similar corrections as part of the GPS system. The service would also provide the nav data bits (ephemeris, etc.), delivered via encrypted data over the internet. This will increase the accuracy of GPS, and also the resilience: allowing coherent integration across data bits for increased receiver sensitivity, as well as providing an encrypted means of delivering ephemeris.

> Our current work is on creating a GPS service, such as the Galileo High Accuracy Service (HAS) and similar services of QZSS and BeiDou.

The work and meetings of the PNT Advisory Board is public. You can attend the meetings in person or live via YouTube. You can also see a recording of the most recent meeting, and PDFs of presentations, at https://www.gps.gov/governance/advisory/meetings/2022-05/

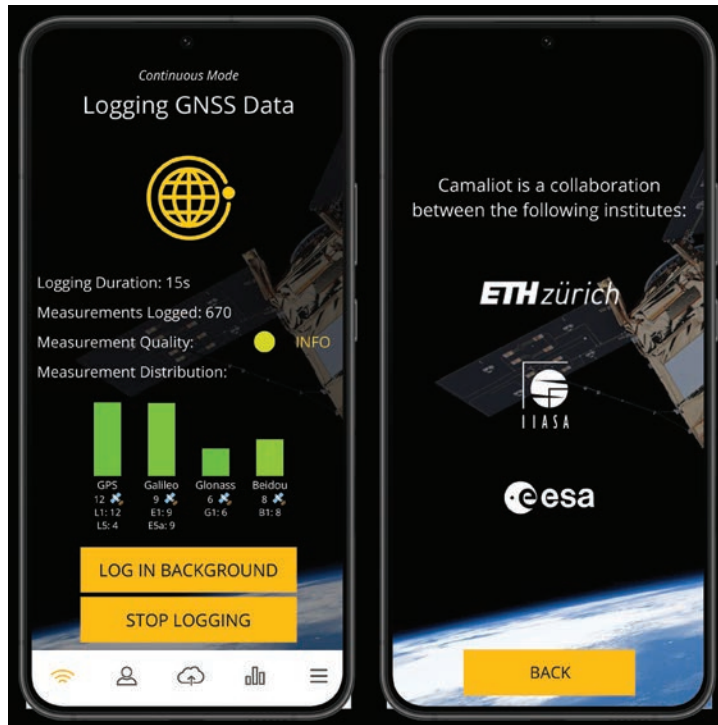*Follow us on Facebook and Twitter @ionavigation.*

Billions of GNSS Measurements Collected through Crowdsourcing with the CAMALIOT App

The CAMALIOT mobile app records raw GNSS data from smartphones, which are contributed by volunteers around the world in the collective development of a crowdsourced GNSS Big Data repository. Such a data resource offers a unique opportunity to apply innovative machine-learning techniques to characterize multiple error sources and serve as input to scientific applications that can benefit society such as weather forecasting. This is the aim of the EL1-038 CAMALIOT project, developed through ESA's Navigation Innovation and Support Program (NAVISP), with the support of the Agency's Navigation Science Office through its GNSS Science Support Centre, and led by the Space

Geodesy group at ETH Zurich.

Since the crowdsourcing campaign was launched on 17 March 2022, more

than 11,500 participants have contributed around 80 billion measurements. The crowdsourcing campaign runs until 31 July 2022, so there is still time to take part. Download the CAMALIOT mobile app from the Google Play Store today, contribute raw GNSS data from your phone, and become eligible to win prizes. Researchers interested in using the raw GNSS data collected with their phone can download the data in RINEX3 format. The crowdsourced GNSS Big Data repository will be available in the future from the GSSC portal. The project is also offering access to the GSSC Now Preview Program for the first 50 applicants who apply.

For more information, see https://www.camaliot.org. ✸

Dr. Sherman Lo, program chair, moderates Pacific PNT virtually with virtual background of Waikiki Beach, Honolulu, Hawaii.

Dr. Sherman Lo, General Chair

Pacific PNT was back with the biennial 2022 conference held online April 12-14, 2022. It was wonderful to see old friends and to remind ourselves of the importance and vitality of the PNT work being done in the Pacific Rim region. Due to travel restrictions, we hosted the conference with invited speakers, focusing on specific topics, over three days.

BeiDou

The conference kicked off with a session on BeiDou, organized by Prof. Ruizhi Chen (Wuhan University), Prof. Mingquan Lu (Tsinghua University), and Prof. Xingqun Zhan (Shanghai Jiao Tong University). It started with an excellent series of presentations on developments in precise point positioning (PPP) using BeiDou and addressing key performance areas such as fast ambiguity resolution (AR). Prof. Qile Zhao (Wuhan University) examined the question of whether we can have PPP-IAR (instant ambiguity resolution) without needing a dense local network used in PPP-real time kinematic (PPP-RTK). Prof. Jianghui Geng (Wuhan University) presented on PPP-AR using any combination of signal frequencies by untying phase bias products from their proscribed frequency set – so called observable-specific signal biases (OSBs). Dr. Xin Li conducted experiments of PPP-RTK with INS for vehicle navigation demonstrating continuous rapid centimeter-level positioning even in urban canyons. Prof. Yuanxin Wu addressed the question: "With better inertial sensors, what algorithmic improvements are needed to get the best accuracy?" Specifically, he examined handling higher order terms in the INS position solution. These terms were not significant given the errors in less accurate sensors. Zhenyu Tian examined how to make the most of BeiDou, and other binary offset signals using dual tracking. He wanted to do this with reduced computational complexity, particularly lower correlator requirements. Wang Zhongxiao discussed direct finding from Doppler measurements using a maximum likelihood estimate (MLE) technique to determine spoofing.

QZSS

Our next day covered QZSS, with the session organized by Prof Nobuaki Kubo (National Institute of Maritime, Port and Aviation Technology) and Prof. Takeyasu Saki (Tokyo University of Marine Science and Technology). PPP was again in the forefront. QZSS provides several precise positioning services such as centimeter- and submeter-level accuracy services (CLAS, SLAS, respectively) as well as MADOCA PPP. These services were overviewed by Satoshi Kogure (JAXA). Dr. Rui Hirokawa detailed the performance of the QZSS CLAS service, which is guaranteed to be in place until 2032, and tested two commercial receivers (ublox and Septentrio) that support CLAS. It was fantastic to see manufacturers selling receivers that support the service. Prof. Kubo presented field results of CLAS & SLAS performance. Finally, Dr. Izumi Mikami discussed this hardware and the many other applications being developed using QZSS services.

COSMIC/FORMOSAT

The third day had a nicely built set of talks on COSMIC/FORMOSAT organized by Prof. Loren Chang (National Central University) and Dr. Jude Salinas (National Central University). The first two talks presented work in the U.S. and Taiwan validating FORMOSAT-7/COSMIC-2 (F7/C2) results. They showed that it performs as well or better than existing satellites used for radio occultation (RO). The next talks addressed the natural follow-up question: "Given the performance of these RO measurements, what benefits can be conferred to various applications?" These talks looked at their utility for better modeling of the weather, atmospheric/ionospheric science, and monitoring natural events. For example, Guo-Yuan Lien's talk showed the benefits of F7/C2 RO data improved prediction of typhoon behavior – particularly their tracks and rain coverage. Bill Randel discussed all the different equatorial waves (e.g., Kelvin, Rossby) and tides that can be observed in the high quality F7/C2 data set; and made new observations of underlying convection with F7/C2 RO. Yi Duann presented on using F7/C2 RO to study correlation between key metrics such as S4 and maximum height of the F2 layer (hmF2). I listened to the final talk by Charles Lin with awe and amazement. He gave his talk on how RO measurements were used to observe the Hunga-Tonga tsunami from a railway station (due to being in the middle of his commute)!

I encourage ION members and non-members to view these virtual sessions and their engaging talks. Bill Randel expressed this best when he stated he was "learning a lot from every talk."

Looking Forward to 2024

Pacific PNT 2024 is scheduled to be held April 15-18, 2024 at the Hilton Waikiki Beach, in Honolulu, Hawaii where we hope to see everyone in person! ✳

> **Viewing Pacific PNT 2022: FREE FOR ION MEMBERS**
>
> For those of you who may have missed viewing it in real-time, it is hosted on the ION website and can be viewed free for ION members at www.ion.org/pnt.

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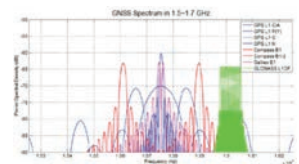
M-code
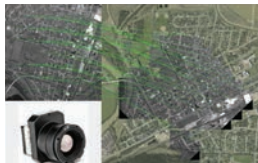*TRL 9, combat proven GPS solution*

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ION JNC 2022 Smashes Attendance Records

By all measures, ION's Joint Navigation Conference (JNC) 2022 is one for the record books. Hosted by the Military Division of the Institute of Navigation, JNC 2022 was held June 6-9 at the Town & Country Hotel in San Diego, California, and attracted more than 1,000 attendees representing a 30% increase in one year and a 29% increase in exhibitor participation. This translates to 54% participation by industry/DOD contractors; 23% attendance from the military; 20% participation of the government/civil servants/federally funded research and development centers (FFRDCs); and the final 3% originated from academia directly supporting DOD contracts. Another new record set this year was a 3% increase in female partici-

pation over the prior year.

What is driving the success of JNC? An unparalleled technical program that focuses on the strategic importance of PNT to the DOD's critical infrastructure and addresses the real-time needs of the warfighter; current innovation in the marketplace; and the desire to reconvene.

The conference attracted more than 230 technical presentations on advancements for the DOD and the warfighter. Technical presentations were complemented by relevant and timely panel discussions, keynote presentations, and the popular Warfighter Panel.

ION Military Division Chair Dr. Thomas Powell opened the conference on Tuesday and welcomed the record-breaking crowd. JNC '22 Program Chair John Del Colliano introduced the first keynote address given by CAPT Brian Emme, Di-

JNC is organized by a group of dedicated volunteers that represent the six branches of the armed services as well as representatives supporting FFRDCs.
Back Row: John Del Colliano, Dr. J.P. Laine, Dr. Keith McDonald, David Wolfe, Brian Louie, Chad Pinkelman, and Dr. Steven Lewis. Front Row: Paul Olson, Dr. Jacob Campbell, Dr. Greg Reynolds, Jan Anszperger, Dr. Madeleine Naudeau, Rodney Earwood, Joe Schnecker, John Langer, and Dr. Thomas Powell. Not Pictured: Elliott Kaplan and Christine Morlock.

Barbara Baker, John Del Colliano, and CAPT Brian Emme

ADM Thad W. Allen and Gen David D. Thompson

JNC 2022 Warfighter Panel and Moderators: Kevin Coggins (co-chair); MAJ Dallas Austin, ETVCM Jonathan Marfield, MSgt Ben Johnis, QMCM Aurora Robles, SSgt Alex Gifford, CTR1 Brian O'Connor, MSgt Dave Nisbeth, and CAPT (RET) Sean Memmen (co-chair)

rector of Air Exercises, USN Third Fleet, followed by Ms. Barbara Baker, Deputy Program Executive Officer (DPEO) for Military Communications (MilComm) & Positioning, Navigation, and Timing (PNT), Space Systems Command, U.S. Air Force.

Wednesday's keynote addresses featured Gen David D. Thompson, Vice Chief of Space Operations, U.S. Space Force, and ADM Thad W. Allen (USCG, Retired), Chair, National Space-Based Positioning, Navigation, and Timing Advisory Board, NASA and James Tyler Chair, Loy Institute for Leadership, U.S. Coast Guard Academy.

Thursday's keynote addresses were presented by Mr. Nicholas W. Freije III, Assistant Chief Engineer for Mission Architecture at the Naval Information Warfare Systems Command (NAVWAR) and Mr. Christopher Solee, Deputy Director of the Capability and Resource Integration Directorate(J8), Space Command (Peterson AFB, CO) followed by the much-anticipated Warfighter Panel—an interactive gathering of uniformed service members with recent operational experiences to discuss how to better formulate military PNT systems. ✴

Leadership Recognized

During JNC 2022, John Langer was recognized for his three-year term of leadership and vision while serving as the ION's Military Division Chair, during which he led the ION's Military Division, including guiding the work and organization of the JNC conference, with his focus on the impact of PNT and its resilience for the warfighter and security of the homeland.


Dr. Thomas Powell, Military Division Chair, presents John Langer, Immediate Past Military Division Chair, with plaque of appreciation.

THANK YOU TO EXHIBITORS AND SPONSORS

The JNC 2022 exhibit hall spread across the sprawling Golden State Ballroom on the Town and Country campus and was packed with more than 50 companies showcasing the latest technological products that support the DOD's PNT critical infrastructure needs.

JNC organizers are already hard at work for the 2023 event to be held on June 12–15 at the same location. ION anticipates a new record to be set again in 2023! ✳
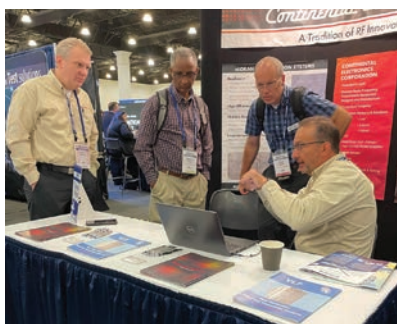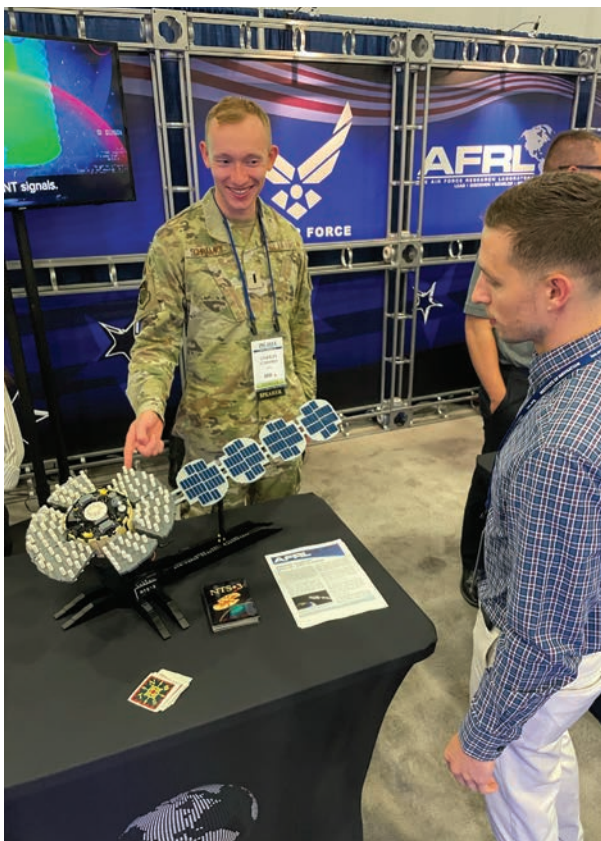
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AEROSPACE & DEFENCE REVIEW

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JOINT NAVIGATION CONFERENCE
June 12-15, 2023
San Diego, California

SAVE THE DATE

Top Downloaded Articles from 2021

*N**AVIGATION:* Journal of the Institute of Navigation is proud to recognize the following as the top ten downloaded articles from 2021:

Montenbruck O, Steigenberger P, Aicher M. A long-term broadcast ephemeris model for extended operation of GNSS satellites. *NAVIGATION*. 2021;68:199–215. https://doi.org/10.1002/navi.404

Borio D, Gioia C. GNSS interference mitigation: A measurement and position domain assessment. *NAVIGATION*. 2021;68:93–114. https://doi.org/10.1002/navi.391

Hauschild A, Montenbruck O. Precise real-time navigation of LEO satellites using GNSS broadcast ephemerides. *NAVIGATION*. 2021;68(2):419–432. https://doi.org/10.1002/navi.416

Gunawardena S, Pany T, Curran J. ION GNSS software-defined radio Metadata Standard. *NAVIGATION*.2021;68:11–20. https://doi.org/10.1002/navi.407

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

Rothmaier F, Chen Y-H, Lo S, Walter T. GNSS spoofing detection through spatial processing. *NAVIGATION*. 2021;68(2):243–258. https://doi.org/10.1002/navi.420

Wang P, Morton YJ. Performance comparison of time-of-arrival estimation techniques for LTE signals in realistic multipath propagation channels. *NAVIGATION*. 2020;67:691–712. https://doi.org/10.1002/navi.395

Caamano M, Juan JM, Felux M, Gerbeth D, González-Casado G, Sanz J. Network-based ionospheric gradient monitoring to support GBAS. *NAVIGATION*. 2021;68:135–156. https://doi.org/10.1002/navi.411

Wen W, Pfeifer T, Bai X, Hsu L-T. Factor graph optimization for GNSS/INS integration: A comparison with the extended Kalman filter. *NAVIGATION*, 2021;68(2):315–331. https://doi.org/10.1002/navi.421

Zhou N, Lau L, Bai R, Moore T. Novel prior position determination approaches in particle filter for ultra wideband (UWB)-based indoor positioning. *NAVIGATION*. 2021; 68(2):277–292. https://doi.org/10.1002/navi.415

New Associate Editors Join

This past spring the following ION members accepted appointments as *Navigation* associate editors:

Dr. Y. Jade Morton is a Helen and Hubert Croft Professor of Engineering, Director for Colorado Center for Astrodynamics Research (CCAR), and the head of the Satellite Navigation and Sensing (SeNSe) Laboratory at the University of Colorado (CU), Boulder. Dr. Morton received her PhD in Electrical Engineering from Penn State. Her research interests lie at the intersection of satellite navigation technologies and remote sensing of the Earth's space environment, atmosphere, and surface. She was a president of the ION and a recipient of the ION Burka, Thurlow, and Kepler awards, and the IEEE PLANS Richard Kershner award. Dr. Morton is a Fellow of IEEE, ION, and the Royal Institute of Navigation (RIN).

Dr. Zhe "Jenny" Yang is currently working as an assistant professor at Tongji University in China. She obtained her PhD from The Hong Kong Polytechnic University in 2018. Her research interests are in ionospheric remote sensing using GNSS signals.

Review Papers WANTED!

NAVIGATION has a new review paper published in the Summer 2022 issue that reviews the current status, particular challenges, and development trends in visual positioning integrity monitoring. Additionally, this review paper proposes a preliminary framework for future developments in visual navigation integrity.

Zhu, C., Meurer, M., & Günther, C. (2022) Integrity of visual navigation—Developments, challenges, and prospects. *NAVIGATION*, 69(2). https://doi.org/10.33012/navi.518

Dr. Morton will be focusing on soliciting additional review papers. Please feel free to reach out if you are willing, and able, to provide review papers on current topical areas where this is needed, jade.morton@colorado.edu. Review papers are both highly cited and desirable. ✷

Multi-Objective Design of a Lunar GNSS

Filipe Pereira

High-performance computing (HPC) and the state-of-the-art Multi-Objective Evolutionary Algorithm (MOEA), guided by high-fidelity orbital models, are a unique approach to the design of a lunar GNSS. The intuition was developed over decades of satellite constellation design. The strong effects of third-body perturbations (Earth and Sun) on the nominal lunar orbits are crucial to the long-term stability of the orbits, both in terms of GDOP evolution and station-keeping ΔV. Thus, each candidate satellite constellation is simulated over a one-year period. Over this period, even the so-called lunar frozen orbits—derived analytically by including several simplifications—appear much less frozen than you would think. The approach revealed new insights into this problem, including major design trade-offs and common features of Pareto-front approximate solutions in a high-dimensional objective space consisting of performance, cost, and robustness metrics.
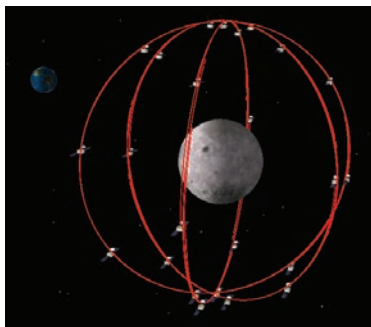
Constellations of Satellites in Near-Circular Polar Orbit Candidates for a Lunar GNSS

In total, the MOEA orchestrated a total of 250,000 experiments; each experiment resulted in the high-fidelity simulation of a different lunar GNSS constellation for one year. Using the data from this simulation, each constellation was evaluated across five conflicting objectives: GDOP, GDOP availability, station-keeping ΔV, space segment cost, and impact of satellite failure (on GDOP).

The objective functions used result from high-fidelity orbit propagation using NASA's GMAT software. The Lunar LP-165-P gravity field model was used, with spherical harmonics up to degree and order 10. Crucially, the strong third-body perturbations of the Earth and the Sun, as well as solar radiation pressure, were modeled.

The results revealed some unexpected findings. For example, constellations consisting of satellites in near-circular polar orbits at an altitude of ~2 lunar radii are shown to be great candidates for a lunar GNSS. Such constellations can deliver excellent GDOP performance over many years with moderate station-keeping ΔV needs.

Economic Justification for a Lunar GNSS

The deployment of a lunar GNSS constellation could effectively extend the GNSS space service volume to cislunar space and benefit future lunar missions. An economic justification for a lunar GNSS constellation can be made if DSN-tracking costs and savings related to a reduced user NAV payload mass are accounted for, especially in a scenario of sustained PNT service demand as the current number of planned lunar missions suggests.
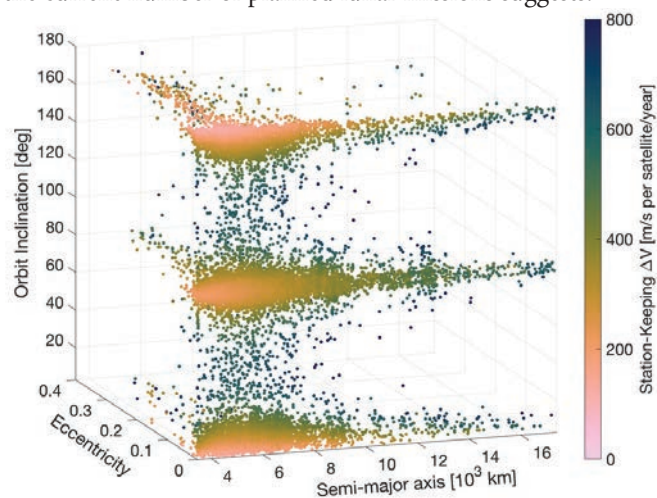
For the full article, and accompanying data and figures, please see:

Pereira, F., Reed, P. M., & Selva, D. (2022) Multi-objective design of a lunar GNSS. NAVIGATION, 69(1). https://doi.org/10.33012/navi.504

A follow-up paper on this research was also presented at ITM 2022, see:

Pereira, F., & Selva, D. (2022) Analysis of navigation performance with lunar GNSS evolution. *Proc. of the 2022 International Technical Meeting of the Institute of Navigation,* Long Beach, CA, 514–529. https://doi.org/10.33012/2022.18210

A Flexible GNSS Spoofer Localization System: Spoofing Discrimination and Localization Method

Hong Li

In previous research, to locate a spoofer, time-difference-of-arrival (TDOA) technology was often used, which uses multiple sensors to measure the time differences of spoofing signals arriving at the sensors and then to compute the location of the spoofer through the time differences. However, for TDOA, the synchronization of the sensors is a prerequisite. The required cables and optical fibers are expensive and need to be installed in advance, which significantly limit its application.
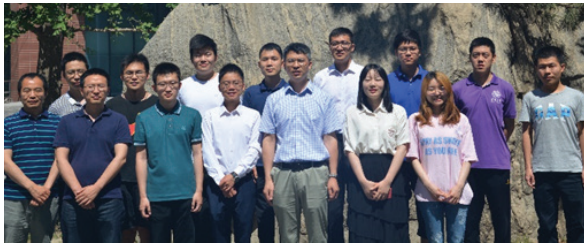
The GNSS Security group of Position, Navigation, and Timing (PNT) center; Department of Electronic Engineering, Tsinghua University

The spoofing signal itself is a signal, transferring incorrect information to mislead users, and processed by conventional GNSS signal processing techniques. This characteristic is quite different from jamming. Hence, it inspired us to think about the following questions: Is it possible to use this characteristic to complete the synchronization of sensors and consequently locate a spoofer? If so, a spoofer localization system would be free of cables and optical fibers, which makes it quite attractive. How to construct such a system?

A New Spoofing Discrimination and Localization Method Proposed

The proposed spoofing discrimination and localization method employs multiple independent GNSS receivers as sensors that do not require long cables or optical fibers to synchronize. Indeed, spoofing signals are developed to assist the synchronization of the sensors since spoofing signals would be processed and they transfer time information, which is a reasonable utilization of spoofing signals. Hence, compared with previous spoofer localization methods, the proposed method is much easier to be implemented and lower cost.

Testing the Method

As shown in the above figures, we placed four independent GNSS receivers which could process GPS L1 C/A code signals on a sport field. A spoofer was also placed on the ground and transmitted GPS signals to the receivers. The aim was to locate the spoofer using merely the raw measurements of the four receivers, without cables or optical fibers to synchronize the receivers in advance. The raw measurements included pseudorange, pseudorandom noise (PRN), number of signals, etc., which were quite common and could be easily acquired from GNSS receivers. As a result, spoofing signals could be discriminated successfully with merely asynchronous measurements of the receivers. In this case, the spoofer was located with an accuracy of several meters. If more receivers were used, the localization accuracy would be much higher.

Technology Headed to Market

In March 2022, patents associated with the spoofer location system were formally awarded to Navisech Corporation (in Chinese 纳微星科) to develop spoofer localization products for the market to promote the security of GNSS applications. In the future, developers would like to get the method implemented and widely used in the market to protect GNSS users.

For the full article, and accompanying data and figures, please see:
Wen, J., Li, H., & Lu, M. (2022) A flexible GNSS spoofer localization system: Spoofing discrimination and localization method. *NAVIGATION, 69*(1). https://doi.org/10.33012/navi.511

Results on GNSS Spoofing Mitigation Using Multiple Receivers

Erik Axell

Spirent GSS9000 Simulator

A new algorithm is proposed for spoofing mitigation, generalized to using an arbitrary number (≥2) of receivers. The algorithm has been verified in the lab and in over-the-air test using a Spirent GSS9000 simulator. The methodology can be used by any system of multiple connected GNSS receivers to mitigate spoofing attacks and thereby achieve more robust and reliable positioning, navigation, and time (PNT).

Implementation and evaluation of the algorithm are currently being performed. Outstanding issues are addressed in the paper to make the methodology work in (near) real-time.

For the full article, and accompanying data and figures, please see:
Stenberg, N., Axell, E., Rantakokko, J., & Hendeby, G. (2022) Results on GNSS spoofing mitigation using multiple receivers. *NAVIGATION, 69*(1).
https://doi.org/10.33012/navi.510

On Enhanced PPP with Single Difference Between-Satellite Ionospheric Constraints

Yan Xiang

The precise point positioning (PPP) technique has become popular in many fields due to its cost-effectiveness and operational flexibility. However, PPP suffers from a long convergence time, taking 15 to 60 minutes to reach centimeter-level positioning accuracy, which significantly limits its applications.

To address the long-standing issue of the convergence time of PPP, ionospheric correction is exploited to achieve faster high-precision positioning in the GNSS community. As the ionospheric corrections are highly correlated to frequency-related hardware biases, the receiver-related code biases become tricky when adding the ionospheric constraints.

The Single-Difference Between-Satellite (SDBS) Method

One approach to address the long convergence time is to estimate the receiver biases to mitigate

the effects of receiver-related biases. But this method requires common satellite visibility from all the same reference stations. Instead, we create the single-difference between-satellite ionospheric constraints, the SDBS-ION method. The SDBS-ION method is more flexible to add external ionospheric constraints when the ionospheric constraints do not have common visibility from the same set of reference stations.

We processed 130 stations within 300 km to investigate related questions: What are the differences between the direct and the SDBS-ION methods? How does the accuracy of ionospheric corrections change with distance? What is the performance of single-station augmentation? What is the difference between network augmentation and single-station augmentation? How are ionospheric constraints effective in reducing PPP's convergence time?

Differences in the SDBS and ION Methods

Results show that these two methods have few differences. These two methods generate similar solutions if receiver DCBs are modeled as white noise with common satellite visibility. The direct-but-biased ionospheric constraints need to model one more parameter of receiver DCBs, whereas the SDBS-ION method sacrifices one constraint when forming single differences between satellites. But when there is no common satellite visibility, the proposed SDBS-ION method still works well.

In addition, the effectiveness of enhancing PPP performance degrades with the increase of distance between users and reference stations due to less accurate ionospheric corrections. Besides, the ionospheric constraints using the network are more effective when compared with a single reference station. We also found that only the first 5-minute ionospheric constraints are beneficial to PPP when state vectors remain the same. The positioning errors could be biased when ionospheric constraints are inaccurate.

Achieving Enhanced PPP

The SDBS-ION method is important to the GNSS PNT community in achieving enhanced PPP with regional ionosphere augmentation. Rapid and precise positioning performance is needed in applications that are operating in real time. More available satellite ionospheric augmentation information means faster positioning solutions. The proposed method is able to work well when all the reference stations do not have common satellite visibility. We are looking forward to seeing more applications in commercial applications.

Our next research project investigates the uncertainty of ionospheric corrections using different modeling methods, because we find that the uncertainty also plays an important role in achieving rapid and robust positioning. Another challenging issue is ionospheric conditions. The active ionospheric condition poses a threat to the high performance of high-precision positioning.

For the full article, and accompanying data and figures, please see:

Xiang, Y., Chen, X., Pei, L., Luo, Y., Gao, Y., & Yu, W. (2022) On enhanced PPP with single difference between-satellite ionospheric constraints. *NAVIGATION,* 69(1). https://doi.org/10.33012/navi.505

deployment for 6 months. The story of who did what when in this debacle is well covered in my articles in the press. Suffice it to say there is plenty of culpability to go around. In this article we will focus more on the technical aspects of what is being done to move forward.

RF Compatibility Between Existing Aviation Radar Altimeters and 5G

Since the initial compromise was struck, the U.S. aviation and cellular telecommunications industries and their regulators have been working together toward a coherent framework to assure radio frequency (RF) compatibility between existing aviation radar altimeters and new fifth generation (5G) cellular base stations operating in the mid-band (i.e., from 3 to 4 GHz). Such a framework is difficult to define due to the demonstrated potential for 5G interference to cause hazardously misleading altimeter outputs combined with the potential for aircraft to operate relatively close to high-power cellular base stations. The task at hand is to coordinate cellular and/or aviation regulatory frameworks that account for and bound the numerous parameters that contribute to compatibility in order to assure operational safety in both the near term and longer terms. The methodology will eventually be documented and shared for potential general global application. Without such a framework the potential economic disaster has only been delayed and aviation safety is still potentially at risk.

A few key aspects that must be accounted for if a framework is to ensure compatibility include some limitations on the ground station radiation. It would be impossible to design new radio altimeters that would be able to survive literally any arbitrarily high level of adjacent band interference energy. The total received interference power depends on the power of the ground station transmitter and the directionality of 5G antenna array. The radiated power may only be bounded if limitations on the directionality will be adopted, enforced, and assured long

term, which is not currently the case in many spectrum regulations. Characterization of some current point designs is not sufficient to ensure that safety will be maintained over the long term since designs change, and new designs can only be expected to comply with regulatory limits. Also, aircraft operations must be protected from the most severe safety hazards not only on the procedure designed paths, but similarly on any possible paths with navigation sensor error and path following error, as well as during nominal and off-nominal situations. Most airports have a wide range of operations, each with their unique operational volumes where airplanes will periodically appear. Each operation must be considered, along with any hazards applicable for that operation. Additionally, multiple interference mechanisms are relevant for high 5G power within relatively close proximity to altimeters. A 5G base station could have spurious emissions in the altimeter band, but also the fundamental 5G emissions can be so strong at their intended frequency adjacent to the altimeter that the altimeter is affected within a certain distance, even with excellent adjacent frequency filtering in the altimeter.

Assuring the Compatibility of 5G and Radar Altimeters

While there exists a patch work of unique compatibility solutions in states with operational mid-band 5G, compatibility of 5G and radar altimeters is currently assured in the U.S. as follows. Cellular providers regularly share the locations and power levels of all operating 5G mid-band transmitters in the U.S. with the Federal Aviation Administration (FAA). Next, the FAA issues a Notice to Airmen (NOTAM) for each aerodrome with 5G nearby and restricts aviation operations using Airworthiness Directives (ADs) at those NOTAMed aerodromes. The AD restrictions disallow operations for which safety cannot be assured if radar altimeters are less reliable. Aircraft and altimeter manufacturers submit paperwork to the FAA called an Alternative Means of Compliance (AMOC) to request exemption from AD restrictions

where altimeter tolerance to interference can be checked against 5G station locations and power for safe separation distances. The FAA grants and updates AMOC approval on a runway-by-runway, altimeter-by-altimeter, aircraft-by-aircraft basis by checking operational volumes and safe distances against the latest operational 5G base station locations. Aircraft operators must cross-check flight plans against runway lists with and without AMOC approval to determine how or if they can operate at their departure, destination, and alternate airports. Clearly this level of coordination is burdensome, expensive and not suitable for a long-term solution.

The compatibility process described above, on its own, would have resulted in major disruption to air travel, so cellular providers have temporarily and voluntarily kept certain 5G base stations turned off or at reduced power levels if they were close enough to major airports where inability to approve AMOCs would have significant economic impacts to the aviation sector. The entire process and the voluntary mitigations being used today are a stop gap to ensure continued safety, but these measures are in no way sustainable for any stakeholder. The pain of these measures motivates the ongoing collaboration to converge on a more sustainable end state.

Retrofitting Aviation Radar Altimeters with Modified Altimeters

The ideal end state for cellular is to be able to operate 5G base stations according only to their regulatory rules and standard obstacle clearance criteria for physical structures around airports. The ideal end state for the FAA is to maintain continued safety without having a need to keep track of 5G station locations and power levels to approve AMOCs by runway. And the ideal end state for large air transport operators is to continue safe operations with reliable radar altimeters, avoiding 5G-related operational restrictions. In order to give the best chance of accomplishing those end state goals, the vast majority of aviation radar altimeters will ultimately be retrofit with altimeters

redesigned or modified with additional filtering for adjacent band interference.

The time frame targeted for design, certification, and retrofit with modified altimeters has been dramatically accelerated relative to standard aviation certification time frames. Radar altimeter design modifications are mostly complete, certification projects for those new designs are already under way, and at least two-thirds of the large air transport fleet will be replaced as fast as possible over the next year, at a cost of billions of dollars to the aviation sector. A phased prioritization is planned such that cellular providers can increase 5G power levels and activate new base stations as a small number of most vulnerable radar altimeters are replaced first, followed by the replacement of large numbers of additional units.

One risk of this schedule is that there are no new definitive 5G compatibility performance criteria for which these new altimeters can be designed and certified. Manufacturers have incorporated the highest level of adjacent frequency filtering they could achieve while maintaining minimum performance of the intended functions of their altimeter designs. U.S. and Europe standards organizations will not complete new radar altimeter requirement standards with 5G robustness criteria until the end of 2023, although an interim deliverable with guidance material is planned by the end of 2022. The risk of this timing is that some newly replaced altimeters may not be able to meet the future new standard and would need to be replaced a second time in the future.

Manufacturer Testing for Adjacent 5G Signal Levels

Altimeter manufacturers are currently testing their new designs to estimate the tolerance thresholds for adjacent 5G signal levels. These are the best achievable tolerance thresholds for the near term time frame. The FAA is refining definitions of operational volumes and minimum 5G-altimeter separation distances that must be protected. Aviation and cellular teams continue to iterate on simulation and analysis methods to compare 5G power levels with altimeter tolerance thresholds at minimum safe distances everywhere in the operational volumes. With luck, near term altimeter design updates will support compatibility with U.S. and global 5G deployments for years to come.

Avoiding Future RF Compatibility and Interference Impacts

Assured compatibility of RF systems, while not a new problem, may become increasingly critical as autonomous applications using RF measurement sensors proliferate in an increasingly dense RF environment. Engineers designing any autonomous functions or system architectures must be careful to consider RF compatibility and interference impacts since multiple redundant sensors cannot overcome common-mode interference effects. Whether interference is intentional, unintentional, or due to incorrect or neglected compatibility assessments, system architectures will benefit from sensors that are designed to avoid misleading outputs. In addition, dissimilar sources of information should be used to detect and exclude erroneous data and gracefully play through interference, especially where safety is at risk. When interference sources are co-sited on a platform, for example 5G communications antennas sited next to satellite navigation or radar altimeter antennas, the requirement and design space can be well controlled and understood. However, as trends move toward autonomous vehicles that may operate close to off-vehicle interference sources that have no design assurance or real-time performance monitoring, RF interference robustness measures should consider the worst. ✦

Congressional Fellow

Dr. Benjamin Ashman

A Perspective on the Senate's Inaction

As the Institute of Navigation's congressional fellow, I've written about Senate office methods for advancing policy and about the specific successes I've contributed to. But it is often Senate failures that made headlines. This year, I've seen the Senate fail to extend the Child Tax Credit, protect voting rights, or safeguard reproductive rights. Anyone passionate about a policy issue, whether Democrat or Republican, has been frustrated by the Senate at some point. Through this fellowship I've learned how the institution is insulated from public outcry by design.

Six-year terms are intended to free senators from immediate political pressure and said terms are staggered so that only one-third of the Senate is ever up for election at a time. No wave of public sentiment can wholly reshape the chamber as it can the House. Furthermore, the Senate's equal representation of states, rather than people, gives less-populous states greater weight. In the 117th Congress, the 50 Democratic senators represent 40.5 million more people than the 50 Republicans. And the modern filibuster ensures that not only does the minority have a voice in the Senate, but it effectively has a veto that can only be overcome with 60 votes.

My fellowship began in the midst of negotiations on Build Back Better (H.R. 5376), a Biden Administration priority that included an extension of the popular Child Tax Credit. Democrats hoped to pass this bill using budget reconciliation, a procedure created by the Congressional Budget Act of 1974 that allows one bill per fiscal year to pass with a simple majority.

Budget Reconciliation as a Tool to Advance Legislation

In the modern Senate, almost all other bills require 60 votes to pass, so budget reconciliation has become the principal way that the Senate passes major legislation (despite the restriction that all provisions contained in a reconciliation bill must be expenditure-related). With a 50-50 Senate and uniform Republican opposition, however, the effort effectively failed on December 21 when Senator Joe Manchin (D-WV) announced that he would not support the bill.

After the holiday recess, Democratic congressional leaders made a renewed push on another administration priority: voting rights legislation. For this bill (H.R. 5746), however, they would need to overcome the 60-vote threshold. Through procedural maneuvering, Majority Leader Chuck Schumer (D-NY) was able to bring the issue to the Senate floor for debate.

The day of debate, January 19, was a dramatic day: dozens of senators sat at their desks on the Senate floor and House members of the Congressional Black Caucus watched from the gallery as senators from both sides of the aisle exchanged speeches for and against the bill. When the vote was taken that evening, Vice President Kamala Harris presided, calling the vote from the dais as senators responded yea or nay from their desks.

Cloture

But the vote taken was not on the bill itself; it was a vote on a motion to invoke cloture. Because the Senate is designed to allow senators as much time to debate an issue

Benjamin Ashman and Senator Sherrod Brown (D-OH) at the Capitol

as they deem necessary, three-fifths of senators (i.e., 60) must vote for a "closure of debate," or cloture. Historians dispute who first pioneered the filibuster (derived from the Dutch word for "pirate"), but by the mid-19th century, senators were strategically talking at length to prevent progress on legislation they opposed. A precedent established in 1872 removed the need for this talking to be relevant to the pending measure, and the move to a two-track process in 1971 (allowing the Senate to consider other business while a bill is blocked) effectively removed the requirement to talk at all.

The January 19 vote to invoke cloture split down party lines and failed to reach the three-fifths' threshold. Senator Schumer then moved to vote on the voting rights legislation itself, but subject to a proposed rule that would effectively re-establish a talking filibuster: any debate would have to be germane and other Senate business would be put on hold. Republicans were joined by Senators Manchin and Kyrsten Sinema (D-AZ) in defeating the measure, preserving

the three-fifths' threshold that Minority Leader Mitch McConnell (R-KY) called, "the soul of the Senate." The result: no vote on voting rights, and no further progress on a top priority for the Senate majority.

Senate gridlock was again in the spotlight on May 2 when *Politico* published a leaked draft Supreme Court opinion by Justice Samuel Alito that would strike down Roe v. Wade. The leak spurred waves of protest with both pro-life and pro-choice groups demonstrating outside the Supreme Court building for weeks. Democrats in Congress rushed to respond to the outcry by introducing the Women's Health Protection Act of 2021 (S.1975) on May 6. The cloture vote in the Senate, however, failed even the majority threshold (49-51), with Senator Manchin and all Republicans opposed.

Legislation Passed

It's not that the Senate hasn't passed any legislation this year. Over the past six months, Congress passed a fiscal year 2022 appropriations bill, a postal reform bill, an anti-lynching bill, and several

bills in response to Russia's invasion of Ukraine. And this Congress isn't unique (or even unusual) in its struggle to move other high-profile bills; both Democratic and Republican administrations have found their most pressing legislative priorities quickly taken up and passed in the House only to grind to a standstill in the Senate. In 2017, for example, Republicans were unable to repeal the Affordable Care Act through the budget reconciliation process due to the opposition of all 48 Democrats and Republican Senators Susan Collins (R-ME), John McCain (R-AZ), and Lisa Murkowski (R-AK).

The May 24 shooting of 19 children and two teachers in Uvalde, Texas and the ensuing debate on gun regulations prompted a renewed examination of the balance between responsiveness and deliberation in the Senate. Are Senate procedures justly tempering the passions of a majority party or giving outsized powers of obstruction to the minority? Unfortunately, it depends who you ask—and when. ✳
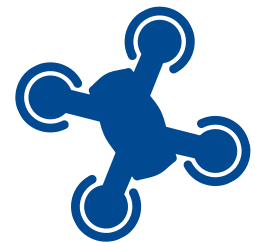
Navigating Towards Diversity

Marvin B. May

I don't think I am a racist. I don't believe I am a misogynist. I don't consider myself a prejudiced person. So, what has me concerned is thinking about updating the selections to the Navigation Hall of Fame. My previous selections, limited to individuals whose accomplishments occurred more than 50 years ago, were reported in the Historian article of Fall 2018, and they are repeated below with the corresponding Historian Newsletter article in italics:

Eratosthenes: **Eratosthenes** (c. 276 BC – c. 194 BC; *Summer 2001*)

Ptolemy: **Claudius Ptolemy** (c. 100 CE – c. 170 CE; *Summer 2015*)

Copernicus: **Nicolaus Copernicus** (February 19, 1473 – May 24, 1543; *Winter 2016*)

Magellan: **Ferdinand Magellan** (February 4, 1480 – April 27, 1521; *Fall 2013*)

Piri Reis: **Ahmed Muhiddin Piri** (1465 – 1553; *Summer 2018*)

Galileo: **Galileo Galilei** (February 15, 1564 – January 8, 1642; *Fall 2018*)

Isaac Newton: **Sir Isaac Newton** (January 4, 1643 – March 31, 1727; *Fall 2001*)

Bowditch: **Nathaniel Bowditch** (March 26, 1773 – March 16, 1838; *Summer 2003*)

Elmer Sperry: **Elmer Ambrose Sperry**, Sr. (October 12, 1860 – June 16, 1930; *Fall 2007*)

Albert Einstein: **Albert Einstein** (March 14, 1879 – April 18, 1955; *Spring 2005*)

Frank McClure: **Frank McClure** (August 21, 1916 – October 18, 1973; *Winter 2019)*

Times are "a Changing"

However, in reflection, all the selections have been white males. The absence of females or persons of color is glaring! I don't think that I can absolve myself from this situation of obvious inequity. Maybe I have not tried hard enough. In the lyrical words of Bob Dylan,"... the times they are a changin'."

After all, President Biden, who famously limited his nomination to black women to fill a Supreme Court vacancy, was able to secure the appointment of Judge Ketanji Brown Jackson to the highest court of the land. It should be apparent that unless the broad scientific community achieves gender and racial equality, the quality of science will be severely diminished.

Looking back to 1872, the British Challenger expedition set out to travel the globe to study and take samples of the oceans of the world. While the expedition is thought to be the first scientific oceanographic cruise, of the 243 people onboard, not one was a woman.

Jeanne Baret

Somehow, though, nearly a century before the Challenger, a woman by the name of Jeanne Baret sailed around the globe on a scientific voyage of her own. Baret had to disguise herself as a male

Imagined portrait of Jeanne Baret dressed as a sailor, dating from 1817, after her death.

worker on the 1766 voyage led by the French admiral and explorer Louis-Antoine de Bougainville to document plants and ecosystems in foreign countries. She is considered to be the first woman on record to circumnavigate the globe.

Today, although the battle for equality continues, women have managed to secure major roles in the Navy as well as in scientific expeditions. Ultimately, good education can be an antidote to inequities, particularly in the more recent example of Dr. Gladys West.

Dr. Gladys West

Born in 1930s rural Virginia, when Gladys West wasn't in school, she spent long periods of time helping harvest crops on the family farm. In her community, the only clear options for the future of a young black girl were continuing to farm or working at a tobacco-processing plant. West's aptitude for education navigated her on a new course.

Proudly earning the honor of valedictorian, West went on to receive a full scholarship to Virginia State College (now Virginia State University) where she earned a degree in mathematics. After spending time teaching math in racially segregated Virginia schools, and applying for a series of jobs in Virginia's segregated state government, Gladys returned to school to earn a graduate degree in mathematics.

Just one year later, in 1956, West started work at the Naval Surface Warfare Center, Dahlgren Division, as the second black woman to ever be employed there. She started out collecting satellite data, a job which eventually led to the development of the Global Positioning System (GPS).

By 1986, Gladys had written an illus-

Gladys West and Sam Smith look over data from the Global Positioning System at Dahlgren in 1985.
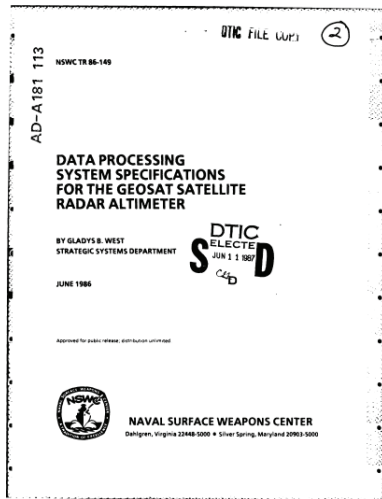
trated guide based on data generated by the radio altimeter on the GEOSAT satellite, entitled *Data Processing System Specifications for the GEOSAT Satellite Radar Altimeter.* The GEOSAT's radar altimetry estimated Earth's geoidal undulation, which in turn, was able to compute anomalies and other variations in the Earth's field of gravity. These anomalies in gravity affected the orbit of observed satellites and were used to refine GPS satellite ephemerides.

Dr. West went on to work at Dahlgren's division for 42 years and made significant history in that time. In 2017, Capt. Godfrey Weekes, the then commanding officer at the Naval Surface Warfare Center Dahlgren Division, wrote about how "she rose through the ranks, worked on the satellite geodesy, and contributed to the accuracy of GPS and the measurement of satellite data."

Data processing report for GeoSat by Gladys West

Times have indeed changed, but the process still takes work and requires a nuanced sensitivity to significant issues of concern to each affected minority. ✳

The following articles were referenced: https://www.britannica.com/biography/Gladys-West

https://eos.org/features/women-in-oceanography-still-navigate-rough-seas

Marvin B. May is Chief Navigation Technologist for Mayven Engineering and Professor Emeritus of the Pennsylvania State University. His email is mbm16@psu.edu or mayven4@comcast.net. He is seeking nominations from the ION membership to add to the original 11 above to the "Navigation Hall of Fame."

Defense Matters

Modernizing GPS Through Change and Challenge
Achieving NAVWAR Compliance with Trusted PNT

Upgrading the Global Positioning System (GPS) to improve navigation warfare (NAVWAR) capabilities for the warfighter is an ongoing multibillion-dollar effort that began in the late-1990s.

Early efforts were championed and guided by the then GPS Joint Program Office (JPO) located at the Los Angeles Air Force Base Space and Missile Systems Center (SMC). The GPS JPO had been in existence since the 1970s, but the joint culture it fostered gradually dissipated as service participants decreased their levels of participation once GPS became operational in the mid-1990s.

In 2006, the GPS JPO was redesignated as the GPS Directorate, maintaining a focused programmatic approach, but under an Air Force-centric management structure. However, even that programmatic focus became further dissipated with the SMC realignment initiative called SMC 2.0, which occurred in July 2019[1] where the segments of the GPS Program were divided among different functional organizations within the SMC.

SSC Restructuring

With the Space Force taking over GPS in May 2020, a restructuring of the three program segments of GPS is being implemented by the newly designated *Space Systems Command* (SSC).

The GPS Program will now reside within a new SSC Program Executive Office (PEO) supporting Military Satellite Communications and PNT (CP). Early indications of this new structure show promise in returning to a more program-focused approach to the management and acquisition of GPS. The new SSC PEO is headed by Mr. Cordell DeLaPena.

It remains to be seen how this new structure, designated toward PNT, but still primarily focused on GPS, may ultimately put the warfighter on the right path to maintaining NAVWAR compliance consistent with the DoD Chief Information Officer (CIO) Instruction 4650.08 issued on December 30, 2020.

With over two decades of modernization activity in the rearview mirror, there are still many years ahead of hardening GPS as a foundational component to bring resilient PNT to the warfighter. With the Army's Assured PNT ap-

> Early indications of this new structure show promise in returning to a more program-focused approach to the management and acquisition of GPS.

proach charting the course, it is encouraging to see SSC follow suit and devote broadened attention to the GPS role in providing resilient PNT and setting the course to NAVWAR compliance for the warfighter.

GAO's View of GPS Modernization

On May 9 of this year, the Government Accounting Office (GAO) released a report to the House and Senate's Armed Services and Appropriations Committees titled *GPS MODERNIZATION— Better Information and Detailed Test Plans Needed for Timely Fielding of Military User Equipment.*[2]

The report, prepared in response to a provision in the Senate Report that accompanied the National Defense Authorization Act (NDAA) of FY 2020, required the GAO to "examine the military services' determinations on M-code-capable user equipment needs for their weapon systems." The report was prepared over a 14-month period from March 2021 to May 2022.

Contained within the report are a number of conclusions about the ability of the DoD's PNT Oversight Council to maintain oversight and facilitate planning for the integration of M-Code across approximately 700 DoD weapon systems. Specifically, the report suggests that the department's senior leadership needs to have available "data that is complete, consistent, and up-to-date, [as the] DoD cannot effectively plan and budget for the fielding of M-Code…" It is also stated that "due to delays in user equipment development, service plans for testing M-code capability in an operational environ-

> "due to delays in user equipment development, service plans for testing M-code capability in an operational environment are not fully developed."

Doug Taggart
President
Overlook
Systems
Technologies, Inc.

ment are not fully developed."

Information contained in the report includes progress being made on: (1) the space, ground control, and user equipment segments of the GPS enterprise; (2) the extent the services have identified and prioritized systems to field M-code-capable equipment; and (3) the extent to which the services have planned for the procurement, installation, and fielding of M-code-capable user equipment into priority weapon systems.

With respect to progress being made on more jam-resistant, military-specific signals (e.g., M-Code to the warfighter), the space segment is forecast to be the first to meet the minimum requirement for fully operational M-code signal broadcasts when the 24th M-code capable satellite (launched in June 2021) is declared operational later this year. No specific month was identified for this to occur, but in any event, it will be before either the ground control and/or user segments are operational.

Modernization of the Ground Control Segment

Modernization of the ground control segment is being worked through the Raytheon Next Generation Operational Control System (OCX) program. Raytheon's plan for making OCX operational is to roll out new capabilities through a series of blocks (e.g., Block 0, 1, 2, and 3F).

As noted in the GAO report, Block 0 is the Launch and Control System (LCS) intended to control Launch and Early Orbit (LEO) operations and the on-orbit checkout of all GPS III satellites.

Blocks 1 and 2, which the report indicates will begin operations in April 2023, will be delivered concurrently. Block 1 fields the operational capability to control all legacy satellites and civil signals (L1 C/A), military signals (L1P[Y], L2P[Y]) as well as the GPS III satellites and the modernized civil signal (L2C) and the aviation safety-of-flight signal (L5). In addition, Block 1 will field the

basic operational capability to control the modernized military signals (L1M and L2M [M-Code]), and the globally compatible signal (L1C). Block 2 fields the advanced operational capability to control the advanced features of the modernized military signals (L1M and L2M [M-Code]).

The final OCX Block 3F rollout will enable control of the next block of GPS-III satellites, GPS-IIIF, and will also enable operation of the full complement of Military GPS User Equipment Increment 2 capabilities. The forecast for when Block IIIF will be operational was not stated in the report, but other Space Force enterprise sources forecast operational acceptance of the final OCX Block IIIF in the 1st quarter of FY2028.

Finally, the user segment, which is the focus of the GAO report, will be the last segment to reach the warfighter in any significant quantities. Consistent with prior GAO reports (e.g., Dec 2017, GAO Report GAO-18-74), the May 2022 report continues to reflect plans to add M-code-capable user equipment to approximately 700 weapon systems with a total number of receivers to be purchased reaching an estimate of 1 million.

The report provides a significant amount of detail on the Military GPS User Equipment (MGUE) Increment 1 and Increment 2 activities and how new capabilities will be introduced, first into lead weapon systems service platforms and then in a collection of priority weapon systems that are estimated to be in the range of 50. The remaining 650 weapons systems and platforms are years away from the most optimistic perspective.

DoD Tracking Progress

In 2015 the office of the DOD Chief Information Officer (CIO) established

a database to track M-code development and integration across the department. This database is known as the PNT Data Repository.

The PNT Oversight Council uses the database for tracking progress toward M-code integration and fielding. OUSD(A&S) is using the PNT Data Repository to inform implementation of a waiver policy to account for delays in M-Code equipage, despite a statutory requirement that GPS user equipment purchased after fiscal year 2017 be capable of receiving M-code.

The requirement for NAVWAR compliance is spelled out in DoDI 4650.08. Paraphrasing, PNT applications have to be able to provide PNT necessary for systems to complete missions in the NAVWAR environment where they are expected to operate. Assessing PNT functionality for any particular weapon system/platform is performed as part of the developmental testing (DT)/operational test (OT) of DoD's acquisition process.

Although the DOD CIO is responsible for maintaining the PNT Data Repository, the military services are responsible for inputting data and ensuring that their data are accurate for the warfighters who depend on PNT.

Our warfighters are the ultimate customers, and if the PNT reliant weapon system doesn't work, it is they who will suffer the consequences. ✵

[1] See ION Quarterly Newsletter Fall 2019, Defense Matters, "Where, Oh Where Did the GPS Directorate Go?" https://www.ion.org/newsletter/upload/v29n4.pdf

[2] https://www.gao.gov/products/gao-22-105086. https://www.gao.gov/products/gao-22-105086.

> PNT applications have to be able to provide PNT necessary for systems to complete missions in the NAVWAR environment where they are expected to operate.
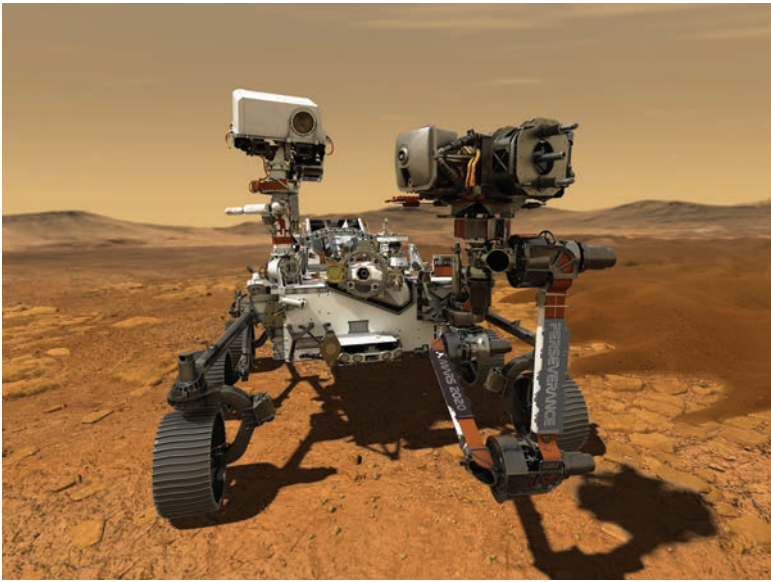
Mars Rover Perseverance

to 6,000 meters in depth) to obtain large amounts of information from the oceans and seabed, combining autonomous technologies to gather and analyze data from our oceans.

Additionally, ION GNSS+ attendees will hear from Dr. Michael McHenry who leads the navigation team for the Perseverance Rover. Operating completely autonomously, Perseverance has traversed the surface of Mars, launched the first aircraft ever flown on another planet, and made fascinating discoveries.

A Full Technical Program

ION has a full in-person program being hosted with six tracks of commercial, research, and policy sessions with panel discussions offered over three days (Wednesday through Friday) and the pre-conference tutorial day on Tuesday.

Anticipated highlights in the commercial tracks include sessions on autonomous and safety critical applications including aviation, aeronautics, and augmentation services. Status and future trends of navigation will present applications in space and scientific and sectorial applications including hosting the annual status of the GNSS systems session. Navigation for the mass market sessions include a session on new technologies, opportunities, and challenges that will cover applications of machine learning, smartphone positioning, and GNSS-less aircraft navigation. Commercial applications for urban and indoor are sure to be of interest too.

The research tracks will host peer-reviewed technical presentations on multi-sensor and autonomous navigation; algorithms and methods; and advanced GNSS technologies. Highlights are sure to include panel discussions on emerging trends in LEO-based Satnav and signals of opportunity for PNT;

ION GNSS+ 2021 session in progress

autonomous navigation for ground, seaborne, and airborne vehicles; and a panel on algorithms and methods for GNSS cyber physical security.

All presenters will be providing a virtual video presentation again this year. Video presentations will be available to both in-person and virtual attendees. Attendees will be able to view the online presentations through the virtual meeting portal and post questions online.

Attendees are encouraged to review the pre-conference tutorial offerings that have been organized to provide in-depth learning of specific GNSS-related disciplines. The pre-conference tutorials will be taught in person, in a classroom setting, and with a virtual attendance option. Instructors are internationally renowned experts and this is some of the best learning opportunities available. Both introductory and more advanced courses are offered, with a new course in factor graphs being offered for the first time this year.

2nd Smartphone Decimeter Challenge

Google, Kaggle, and the ION's Satellite Division are co-sponsoring the 2nd Smartphone Decimeter Challenge this year. (For details on entering see page 23.) In 2021, competitors had to process raw GNSS and IMU data from smartphones to obtain the most accurate solutions. Each competitor submitted their location solutions for the data sets, which were then compared to ground truth calculated from a NovAtel RTK-IMU reference system. The data was gathered from Android phones in cars driving on roads in the San Francisco bay area. One of the most interesting things about the competition is the prevalence of AI, machine learning (ML), and factor graph optimization that was used by many of the entrants; probably a bit of surprise to ION's GNSS-centric audience.

The 2022 Smartphone Decimeter Challenge data will include some of the San Francisco bay area data from 2021, plus new data collected this past year from the bay area and Los Angeles. Other

Dr. Michael Fu, Chairs the 1st Smartphone Decimeter Challenge in 2021 in St. Louis, MO

competition differences implemented in 2022 include using newly released phones (Pixel 5/6, Samsung S-series) and a limit of one phone per drive in the test data set that prevents participants from merging multiple phones' observations to produce a combined solution.

The competition was also designed to increase the variety of the driving routes, so the participants would not be able to reuse the ground truth of the training data set to constrain the position estimation of the test data set in the same route. Additionally, in order to make the competition as accessible as possible to ML scientists, the organizers revised the data format to combine raw measurements (such as C/N_0) and computed values (e.g., pseudorange, satellite positions, delays, weighted least squares positions) in one single line.

Dr. Michael Fu, Google, reported that he anticipates, "There will continue to be a lot of ML/AI participants this year, as people are having better understandings of the data format and the nature of this problem. Factor graph optimization (FGO) will be popular, too."

Dr. Fu suggests, if you are planning to participate in the competition this year, that you review the winning solutions and methods from last year (see https://www.kaggle.com/competitions/smartphone-decimeter-2022/discussion/322510). "I'll not be surprised as well when seeing traditional GPS methods like RTK get good results in the end," said Dr. Fu. But act fast because the competition closes July 29!

Other ION GNSS+ Offerings

Commercial vendors will be displaying their wares, talking shop, and expounding upon the developments in the GNSS marketplace in the exhibit hall. The Satellite Division's Kepler Award will be presented at Friday's Awards' program to honor sustained contributions to the development of satellite navigation. Additionally, the Parkinson Award will be presented to an outstanding graduate student in the field of GNSS. Winners of the Smartphone Decimeter Challenge will also be recognized.

And of course, this is the best time of the year to reconnect; for some of us, it may have been a while. This is an opportunity to get feedback on your work, mentor and be mentored, and generally interact with people like YOU! See you in September. ✳

SMARTPHONE DECIMETER CHALLENGE WINNERS TO PRESENT AT ION GNSS+ 2022

The Institute of Navigation's Satellite Division, in partnership with Google, will host the 2nd Annual Smartphone Decimeter Challenge with the winning teams presenting their methods at the ION GNSS+ 2022 meeting, September 19–23, 2022, at the Hyatt Regency Denver (located adjacent to the Colorado Convention Center) in Denver, Colorado.

The Smartphone Decimeter Challenge is designed to advance research in smartphone GNSS positioning accuracy using state-of-the-art algorithms and technologies such as advanced machine-learning models and precision GNSS algorithms.

While standard GPS, other GNSS (Galileo, BeiDou, and GLONASS), and regional satellite navigation system (QZSS and IRNSS) receivers provide accuracy between three and 10 meters (often worse in urban environments), better location can be obtained by processing carrier-phase measurements, IMU data, and base station corrections.

Teams will use data sets collected using GPS and inertial measurement units (IMUs) of Android smartphones to compute location down to an accuracy of decimeters. Mobile users will benefit from lane-level-accuracy-based services, enhanced experience in location-based gaming, and greater specificity in location of road safety issues.

Winner selection is based on the accuracy of results from the test data sets compared to highly accurate ground truth. The top three winners will receive prizes valued at $15K+ that includes a guaranteed speaking slot at the highly competitive ION GNSS+ 2022 conference (subject to technical paper and ION presentation requirements); travel subsidy; and complimentary registration to attend ION GNSS+ 2022 in Denver.

To learn more about the Smartphone Decimeter Challenge, go to g.co/gnsstools. The deadline to submit a competition entry is July 29, 2022. ✳

GNSS Program Updates
News from Systems Around the World

Dee Ann Divis

Galileo

A new Galileo satellite named Nikolina (GSAT0223) entered service on May 5, 2022, filling the last empty slot in the constellation's Orbital Plane B. The satellite was launched into orbit December 5, 2021, along with sister spacecraft Shriya (GSAT0224), which was still undergoing in-orbit validation as of early June.

The mission was the first for which the early orbit operations were handled directly from the operational center in Germany, under the responsibility of European Union Agency for the Space Program (EUSPA). The addition to the Galileo constellation occurred just a week before EUSPA's first birthday as an organization.

"EUSPA's launch one year ago today represented the start of a new era for the EU Space Program," EUSPA Executive Director Rodrigo da Costa said in a statement. "With an expanded mandate and new responsibilities, we are committed to helping the EU, its citizens, and its businesses maximize the many social and economic benefits of space."

Four programs now exist under EUSPA: The Galileo satellite navigation system; EGNOS, which provides satellite-based augmentation for satellite navigation; Copernicus, which draws on satellites and a variety of other sensors for Earth observation; and the recently added GOVSATCOM, which will provide secure satellite communications. One of the objectives of EUSPA is to integrate these disparate programs in support of EU's space policy.

The potential for integration may get a real test as the EU works to bring together aid organizations, technology innovators, and data experts to help refugees fleeing the war in Ukraine.

In April, EUSPA launched the hashtag #EUSpace4Ukraine representing an effort to connect non-governmental organizations involved in Ukraine relief with data providers and innovators who can take space data and other resources and come up with tools to help the NGOs reach, guide, and serve those in trouble.

EUSPA's focus is on using the navigation and remote sensing capabilities of Galileo and of Copernicus according to their website (see https://www.euspa.europa.eu/euspace4ukraine-humanitarian-help-1).

The organizers have categorized the kinds of needs they hope to serve as follows:

- Unmanned solutions for transport and delivery of goods;
- Safety and rescue;
- Integration in a new country;
- Applications to help understanding and taking inventory of the damages in Ukraine territories; and
- Safe, timely, and accurate navigation for population migration

The NGOs listed on the EUSPA website so far include groups operating both inside and outside of Ukraine to supply the Ukrainians with everything from food, water, and medical care to shelter, logistics, education, and administrative support.

Both the website, and the hashtag, have information on opportunities to participate.

UKSBAS

The United Kingdom took a step towards establishing its own national capability for resilient positioning, navigation, and

Galileo's Nikolina and Shriya satellites launched December 5, 2021, from Europe's spaceport in French Guiana.

Photo: ©EUSPA, ©European Agency for the Space Program

timing (PNT) with the broadcast of a new satellite navigation signal in June.

The signal is being transmitted by a re-purposed space-based augmentation system (SBAS) transponder on Inmarsat's I-3 F5 satellite in geostationary orbit at 54° west, the company said in a June 8 announcement. The goal is to provide more precise, resilient, and high-integrity navigation for maritime and aviation users in UK waters and airspace with the UK Space-Based Augmentation System or UKSBAS.

The June test involved the generation of an overlay test signal to GPS that was fully compliant with International Civil Aviation Organization (ICAO) standards. "It increases accuracy in positioning to a few centimeters of accuracy, rather than the few meters provided by standard GPS," Inmarsat said.

The signal was "stable and operational, enabling ongoing testing and validation by industry, regulators, and users," Inmarsat said.

UKSBAS is similar to an Inmarsat-supported system under evaluation in Australia and New Zealand.

Inmarsat led a team that included the UK firms Goonhilly Earth Station Limited and GMVNSL Limited. The signal is being broadcast in coordination with the US Federal Aviation Administration (FAA), the European Space Agency (ESA), and EUSPA. Inmarsat is delivering the UK Space Agency-funded tests with ESA via the latter's Navigation Innovation and Support Program (NAVISP).

GLONASS

According to the constellation's status page, GLONASS had three satellites that

Inmarsat-3 Computer Artists Impression of an Inmarsat-3 spacecraft
Art courtesy of Inmarsat

were unusable as of press time. The third spacecraft, located in Plane 3, was designated unusable on June 5, 2022.

Public information about the use of GLONASS and other Russian navigation technologies is thin as the war in Ukraine rages on. Ben Wallace, the United Kingdom's Secretary of State for Defense, offered some insights during a May 9 speech at the National Army Museum in London.

Wallace cited examples of what he said were "inadequate equipment and support" given by Russian military leaders to their invading troops.

"'GPS' receivers have been found taped to the dashboards of downed Russian SU-34s so the pilots knew where they were due to the poor quality of their own systems," Wallace said, according to a copy of the speech posted by the Ministry of Defense.

"Almost none of their vehicles contain situational awareness and digital battle management," he noted. "Vehicles are frequently found with 1980s paper maps of Ukraine in them."

According to news reports, not even the maps were going to help. A call went out via Facebook from Ukravtodor, the government agency responsible for

Ukraine's national road system, telling Ukrainian civilians to dismantle street, road, and public signs to confound the invading troops.

GPS

Space Systems Command (SSC) announced in June that the GPS Next Generation Operational Control System Follow-On (OCX 3F) program had achieved Milestone B; the baseline requirements for the program now have been set including the establishment of technical, cost, and schedule caps that will govern the contract through completion. OCX 3F will enable the Space Force to control the GPS IIIF satellites now under construction.

OCX 3F upgrades the capability of OCX Blocks 1 and 2 to "utilize the enhanced capabilities of the new GPS IIIF space vehicles being developed by Lockheed Martin," SSC said in a statement.

Blocks 1 and 2 are expected to be delivered later this year.

The Government Accountability Office (GAO), which has been following OCX for a number of years, described Blocks 0, 1, and 2 in a recent report as being primarily a software program. In the 2022 release of its Weapons System Annual Assessment, GAO calculated that 42 percent of the software in Blocks 0, 1, and 2 was custom while another 21 percent was off-the-shelf software that had to be modified.

The OCX program has suffered delays due to COVID and the sale of a key hardware supplier to a foreign company—a development that necessitated the replacement of some hardware. The schedule also slipped repeatedly due to the unanticipated complexity of the software and the cybersecurity elements it had to incorporate. At the suggestion of an outside team of computer experts, the Air Force made a crucial decision to shift to cloud-based development which enabled simultaneous testing and helped

ION News and Notes

MEMBER NEWS

2022-2024 Satellite Division Nominations & Voting

The Satellite Division Nominating Committee, chaired by Dr. Chris Hegarty, has submitted the following nominations for Satellite Division Officers:

Chair:

Sandy Kennedy, Hexagon Positioning/NovAtel

Vice Chair:

Dr. Dorota Grejner-Brzezinska, The Ohio State University

Prof. Terry Moore, Professor Emeritus, The University of Nottingham

Secretary:

Dr. Jiyun Lee, KAIST

Dr. Jihye Park, Oregon State University

Treasurer:

Dr. Paul McBurney, OneNav, Inc.

Dr. Alexander Mitelman, AMM Technical Consulting

Pursuant to Article IV of the Institute of Navigation Satellite Division Bylaws, "Additional nominations may be made by petition signed by at least 25 members entitled to vote for the office for which the candidate is nominated." All additional nominees must fulfill nomination requirements as indicated in the ION Satellite Division Bylaws and the nomination must be received at the ION National Office by July 15, 2022.

Online voting for the ION Satellite Division Officers will be available after July 18. Completed ballots must be received at the ION office by August 4, 2022, in order to be counted.

Election results will be announced during the 35th International Technical Meeting of the ION Satellite Division being held September 20-23, 2022. The newly elected officers will take office on September 23, 2022, at the conclusion of the meeting and will serve for two years. Election results will be reported in the *ION Newsletter*.

Etienne Elected RIN Fellow

Ernesto Etienne was elected to Fellow of the Royal Institute of Navigation in recognition of leading test campaigns which directly led to the FAA adoption of extended Standard Service Volumes in a ceremony that took place in London on June 30. Mr. Etienne is a senior systems engineer with the Federal Aviation Administration's (FAA) Navigation Programs Engineering Team. In his current assignments, he serves as the lead engineer for the very high frequency (VHF) omnidirectional range (VOR) Minimum Operational Network program. He has participated in operational test and evaluations (OT&E), developmental test & evaluation (DT&E) and engineering design reviews for the ILS, the REIL, the PAPI and the MALSR. Mr. Etienne received his BS in EE from Pratt Institute and his MSEE from Columbia University. Mr. Etienne is currently a PhD student in Aviation Science at St. Louis University.

Sir Alan Massey presents Ernesto Etienne with RIN Fellow

Dayton Section News

The ION's Dayton Section hosted virtual meetings on February and April. In February, two engineers from the Air Force Institute Technology's ANT Center, Jonnathan Bonifaz and Brandon Blakely, presented some of their recent work on navigating using magnetic anomalies, including results of field testing conducted at Camp Atterbury, Indiana. Both a UAV and a truck were used as platforms. Attendance, including the speakers, was 14. In April, 16 people connected to hear Josh Hiatt of Alion Science, an ANT contractor, discuss a related subject: A Comparison of Correlation-Agnostic Techniques for Magnetic Navigation. Two techniques were evaluated in one dimension, covariance intersection and probabilistically conservative fusion. The second gave good estimates regardless of the correlated error structure in the anomaly data.

The section plans to hold a family-style picnic out of doors on June 30. Election of next year's section officers will also be conducted. ✳

In our ongoing effort to broaden our reach and access new opportunities, ION exhibited at the 22nd Integrated Communications, Navigation, and Surveillance Systems (ICNS) conference that took place April 5-7 at the Westin Washington Dulles Airport Hotel. ICNS is an international aviation conference on communications, navigation, and surveillance. The meeting took place as a hybrid in-person and virtual event. ION held a drawing for the on-site attendees. Pictured is Claude Pichavant, AIRBUS, winner of an ION backpack.

Calendar of Upcoming Events

SEPTEMBER 2022
5-8: The 2nd International Symposium of Commission 4: Positioning, the Wissenschaftsetage Potsdam, Germany

Contact: International GNSS Service (IGS)

Web: www.iag-commission4-symposium2022.net

19-23: ION GNSS+ 2022, Hyatt Regency Denver (adjacent to Colorado Convention Center), Denver, Colorado

Contact: ION

Web: ion.org

JANUARY 2023
23-26: ION International Technical Meeting (ITM) & ION Precise Time and Time Interval (PTTI) Meeting 2023, Hyatt Regency Long Beach, Long Beach, California

Contact: ION

Web: ion.org

MARCH 2023
13-15: Munich Satellite Navigation Summit 2023, Munich, Germany

Contact: Bundeswehr University Munich

Web: https://www.munich-satellite-navigation-summit.org/

APRIL 2023
24-27: ION/IEEE Position Location and Navigation Symposium (PLANS) 2023, Hyatt Regency Monterey, Monterey, California

Contact: ION

Web: ion.org

JUNE 2023
12-15: ION Joint Navigation Conference (JNC) 2023, Town and Country Hotel, San Diego, California

Contact: ION

Web: ion.org

SEPTEMBER 2023
11-15: ION GNSS+ 2023, Hyatt Regency Denver at Colorado Convention Center, Denver, Colorado

Contact: ION

Web: ion.org

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the program proceed.

PNT-focused cybersecurity, this time for American critical infrastructure, was the focus of two documents released by the U.S. Department of Homeland Security (DHS) in May.

The first was an update to DHS's Resilient Positioning, Navigation, and Timing (PNT) Conformance Framework first released in December 2020. The framework describes different levels of resilience though not detailing how to achieve those levels in order to not chill technical innovation.

The new Resilient PNT Reference Architecture builds on the framework and gives more specific examples on how to thwart jamming, spoofing, and other risks. Some of the simpler techniques described in the framework include protecting GNSS receivers from being targeted by deploying decoys or obscuring their location. Other approaches draw on cybersecurity practices like incorporating multiple PNT sources or checking a GPS receiver's results at multiple points in the receiver's process.

The framework's examples are supported by a seven-page reference list of technical papers and tools. Among the tools are the Epsilon Algorithm Suite, the PNT Integrity Library, and the GPS Receiver White List Development Guide. The Epsilon Algorithm Suite and the PNT Integrity Library are open-source algorithms that can be incorporated into receivers. The White List is an "allow list" based on the GPS Interface Control Document.

BeiDou

China's BeiDou system may be going through an annual upgrade and maintenance process for its BDS-3 satellites. The June 2022 announcement on the system website referred to the event though the start date noted in the text was May 31, 2021.

"A single satellite will be set to be unusable for some period of time," said the announcement. During the upgrade and maintenance operation, the service performance indicators for BDS will be in line with the BeiDou Navigation Satellite System Open Service Performance Standard, the posting said. ✳

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2022

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Denver, Colorado

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