Volume 33 No 3 **Summer 2023**

Quarterly Newsletter

ION®
INSTITUTE OF NAVIGATION

NEW ERVA REPORT

Engineering Research Priorities for Sustainable Transportation Networks

Engineering Research Visioning Alliance's (ERVA's) latest report outlines how engineering research can help shape the future of sustainable transportation

Whether moving people or freight, transportation is the largest user of energy in developed countries, and the most rapidly growing energy consumer in developing nations. Achieving a future where transportation works efficiently and sustainably is the focus of a new report from the Engineering Research Visioning Alliance (ERVA), an

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WEIGHING WATER

Solid Earth as a Mass Scale

Little Lakes Basin Nevada Range Inyo National Forest, California

Dr. Donald F. Argus

Capability

Scientists are using GPS observations of vertical movement of Earth's surface to estimate change in the total amount of water, snow, and ice. The method is identical to you weighing yourself on a bathroom scale. When you get on the scale, you depress a spring. The amount the spring is depressed is proportional to your weight. Because we know the strength of the spring, we can deduce your weight. The scale is elastic: when you step off the scale the spring recovers its initial position.

As rain and snow increase water stored at Earth's surface, the ground is depressed. We measure vertical ground displacement to an accuracy of 2–5 mm using GPS. (In your car, GPS informs you of your location to within 10 m; at the Jet Propulsion Laboratory, we estimate GPS position to a higher accuracy, although it takes several days to do so.) Because the approximate strength of the Earth is known (for surface loads more than 50 km across), changes in water stored at Earth's surface can be inferred. The solid

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Manassas, Virginia 20109

PRESIDENT'S COLUMN | DR. SHERMAN LO

Summertime Plans and Preparations

Summer is a time many of us look forward to breathing a sigh of relief. For many of us, school is out. This means for some of us we are relaxing, kids are home from school and perhaps you are looking forward to a summer getaway.

But summer is also a great season to be planning for upcoming ION activities.

- ION GNSS+ technical papers accepted in the academic track are due for peer review on June 30.
- Abstracts for ITM/PTTI 2024 (being held January 22-25, 2024) are due October 4.
- And my personal favorite – Abstracts for ION's Pacific PNT conference, being held April 15-18, 2024, in Honolulu, Hawaii, are due November 1.

Summertime is also when some of us try to wrap up or even start research that we didn't get to during the academic year. And so, it is a good time to consider what you are working on now, what you want to share with the PNT community, and which venue is the most appropriate, timely, and has the best suited audience.

I would also be remiss if I did not thank all of those who were involved in a very successful IEEE/ION PLANS 2023 meeting that was held in-person April 24-27 in Monterey, California, with a special acknowledgement to Dr. Zak Kassas who served as the technical program chair. We had excellent attendance and a strong technical program. Please see pages 4–6 in this newsletter for more detailed information. ION and IEEE have been collaborating on PLANS since 2006; and it is my understanding that we are in the process of securing dates and a location for the spring of 2025.

ION GNSS+ 2019 short course master instructor Dr. Frank van Diggelen and attendees

Short Courses Return to ION GNSS+ Program

I also hope you spend some time this summer preparing to join me at ION GNSS+ 2023 which will once again be hosted September 11-15, 2023, in Denver, Colorado. Be sure to arrive early on Monday, September 11 to participate in the free short courses that are being offered Monday afternoon this year that include: GPS/GNSS 101 taught by Dr. John Raquet; Space Applications of GNSS taught by Dr. Penina Axelrad; GNSS Jamming and Spoofing – LEO as Fallback taught by Dr. Todd Humphreys; and LEO PNT – Architectures and Performance Trades taught by Dr. Tyler Reid. We are thrilled to see these in-person courses returning to our program this year and expect lively instruction by these ION masters and celebrities.

Award Nomination Reminder

I encourage you to acknowledge the contributions of your professional associates and nominate one or more of them for an ION award that recognizes individuals making significant contributions or demonstrating outstanding performance relating to the art and science of positioning, navigation, and timing. Nominations for ION's Fellows and Annual Awards can be made at www.ion.org/awards until October 15.

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The Purpose of the ION®

Founded in 1945, the Institute of Navigation is the world's premier non-profit professional society advancing the art and science of positioning, navigation, and timing.

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CALL FOR NOMINATIONS

Nominate a Colleague for ION Fellows and Annual Awards

Submit your nominations today for ION's Fellows and Annual Awards at ion.org/awards. All nominations must conform to ION nomination guidelines. Details of the nomination process and forms are available at ion.org/awards. Nominations must be received in proper form by October 15 to be considered.

The Institute accepts nominations for the following annual awards:

Per Enge Early Achievement Award
recognizing an individual early in his or her career who has made an outstanding achievement in the art and science of navigation

Superior Achievement Award
recognizing individuals who are practicing navigators and have made outstanding contributions to the advancement of navigation

Distinguished PTTI Service Award
recognizing outstanding contributions related to the management of PTTI systems

Captain P.V.H. Weems Award
recognizing contributions to the art and science of navigation

Tycho Brahe Award
recognizing outstanding contributions to the science of space navigation

Norman P. Hays Award
recognizing outstanding encouragement, inspiration, and support contributing to the advancement of navigation

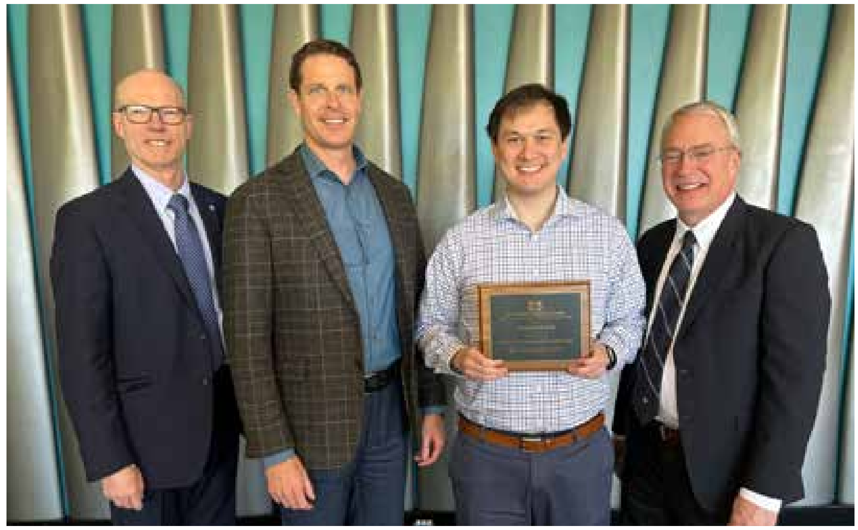
Colonel Thomas L. Thurlow Award
recognizing outstanding contributions to the science of navigation

Election to Fellow membership
recognizes the distinguished contribution of ION members to the advancement of the technology, management, practice and teaching of the art and science of navigation, and/or for lifetime contributions to the Institute

Multi-Sensor Fusion, Inertial Sensors, Spoofing, and Opportunistic Multi-Constellation Navigation … Some of the Many Hot Topics

The IEEE's Aerospace and Electronics Systems Society (AESS) and ION hosted over 370 participants, from 30 countries, to participate in the Position, Location, and Navigation Symposium (PLANS) held April 24-27, 2023, in Monterey, California. Four tracks of technical papers were presented covering topics on inertial sensing and technology; GNSS; integrated, collaborative and opportunistic navigation; and applications to automated, semi-autonomous, and fully-autonomous systems.

Tutorials covering inertial navigation systems; image inertial navigation; magnetic navigation; signals of opportunity-based navigation; and factor graphs were offered on Monday. Additionally, a special Magnetic Navigation Workshop was hosted by the Air Force Institute of Technology (AFIT) prior to the conference that was extremely popular and widely attended. Seventeen commercial exhibits rounded out the offerings.



Dr. Gary McGraw (left) and Dr. Michael Braasch (far right) presented the IEEE's Walter Fried Award to authors Dr. Todd E. Humphreys (left center) and Zachary Clements (right center).

Highlights of the IEEE/ION PLANS meeting include awards given for best papers of the week.

Best Paper from the Inertial Sensing and Technology Track:
UWB-Foot-SLAM: Bounding Position Error of Foot-Mounted Pedestrian INS with Simultaneously Localized UWB Beacons: Chi-Shih Jao, Danmeng Wang, University of California, Irvine; Joseph Grasso, National Institute of Standard and Technology; Andrei M. Shkel, University of California, Irvine

Best Paper from the GNSS Track:
Super-Resolution GPS Receiver: User's Acceleration Computation: Yiran Luo, University of Calgary; Li-Ta Hsu, The Hong Kong Polytechnic University; Naser El-Sheimy, University of Calgary

Best Paper from the Integrated, Collaborative, and Opportunistic Navigation Track:
Jammer Classification with Federated Learning: Peng Wu, Helena Calatrava, Tales Imbiriba, Pau Closas, Northeastern University

Best Paper from the Applications to Automated, Semi-Autonomous, and Fully-Autonomous Systems Track:
Indoor 5G Positioning Using Multipath Measurements: Martin Andersson, Andreas Lidström, University of Linköping; Gustav Lindmark, Ericsson AB

Best Student Paper Award:
Multi-Constellation Blind Beacon Estimation, Doppler Tracking, and Opportunistic Positioning with OneWeb, Starlink, Iridium NEXT, and Orbcomm LEO Satellites: Sharbel Kozhaya, Haitham Kanj, and Zaher M. Kassas, The Ohio State University

The IEEE's Walter Fried Award recognized the best technical paper presented at the PLANS conference:
Dual-Satellite Geolocation of Terrestrial GNSS Jammers from Low Earth Orbit: Zachary Clements, Todd E. Humphreys, University of Texas at Austin; Patrick Ellis, Spire Global

Sharbel Kozhaya and Zaher M. Kassas, The Ohio State University

The ION would like to thank the PLANS Program Committee and all the members of the PLANS Executive Committee that made the organization and execution of the PLANS technical program possible.
Dr. Pau Closas, Track Chair; Dr. Zak Kassas, Program Chair; Dr. Gary McGraw, Executive Committee Chair; Dr. Robert Leishman, Track Chair; Dr. Christian Gentner, Track Chair; Dr. Michael Braasch, Track Chair, ION/IEEE Liaison, and IEEE AESS Board of Governors; and Dr. Sherman Lo, ION President. Not pictured: Dr. Jason Gross, Tutorial Chair; Dr. Kegen Yu, Publications Chair; and Jeff Martin, ION Meetings Chair.

Dr. Dorota Grejner-Brzezinska Recognized with the IEEE/ION PLANS Kershner Award

Dr. Dorota Grejner-Brezezinska was recognized for her numerous outstanding and sustained contributions advancing research in applications of GNSS and multi-sensor integrated systems for assured navigation that contributed to the advancement of GNSS algorithms and creation of its new applications.

The Kershner Award recognizes individuals who have made substantial contributions to the technology of navigation and position equipment, systems, or practices.

PLANS Manufacturers Advancing PNT

Renee Knight, *Inside GNSS*

During the Position, Location, and Navigation Symposium (PLANS) in Monterey, California, attendees not only had the chance to take in a variety of technical sessions, they also had the opportunity to learn from some of the manufacturers helping to advance the PNT industry.

Most IEEE/ION PLANS attendees wanted to talk about the hot industry topics, including spoofing, interference, simulation, and LEO, **Spirent Federal Systems** Senior Systems Engineer Phillip Bonilla said. Many were interested in the company's new all-in-one spoofing solution for the GS9000 GNSS Simulator to generate spoofing scenarios in SimGEN as well as its GNSS testing tools for LEO.

Spirent is partnering with LEO PNT providers like **Xona Space Systems,** he said, "to bring simulation and their signals into our portfolio." Xona's PULSAR service is set to become the first LEO PNT constellation to provide an advanced, independent service while augmenting existing GNSS.

Syntony is also putting a focus on LEO, and Gary Hannum, VP Sales USA, spent time talking with attendees about the company's recently announced partnership with Xona. Through the partnership, Xona Space Systems' LEO PNT constellation will be integrated into the company's GNSS simulators and receiver solutions.

Safran Sensing Technologies featured its tactical grade MEMS gyros and IMUs, as well as its simulation devices for testing receivers in a lab environment. Through a new partnership, **Orolia**, a Safran Electronics & Defense company, also has partnered with Xona to develop support for LEO constellation and navigation signals in its Skydel-powered simulation and testing products.

Exail, the brand that combines **iXblue and ECA Group,** mainly focused on motion simulation during the conference, Motion Simulators Product Line Manager Nicolas Bernard said. The company's two-axis positioning and rate tables, for example, draw a lot of interest from universities and can be expanded with the single axis options to create three-axis solutions for larger projects. **Ideal Aerosmith** also offers motion simulation solutions and an Inertial Test Lab, with the 1281 Single Axis Position and Rate Table System and the 1542C-12-TL Series Two Axis Positioning and Rate Table System among the offerings featured at the show.

CAST Navigation also showcased GNSS/INS simulation systems, including the CAST-INS, CAST-GPS, CAST-GNSS and CAST-Jammer.

Thales AVS France SAS highlighted

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its TopAxyz product line, including a recently launched high navigation grade MEMs accelerometer. The solution features added range for applications that require high accuracy in complex environments, including missile launches and civil aviation.

Inertial Labs showcased its tactical grade, ITAR-free IMUs, which contain three advanced MEMS gyroscopes and three high-performance accelerometers, and its Remote Sensing Payload Instrument (RESEPI). The RESEPI XT-32, launched last year, is a combined dual antenna GNSS-aided inertial navigation system, datalogger, lidar, camera and communications system that allows for real-time and post-processed generation of point cloud solutions. The next version is expected to be released in 2024, as is a new visual navigation solution that can be leveraged when GPS is denied, Product Manager William Dillingham said.

First time PLANs exhibitor **TDK** focused on three new products released earlier this year: the AXO301, a low-noise and high-resolution ±1 g accelerometer for high precision acceleration/deceleration measurements in railway applications and inclination control in industrial applications; AXO305, a ±5 g accelerometer designed for navigation, positioning and motion control of land and marine manned and unmanned systems; and the Tronics GYPRO 4300, a high stability and vibration-tolerant digital MEMS gyroscope for dynamic applications. All three products have a digital output and come in a single package, Product Marketing Manager Pierre Gazull said. “If you know how to integrate one, you know how to integrate the other,” he said. “This is unique in this industry, to have one package for both accelerometers and gyros.”

Silicon Sensing Sales Manager Greg Wilkinson talked with attendees about the company’s latest high-performance non-ITAR MEMS IMU, the DMU41, an upgrade of the DMU30. It’s 30% smaller, lighter weight, lower power and offers more capability than its predecessor. It is designed to aviation standards, so it can be certified for high-end aviation. It will open markets where size, weight and power are critical, such as unmanned vehicle navigation. Variant A will be available in a few weeks for testing and Variant B, which will have all the capabilities incorporated, will be out later this year.

SDI showcased various low-noise, high-performance industrial and navigation grade MEMS-based accelerometers, with MEMS accelerometers the company’s sole focus. While the technology is different from the traditional quartz-based versions, with less noise and more stability over time and temperature ranges, the solutions have the same shape so it’s easy to drop them in as a replacement or to try them out, Test and Support Engineer Pete Hulbert said.

Gladiator Technologies, Acutronic, VectorNav Technologies, FIBERPRO and **InertialWave** were among the other exhibitors showcasing advanced solutions, including motion simulators, IMUs and GNSS/INSS systems, in the exhibit hall.

Reprinted with permission: https://insidegnss.com/ieee-ion-plans-exhibitors-talk-advanced-solutions-hot-industry-topics/

Timing Requirements of 5G Networks

CIRI DHS has announced the funding of a research project at Critical Infrastructure Resilience Institute (CIRI) at the University of Illinois Urbana-Champaign to help mitigate the risk created by 5G's ever-increasing dependence on GPS. The goal is to boost resiliency by identifying alternative sources of timing information.

"5G almost exponentially expands the speed, capacity, reliability, and accessibility of all things wireless," explains Scott Sotebeer, who is the founder and CEO of USA Strategics and an investigator on the new CIRI project. "And in that expansion and growth, there is more dependency and therefore increasing vulnerability when everything revolves around GPS. Timing is the cornerstone. Reliable timing backup is critical going into the future."

The core problem is that there is not currently a backup timing system that's fully ready to step in on a national basis if GPS has a problem.

"Our whole constellation of 32 [GPS] satellites is roughly 12,500 miles out in space," says Sotebeer. "So the signal is very, very weak when it reaches Earth. There are a lot of opportunities for interruption and disruption, either manmade or natural." For example, a solar flare could disrupt GPS signals.

The CIRI project team will start by gathering and synthesizing information on the timing needs of 5G systems. They will then develop a timing strategy and a recommended testing and evaluation structure around the needs of carriers' systems, pointing out the plusses and minuses of different alternative sources of timing information. Such sources might include, for example, low-Earth-orbit (LEO) satellites, or any of various terrestrial systems.

Sotebeer says he is confident that the project will bear real-world fruit because of the notably high level of interest in it from both the private sector and government. He attributes the momentum to the sincere determination of DHS and CIRI staff to step up and "get the work done" to address the timing signal challenge to enhance the resilience of key critical infrastructure systems.

The project's Principal Investigator is Barbara Endicott-Popovsky, President of Endicott Consulting, Inc. Additionally, various distinguished engineers and research professionals from the Institute of Navigation's positioning, navigation, and timing (PNT) industry are serving on the project's Working Advisory Group, including Ed Powers of The Aerospace Corporation.

The following article was used/referenced heavily: https://ciri.illinois.edu/new-ciri-project-to-study-timing-requirements-of-5-g-networks

Courtesy of Colorado State University Walter Scott, Jr. College of Engineering

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initiative funded by the U.S. National Science Foundation. It articulates bold engineering research priorities to advance a future with fully sustainable transportation networks. It also aims to inspire researchers and funders (public, private, and nonprofit) to support and pursue these research priorities. The executive summary and full report can be found at https://www.ervacommunity.org/visioning-report/sustainable-transportation-networks.

As the world faces increasing energy and climate challenges, engineering research is well-positioned to address the science and technology needs for transportation modes, infrastructure, and networks – both physical and digital – in a way that is sustainable, fair, and equitable to all communities.

"One of the greatest challenges in creating a sustainable future is how we move people and goods," said Erin Santini Bell, professor and chair of the University of New Hampshire's Department of Civil and Environmental Engineering and co-chair of the ERVA Thematic Task Force that framed the visioning event. "This report offers a framework for the entire engineering research community to invest their resources and talent to address the problems surrounding transportation networks and their broader impact on society."

The report illuminates three approaches for future transportation research: leveraging data-informed operations to improve transportation systems; advancing sustainable technologies that incorporate versatile materials; and the overarching need to improve equity and accessibility through transportation device and service design.

Although electric vehicles are often the centerpiece of today's sustainable transportation discussions, developments in electrified transportation represent just one aspect of the overall challenge. ERVA convened a diverse array of experts, practitioners, and academics to identify engineering research priorities in four key areas: infrastructure, vehicles and transportation modes, data, and the community. The participants leveraged their combined expertise and identified 12 "big ideas" within these four topic areas to prioritize engineering research investment to advance progress toward more sustainable, equitable transportation systems.

"Transportation networks of the future will be safe, efficient, resilient, and sustainable, with more cooperative traffic patterns facilitated in part by GPS-increased accuracy," said Cathy Choi, chief sustainability officer and vice president of engineering at ClearFlame and a co-chair of the ERVA Thematic Task Force. "However, to address gaps and barriers, we must build trust in critical ways—not simply by having these systems be safe and efficient, but by considering the real-world usage and affordability needs of all users."

About ERVA:

ERVA is a neutral convener that helps define future engineering research directions. Funded by the National Science Foundation Directorate for Engineering, ERVA is a diverse, inclusive, and engaged partnership that enables an array of voices to impact national research priorities. The five-year initiative convenes, catalyzes, and enables the engineering community to identify nascent opportunities and

Courtesy of Clemson University International Center for Automotive Research (CU-ICAR)

12 "Big Ideas" for Sustainable Transportation Networks

Infrastructure

1. Develop sensors and data-informed algorithms to permit self-diagnosing, healing, and adaptive infrastructure that are affordable, scalable, and functional in all elements of transportation systems;
2. Investigate modeling to explore digital twins and how they can assist in increasingly complex planning, predicting in-service performance under extreme demand scenarios, and understanding of the interactions of transportation, climate, economic, and other systems; and
3. Conduct materials research to develop construction materials and methodologies to increase the sustainability, adaptability, and resiliency of transportation infrastructure components.

Vehicles and Transportation Modes

4. Build batteries, charging infrastructure, and power grids that are more efficient and affordable for all modes of electric vehicles;
5. Advance informatics, data science, and civil infrastructures to enable communication systems that aid in the transition from mobility assets (vehicle ownership) to a mobility services (shared rides/mass transit/micromobility) model;
6. Enhance all aspects of freight transport, including fuels, vehicles, infrastructure, and operations management; and
7. Improve sustainability of the air transportation system by:
   - learning more about condensation trails (contrails) and their environmental impact, and
   - enhancing navigation patterns and efficiency to minimize the carbon footprint of the system.

Data

8. Implement enhanced data modeling capable of recognizing and accounting for bias to create safe, robust, equitable, and accessible transportation systems;
9. Rethink and redesign how data is collected, managed, and shared across the engineering spectrum; and
10. Develop adaptive artificial intelligence systems that can account for both human decision-making and other external/contextual elements.

Our People and Community

11. Leverage expertise in mechanical, materials, computer, and electrical engineering, along with urban planning, to explore the concept of self-sustaining community microgrids that democratize accessibility; and
12. Design safe, sustainable transportation models that leverage and respond to the local needs and capacities of each community, with community feedback loops and research engagement.

priorities for engineering-led innovative, high-impact, cross-domain research that addresses national, global, and societal needs. Learn more at ERVAcommunity.org.

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Earth is elastic (at the time scales we are examining). Over periods of drought, the ground rises and we estimate the volume of water lost. Thus, GPS is recording solid Earth's elastic response to changes in surface mass load.

Scientists have, over the past 12 years, developed GPS capability to infer change in water, thereby advancing the study of the water cycle. A key element in the inference is distinguishing between different phenomena deforming solid Earth, thereby isolating Earth's elastic response to changes in mass. Most GPS sites in the western U.S. record primarily elastic response to change in mass. However, about 15% of sites record poroelastic response to change in groundwater, which is opposite in sense to an elastic response. As groundwater enters an aquifer, the pores between the silts, sands, and gravels comprising the aquifer expand, causing Earth's surface to rise. When groundwater is pumped from an aquifer, the aquifer contracts and Earth's surface subsides. Man pumping water out of the Central Valley since 1960 has caused the ground to subside several meters. The effect of known changes in surface water in artificial reservoirs and natural lakes is removed from the GPS displacements.

Scientists have developed rigorous algorithms that accept as input elastic displacements of GPS sites and produce as output change in total water at 1/4° intervals of latitude. Regularization is imposed so that water changes in adjacent pixels are not very different. In areas with a dense GPS array, change in water is determined with an accuracy of 0.1–0.2 m at a spatial resolution of 75 to 225 km. The resolution achieved with GPS is tighter than the 330 km spatial resolution achieved by the Gravity Recovery and Climate Experiment (GRACE).

Results

From December 28, 2022 to January 15, 2023, strong storms associated with atmospheric rivers dumped 48 km³ of rain and snow onto the Sierra Nevada

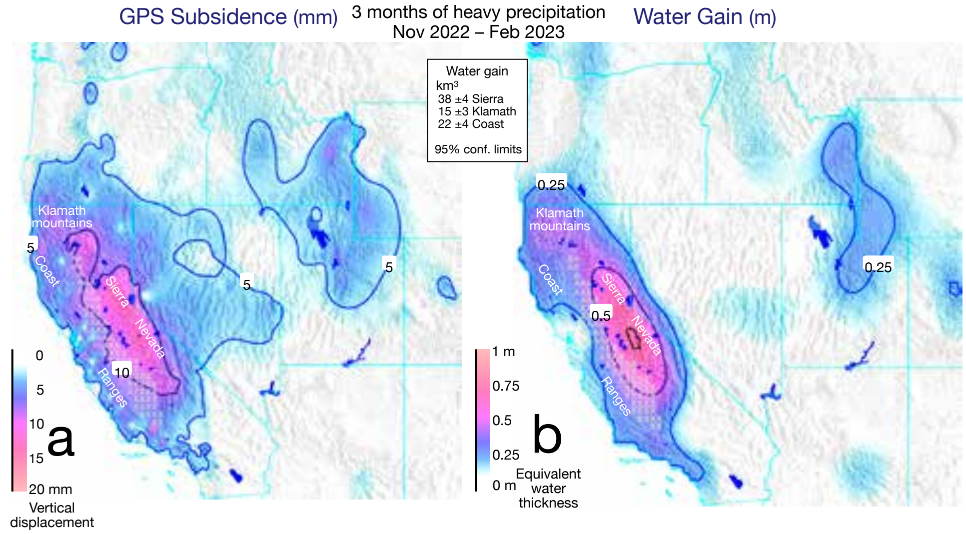


FIGURE 1 At left is subsidence (in mm) from November 2022 to February 2023 estimated from 871 GPS sites recording elastic response. At right is increase in water (in m) from November 2022 to February 2023 inferred from the subsidence at left. Given at center (in the box) is water gain (in km³) in the Sierra Nevada, Klamath mountains, and Coastal Ranges.

mountains in California, which is 0.71 m of water thickness averaged over the 68.1 km² area of the Sierra Nevada. Snowpack increased during the storms by a water equivalent of nearly half (22 km³, 0.32 m) the precipitation dumped. As the rain and snow fell, the GPS sites in the Sierra Nevada, California Coast Ranges, and Klamath mountains subsided 5–15 mm (Figure 1, left). From these elastic displacements, we infer the increase in total water (Figure 1, right) to be 38 km³ or 0.56 m in the Sierra Nevada, 15 km³ or 0.35 m in the Klamath mountains, and 22 km³ or 0.27 m in the Coast Ranges. We take change in subsurface water to be change in total water inferred from GPS minus snow water equivalent in the model: rain infiltrating the ground increased subsurface water in the Sierra Nevada by 26.5 km³ or 0.39 m. Most areas in the western U.S. did not subside during the atmospheric rivers in California, and we infer the water increase elsewhere to be small. An exception is that northern Utah subsided 5–8 mm, suggesting that the groundwater basin beneath the Great Salt Lake watershed was replenished.

We have estimated the change in total water as a function of location in the western U.S. each month from October 2005 to April 2023. In the Sierra Nevada, change in total water exhibits a strong seasonal oscillation having a peak-to-peak amplitude of 50 km³ with a maximum around April 1 (Figure 2, green curve). Rain and snow in the wet autumn and winter each year increase total water storage from October to March. Snow melts in the spring and water evaporates in the hot and dry summer, thus reducing total water from April to September.

GPS determination of water change is advancing hydrologic science. We are finding more water to be lost during periods of drought and gained during years of heavy precipitation than in land surface hydrology models (Figure 2, green curve). Because there is no snow on the ground in October, we quantify change in subsurface water by differencing total water volumes from October to October over a period of years. During the harsh drought from October 2011 to October 2015, 62 km³ of water was lost. During heavy precipitation from October 2015 to October 2019, 40 km³ of water was gained. This finding of sustained change in subsurface water is several times those (6 km³ and 3 km³) in land surface hydrology models. This finding highlights the importance of the role of groundwater; storage in the hydrology models consists of snow and soil moisture but excludes groundwater.

GPS is providing insight into the water cycle. Change in groundwater can be estimated to be total water inferred from GPS minus the sum of snow water equivalent and soil moisture. In the Sierra Nevada, rain and melting snow seep into the ground (Figure 2, violet segments of bottom curve) in the winter and spring

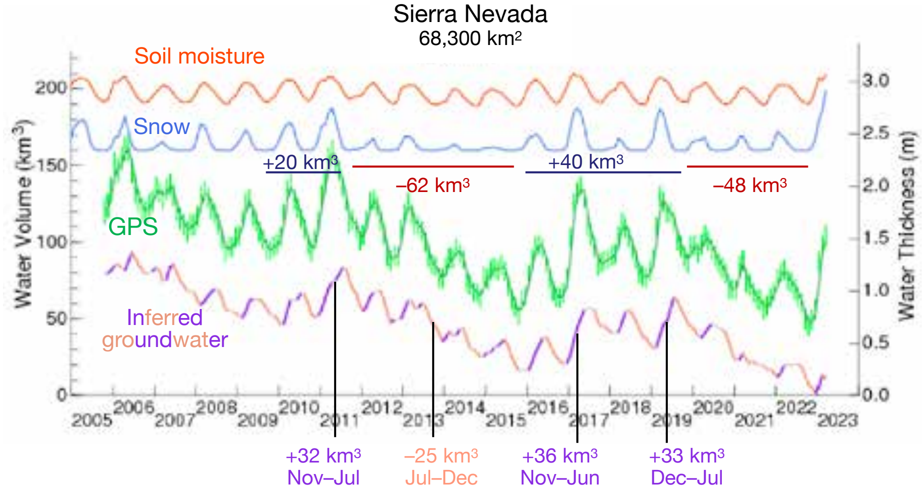


FIGURE 2 Change in water components in the Sierra Nevada as a function of time from October 2005 to April 2023. Left axis is volume change (in km³); the right axis is the average change in water (in m) in the Sierra Nevada. Change in water volume is plotted; the vertical position of the curves is nominal.
At top are snow water equivalent (blue) and soil moisture (orange) in hydrologic models. At center is change in total water (green, not counting artificial reservoir water). Because there is no snow on the ground in October, we quantify change in subsurface water by differencing total water volumes from October to October. During the harsh drought from October 2011 to October 2015, 62 km³ of water was lost. During heavy precipitation from October 2015 to October 2019, 40 km³ of water was gained.
At bottom is change in groundwater, which is change in total water inferred from GPS minus change in the sum of snow water equivalent and soil moisture. Rain and melting snow seep into the ground (violet segments) in the winter and spring of years of heavy precipitation. Water is parched from the ground (orange segments) in the summer and early autumn, in particular in years of drought.

of years of heavy precipitation, increasing groundwater by 34 km³ or 0.5 m. Water is parched from the ground (Figure 2, orange segments) in the summer and early autumn, particularly in years of drought, each year reducing groundwater by an average of 22 km³ or 0.3 m. In contrast, nearly all precipitation runs off into rivers in land surface hydrology models. Thus, the GPS data require there to be transfer of water to and from the groundwater basin.

GPS inference of mass change is revolutionizing the study of hydrology. The application is part of an emerging discipline, "hydrogeodesy" [White et al., 2022, https://doi.org/10.1029/2022WR032078]. Scientists are expanding this GPS capability to all regions in the world that have a medium to dense GPS array. In fact, we at the Jet Propulsion Laboratory are combining GPS positioning and GRACE gravity data to determine a global solution specifying mass change at 1-degree (110 km) spatial resolution.

Dr. Donald Argus is a research scientist in the Satellite Tracking and Applications Sections at the Jet Propulsion Laboratory, California Institute of Technology. He applies GPS to plate tectonics, earthquake strain accumulation, glacial isostatic adjustment, and water resources.

Marvin B. May

Modeling Oneself

If you are looking for direction in life, it's good to recognize the importance of modeling to figure out what you want and to make sure you're not going down a path that isn't right.

When I was eight years old, I began imitating Willie Mays, the great New York baseball centerfielder. It seemed to me Willie Mays was a good person to imitate, as we had similar names. We both loved baseball, and at the time, we were both from New York. I learned to catch baseballs using the breadbasket style, disregarding my coach's pleas. I started to talk like Willie Mays, disregarding my mother's exhortations. It didn't take me very long, however, to discover that I was slow afoot, had poor eye-hand coordination, and I was more suited to eating from a breadbasket than catching a baseball with one.

Several years later, continuing my quest to model myself after some great person, I chose the eminent physicist Albert Einstein (see Historian *ION Newsletter* articles of Fall 2004, Winter 2004-5, Spring 2005, Summer 2005). After all, we were both Ashkenazi Jews of German descent, both had unruly hair, and both had some difficulty with accepting the strict regimens imposed by secondary school teachers.

Again, it didn't take me very long to discover that those were about the only attributes that Einstein and I shared. However, in this case, I was serendipitously involved in navigation projects in my occupation as an electrical engineer that closely related (pun intended) to the broad body of Einstein's work. His 1907 principle of equivalence contributed to a clearer understanding of gravitational effects on inertial navigators. His special and general theories of relativity are crucial to achieving GPS accuracy. His 1917 paper "On the Quantum Theory of Radiation" provided the theoretical framework for the laser gyroscope, which was first demonstrated in 1963.

Stanford Telecommunications' Steel Signal Generator (SSG)

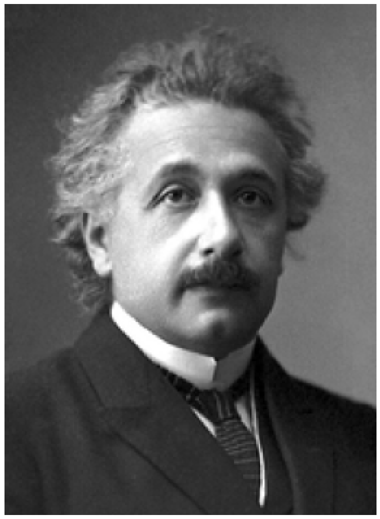
Perhaps my most rude awakening to the dream of following aspects of Albert Einstein was when I had an assignment to review (and modify) the algorithms in the first-generation GPS satellite signal generator (SSG) circa 1989 (see Historian Newsletter Article of Summer 2012). The purpose of the SSG was to test the newly developed and rapidly proliferating next generation of military GPS receivers under stationary laboratory-controlled conditions simulating dynamic applications aboard ground, at-sea, or aircraft platforms. The role of the SSG is to generate the continuous wave (CW) signals at the L1, L2 frequencies (there was no L5 frequency required at this time), modulated by the C/A, and P(Y) codes, as well as the message modulation as dictated by the control segment. The signals being generated by the SSG are to be representative and consistent with those that would be received by the dynamic receiver under test. Clearly, the SSG program, for all satellites in view, had to generate all the above signals as delayed by the range between the satellites and the user antenna, including the Doppler shift due to the relative range rates between the satellites and the receiver under test.

Somewhat less clear, but still tractable, was how propagation effects, such as tropospheric and ionospheric delays should be handled, particularly in those cases where the receiver under test included algorithms to address these compensations. Several of these environmental effects were frequency and code dependent: for example, the ionospheric compensation delays are inversely proportional to the frequency squared, and their corresponding code and carrier phase delays are opposite in sign. Although these effects added complexity to the SSG software algorithms, they were at least understandable and tractable.

Relativistic Effects in the SSG

But what really became muddled in this young electrical engineer's mind was how relativistic effects should be handled in the SSG. I learned that if two observers record the same event, or the time interval between two events, they will measure different lengths and times, if (1) they are moving with respect to each other, (2) one is higher or lower than another in a gravitational field, or (3) one is accelerating with respect to the other. Simplistically, according to special relativity, a moving clock appears to run slow with respect to a similar clock that is at rest. This effect is called "time dilation." In addition, a clock with a weaker gravitational potential appears to run fast in comparison to one that is in a stronger gravitational potential. GPS satellites revolve around the Earth with an inertial velocity of about 3.874 kilometers/second at a nominal altitude of 20,184 kilometers above the surface of the Earth.

Because of the velocity and special relativity, a satellite clock appears to run slow by 7-microseconds per day compared to a stationary clock on Earth. But because

Role Models:

left: Willie Mays 1952 (Bowman Gum baseball card)
Wikipedia

right: Einstein's official portrait after receiving the 1921 Nobel Prize in Physics
Wikipedia

of gravitation and general relativity, the satellite clock appears to run fast by 45-seconds per day. The net effect is that the satellite clock appears to run fast by 38-microseconds per day.

By the late 1970's it was believed, but not universally accepted, that these relativistic effects must be accounted for in the GPS system for it to achieve desired accuracies. It was not established how these compensations should be partitioned among the space, control, and user segments; nor was there a large body of empirical data to guide the early GPS architects.

Gedankenexperiment, (German: "thought experiment") term used by German-born physicist Albert Einstein to describe his unique approach of using conceptual rather than actual experiments in creating the theory of relativity. (Britannica.com)

SSG's and Gedankenexperiments

Throughout the process of examining SSG firmware and software, I stumbled across several issues that Einstein may have labeled "Gedankenexperiments" or thought experiments, but in my case maybe should be labeled "Geschtinken Experiments." Not the least of which was the overriding question: if the SSG was being used to test and certify GPS user equipment, who or how was the tester (the SSG) to be tested? Additional questions I had regarding relativity were:

(1) If the satellite clock's frequency shift accounted for a net 38-microseconds per day, should the SSG oscillator also be shifted? The answer to this should have been an obvious "no" – but remember my head was sometimes spinning in a different coordinate frame of mind.

(2) If the 38-microseconds/day accounted for satellite velocity and the Earth's nominal gravity in a circular orbit about a spherical Earth, what about relativistic effects of user velocity and gravitational effects beyond an assumed spherical Earth? I learned that the major effect of the Earth's non-spherical gravitation was accounted for by GPS architects with receiver algorithms that compensated for the Earth's oblateness. I also discovered that there was considerable disagreement in the GPS community as to the handling of relativistic effects due to high user velocities and higher (beyond oblateness) order gravitational spherical harmonics. How was I to resolve the relativistic simulator issues when notable navigation luminaries as Neil Ashby, Ronald Hatch, and Raymond DiEsposti couldn't agree on some of the fundamental factors? Credit should be given to the GPS pioneers who marched ahead with the constellation population despite some of the theoretical relativity issues still being disputed. It was apparent the GPS pioneers took a pragmatic ap-

continued on page 23

NEW!

A HISTORY OF INERTIAL NAVIGATION DEVELOPMENT

An intriguing and informative recorded history of inertial navigation development

Presented by Marvin May, ION Historian and author of the popular "Historian Column" in the *ION Newsletter*

View it now on ION's YouTube channel at @ionavigation

YouTube

Defense Matters

Train as You Fight

A Challenging Requirement for GPS

The DoD considers GPS interference testing on its U.S. test ranges to be important for warfighters to understand: how systems will function when confronted with interference; how to recognize interference when it is occurring; how to locate the source of interference; and how to develop tactics, techniques, and procedures to successfully complete a mission when GPS is no longer available.

Dealing with the challenges of locating the source of GPS interference, whether intentional or unintentional, is "in the news" as incidents of reported jamming have escalated over the last 15+ months.

Reports of interference in Europe were observed in March 2022 along the Finnish/Russian border. More recently there are a growing number of reports linked to the on-going Russian conflict in Ukraine.

Here in the U.S., noteworthy interference occurrences include those reported around the Denver Airport in January 2022, as well as the Dallas-Fort Worth International Airport experience of having a runway closed and having to reroute air traffic for nearly two days in October 2022.

Eurocontrol Activity On Testing

What is not so commonly available is information on how authorized agencies and organizations go about the process of gaining approval to intentionally radiate interference in the GPS (GNSS) bands within the Continental U.S. (CONUS) so that testing, training, and exercises in the presence of interference can be conducted.

As a representative non-U.S. example of such GNSS test procedures, in early March 2023, EUROCONTROL published a document titled EUROCONTROL Guidelines on a Process for Civil and Military GNSS Interference Testing, Edition No. 2. This document can be found on EUROCONTROL's web site at https://www.eurocontrol.int/publication/eurocontrol-guidelines-process-civil-military-gnss-interference-testing.

The Executive Summary of the guideline emphasizes: "This document describes a process on the planning, notification, and execution of GNSS interference testing activities, to minimise their impact on aviation."

It also states "This document may be applied by any state authorised entity performing GNSS interference tests, such as military, police or customs."

The guideline suggests that any state authorized entity performing GNSS interference test should include an INTERRUPTION procedure "… to halt immediately the GNSS interference testing when unforeseeable events occur, such as reported impacts on airspace users beyond the specified interference range causing hazardous situations."

As the guideline's source is EUROCONTROL, the process it describes is aviation focused and it notes that the "…impact of GNSS interference testing on other user segments (e.g., maritime, terrestrial) is not addressed in this document as they should be alerted through the GNSS users support services (the European GNSS Service Centre (GSC) for GALILEO users, the Navigation Center of the US Department of Homeland Security (NAVCEN) for GPS users…"

FAA's Role in Testing

Here in the U.S. the Federal Aviation Administration (FAA) has a coordination process that is reported to be contained in FAA JO Order 7610.4 Special Operations. A Google search for the document indicated that it contains Sensitive Unclassified Information (SUI) and is only available on a need-to-know basis to the military, government employees, contractors, and grantees.

The FAA's April 20, 2023, Aeronautical Information Manual, Official Guide to Basic Flight Information and ATC Procedures notes that "Recognizing that GPS interference and test events resulting in the loss of GPS services have become more common" the FAA continues to require operators "conducting IFR to retain a non-GPS navigational capability to either DME/DME, IRU, or VOR for enroute and terminal operations, and OR and ILS for final approach."

Although official statistical information regarding the number of DoD initiated interference tests requested, and ultimately approved, cannot be found with internet searches, it is intuitively obvious that the number of tests over the last few years has been rising significantly.

One available source of information on the number of test/training events indicated that in 2012 there were 41 approved tests, and by 2017 the number had grown to 128. As one might expect, the number fell off during the COVID pandemic, but it is now reported to be approaching 200 or more per year.

Doug Taggart
President
Overlook Systems Technologies, Inc.

DOD Processes

Within the DoD, the process to request and gain approval to conduct GPS interference testing is contained in a Chairman of the Joint Chiefs of Staff Manual. Per the Manual, USSTRATCOM must approve all requests for GPS L1 and/or L2 band interference testing prior to engaging in national level coordination via an interagency approval process. In that process, the DoD coordinates test/exercise times and locations with the FAA for interference affecting civil aviation traffic in the National Airspace System (NAS).

Once again, official statistics on how many events are entered into the interagency approval process but not approved are not openly available; nor is information about how long it takes to gain approval through that process.

In an attempt to generate a tally of how many approved events there have been in the NAS for a particular year, one might consider that any approved event would include an issued FAA NOTAM. In an attempt to gather up this data, the FAA's online NOTAM service, e.g., https://notams.aim.faa.gov/notamSearch/ seemed like a logical source. However, it turned out to not be convenient for requesting information on a focused search such as listing all GPS interference NOTAMs issued across the NAS for a particular period (a year).

Similar to the information in the EUROCONTROL guideline, all approved DoD CONUS interference tests include a mandatory CEASE BUZZER notification process for safety-of-flight or safety-of-life purposes. Activating the CEASE BUZZER immediately terminates interference transmissions on notification from the FAA's air traffic control system, based on real time civil pilot reporting of adverse interference effects.

Again, official information on how often a CEASE BUZZER is experienced isn't openly available, but when it does occur, it is safe to assume that months of planning as well as significant test range and military aviation test execution resources will have been lost. In addition, that does not even consider the impact to warfighter training and readiness and other program delays when tests and exercises must be rescheduled.

Civil and Military Cooperation Opportunities

Here, the EUROCONTROL guideline is interesting because it refers to interference testing for "Civil and Military" purposes. And now here in the U.S. the requirement for "civil" interference testing appears to be growing.

For example, Executive Order 13905 of February 12, 2020, Strengthening National Resilience Through Responsible Use of Positioning, Navigation, and Time Services assigns to the Department of Homeland Security the requirement "to develop a plan to test the vulnerability of critical infrastructure systems, networks,

continued on page 23

The Business of GNSS

Kevin Dennehy

The big story since our last column is ION member Xona Space Systems' announcement that its on-orbit position, navigation, and timing demonstration satellite mission, Huginn, successfully transmitted precision LEO PNT signals from space to ground. The satellite was launched one year ago as the first-ever, commercially funded LEO PNT mission.

Xona's PULSAR system will eventually consist of 260 LEO satellites orbiting the Earth 25 times closer than GPS satellites. Hexagon-NovAtel said it demonstrated their OEM7 GNSS receivers to track PULSAR signals, which are generated by a Spirent Communications simulator.

As part of the recent ION 2023 Joint Navigation Conference technical program, Spirent, Xona, and NovAtel shared initial test results. Other companies, including ION members Septentrio and Orolia, worked with Xona on developing experimental receivers compatible with the PULSAR signal, simulation and testing.

In other business news, ION members Qualcomm and Trimble demonstrated mobile meter-level positioning on Xiaomi handsets. Through Qualcomm's Meter-Level Positioning for Mobile, and Trimble's RTX correction services, the companies said the accuracy can improve mapping, driving and other applications.

CNH Industrial Buys Hemisphere GNSS

Construction and agriculture equipment giant CNH Industrial agreed to purchase ION member Hemisphere GNSS from China-based Unistrong for an estimated $175 million. The company said that Hemisphere, when combined with its Raven agriculture brand, will give it full control over precision and navigation technologies.

However, Hemisphere, with operations in the United States, Canada and Australia, will continue to operate as a standalone unit, the company said.

ION member u-blox was busy in the past three months as it partnered with Position Partners to expand coverage of its PointPerfect GNSS augmentation service to Victoria and New South Wales, including Melbourne and Sydney as an initial step to rolling out the service in Australia and New Zealand.

The u-blox NEO-F9P tailored for robotics and other markets.
u-blox

The company also launched two modules based on its F9 GNSS platform. The NEO-F9P supports navigation and automation of moving industrial machinery, while the ZED-F9P-15B provides customers in the mobile robotics market with an L1/L5 option in addition to the L1/L2 bands, the company said.

Trimble Rolls Out Drone Delivery Solution

Trimble rolled out its PX-1 RTX solution for positioning and heading of commercial drone delivery applications. PX-1 RTX allows drone integration companies to add positioning capabilities to allow operators to efficiently plan and execute takeoff, navigation, and landing, the company said.

ION member Topcon Positioning Systems and Fixposition have announced an agreement for Fixposition to provide Topcon correction services to Fixposition customers in North America and Europe. Topcon operates the Topnet Live network, one of the largest GNSS base-station networks in Europe and North America.

In other GNSS business news:

• ION member oneNav has announced the


Hexagon-NovAtel, Spirent, and Xona shared initial tracking signals test results at JNC
Xona

Trimble launches PX-1 RTX for drone delivery apps
Trimble

closing of a $17 million Series C funding round and launched its pureL5 Acquisition Receiver Core (pARC).

• At the Joint Navigation Conference, Safran's Orolia Defense & Security, announced that it will re-brand under a new name, Safran Federal Systems.

• Hexagon's Autonomy and Positioning division and Hitachi Zosen have announced an agreement to launch the TerraStar-X Enterprise correction service in Japan. Among other applications, TerraStar-X Enterprise will provide lane-level accuracy for automotive and consumer markets in the country, the company said.

• ION member BAE Systems unveiled NavGuide, a next-generation Assured-Positioning, Navigation and Timing (A-PNT) device featuring M-Code GPS technology. NavGuide is a replacement to the Defense Advanced GPS Receiver (DAGR).

Hexagon's Autonomy and Positioning division and Hitachi Zosen will launch the TerraStar-X Enterprise in Japan
Hexagon

• HERE Technologies has announced that Edzard Overbeek stepped down as the company's CEO. The company's board appointed Denise Doyle and Adeel Manzoor, the company's chief data officer and CFO, respectively, as interim co-CEOs during the transition phase to find a new boss.

Kevin Dennehy has been writing about GNSS for 30 years. He is editor of Location Business News, http://locationbusinessnews.substack.com. If your company has an idea for a business story contact kdennehy@locationbusinessnews.com.

ION's JOURNAL

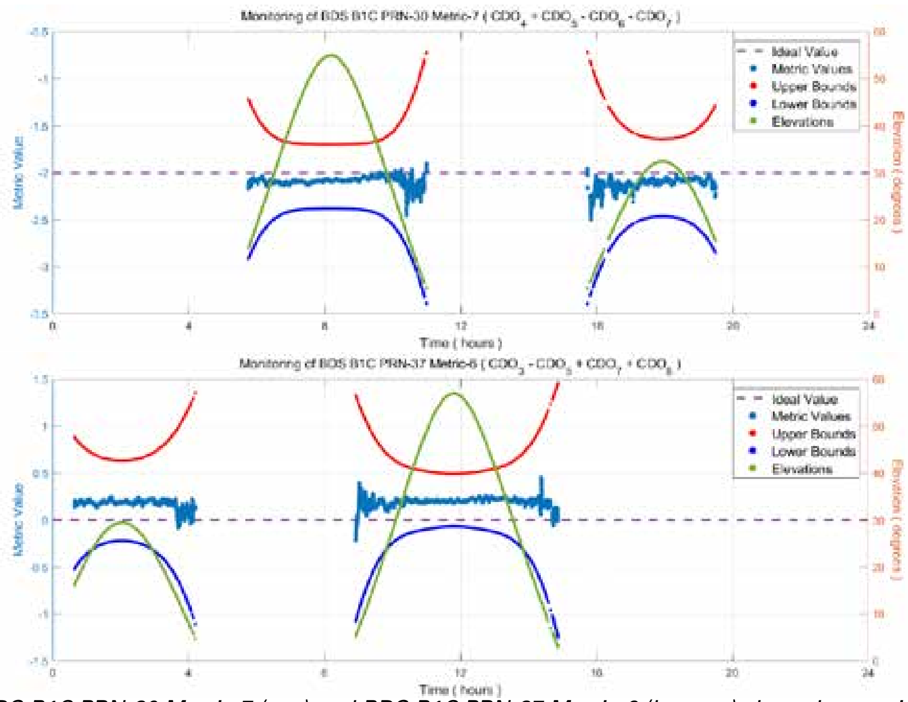
NAVIGATION Spotlight

navi.ion.org

Signal Quality Monitoring Based on Chip Domain Observables: Theory, Design, and Implementation

Xiang Wang

Since the GPS SVN-19 event in 1993, research on signal quality monitoring (SQM) has been carried out, and the corresponding monitoring, based on multi-correlator techniques, has been playing an important role in the integrity monitoring of SBAS. While in the context of dual-frequency multi-constellation (DFMC) in 2025 time-frame, SQM technology that is more sensitive in detection and less dependent on modulation is emerging, which is based on the chip domain observable (CDO). The traditional SQM focuses on the correlation function, treating the signal as a moving object. Thanks to the concept of CDO, abstractly, we are capable of changing our reference framework from the local static to the one accompanying the signal. Or specifically, we are virtually moving at light speed to gaze at the signal and thereby manage the samples like grapes on a vine.



BDS B1C PRN-30 Metric-7 (top) and BDS B1C PRN-37 Metric-6 (bottom) show the monitoring results of two PRNs of BDS B1C signal within the same 24 hours.

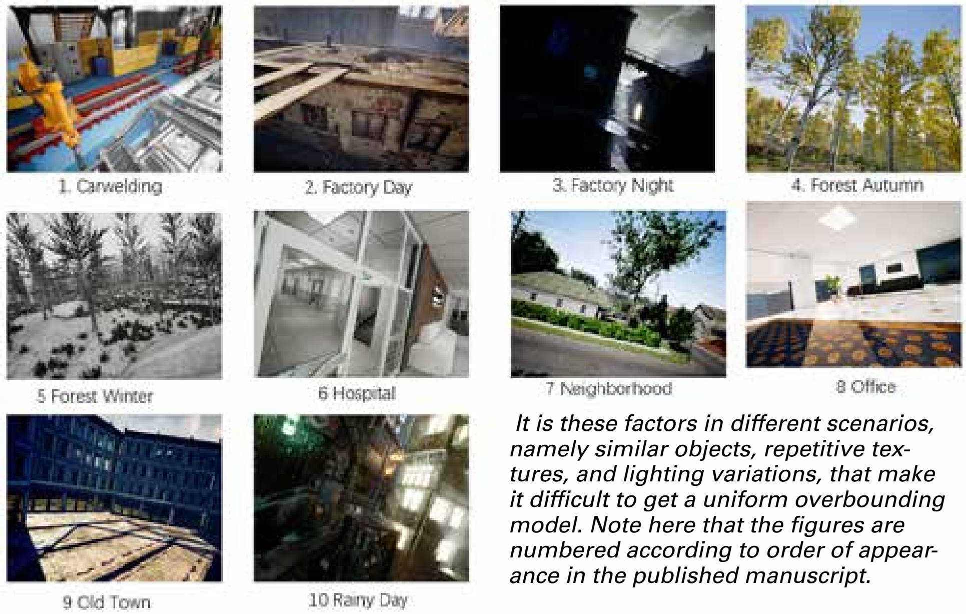
CDO-based SQM involves different influential factors than traditional SQM, of which the code-phase BIN length (BIN) and the sampling frequency (Fs), are the core and featured ones. In order to perform a systematic research, a methodology with factor-separation and object-orientation is required, which makes this research unique. In the methodology, all the ten influential factors are coagulated into the only one that is called the figure of metric (FoM), and massive simulations are performed as the key experiment of the methodology to produce contours of FoM values across the ranges of BIN and Fs. By examining and analyzing the FoM contours that represent the performances of a vast range of SQM configurations, the generally optimal configuration(s) might be found out, and hence an SQM baseline algorithm with optimal performance would be reached.

The THUEESDR, the software-defined-ratio (SDR) receiver developed by Tsinghua University Electrical Engineering Laboratory. By utilizing the THUEESDR, the developers deployed a CDO-based SQM algorithm toward dual-frequency signals of the four core constellations. Eight metrics are applied, and the optimal code-phase BIN length for BDS B1C/B2a combinations is 0.020 L1-chips or 0.20 L5-chips.

Research on SQM has always been based on simulations. Simulation is only the tool but not the root. In this study, a factor-separated and object-oriented methodology assisted with computer simulations is proved able to connect the laboratory theory to the real-world engineering implementation. In our laboratory in Tsinghua University, we have developed the technique of a chip-shape correlator with GPU-equipped software-defined-radio (SDR) receiver and achieved high definition measurements of correlation function and chip transition of DFMC signals in real time, enabling highly sensitive SQM and multipath mitigation technology (MMT) in either high-integrity or other applications.

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

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



It is these factors in different scenarios, namely similar objects, repetitive textures, and lighting variations, that make it difficult to get a uniform overbounding model. Note here that the figures are numbered according to order of appearance in the published manuscript.

Measurement Error Detection for Stereo Visual Odometry Integrity

Yuanwen Fu

Visual navigation is an indispensible alternative in GNSS, partially in an occluded or denied environment. This work features a two-tiered approach to detecting and removing visual measurement outliers that otherwise cannot be identified by state-of-the-art visual navigation pipelines. By rejecting these outliers, measurement residuals can now be safely bounded by mainstream overbounding methods to provide salient measurement probability distribution functions, thus removing one hurdle of initializing any integrity algorithm. Extensive evaluations have been conducted using an open-source data set. The results show that overbounding performance is improved in terms of tightness, computational efficiency, and most important of all, scenario tolerance (e.g., repetitive features, day and night, indoor and outdoor).

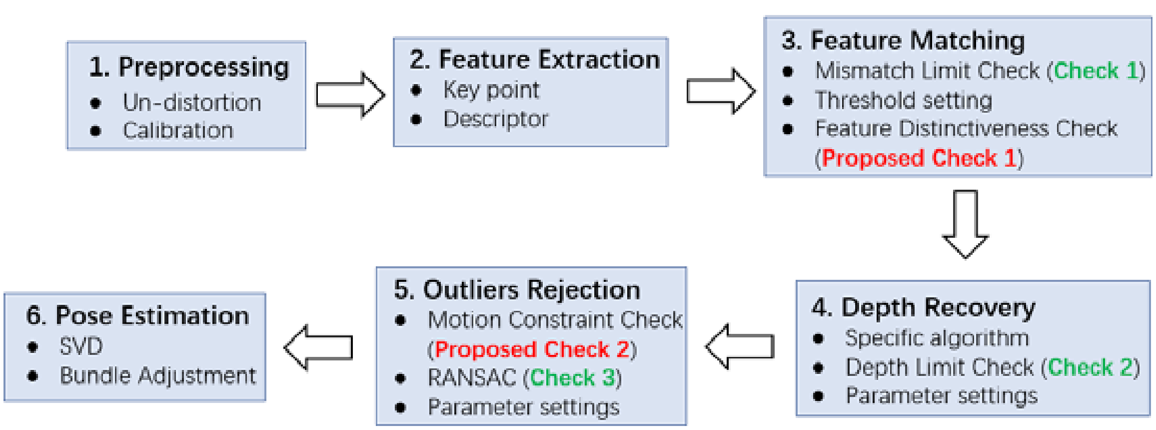
The two-tiered, or two-factor, approach consists of two checks. They can be easily inserted into any typical visual navigation pipeline without interrupting existing algorithmic modules, as shown in the figure below.

The work describes two proposed checks: the first is a feature distinctiveness check that tries to match the two descriptors recorded by two consecutive images and tag them as belonging to the same feature. However, there is a high probability that the conventional check wrongly matches two descriptors that, in fact, belong to different objects. Please see the paper for full details. The second proposed check is a motion constraint check to constrain the movement between two successive frames.

Through the feature distinctiveness check and motion constraint check proposed in this paper, an overbounding model suitable for multi-scenario operation can be obtained. This could be a good starting point for developing future integrity-monitoring algorithms for visual navigation and, in particular, stereo visual odometry.

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

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



The two proposed checks (red) vs existing checks (green) to detect/remove outliers in a typical visual odometry (VO) framework

Time Transfer from GPS for Designing a SmallSat-Based Lunar Navigation Satellite System

Grace Gao

A unique technology proposes the design of a smallsat-based lunar navigation satellite system (LNSS) with time-transfer from Earth GPS, wherein the lunar navigation satellites would listen to signals already broadcast by the terrestrial GPS satellites and process those signals to estimate onboard timing corrections.

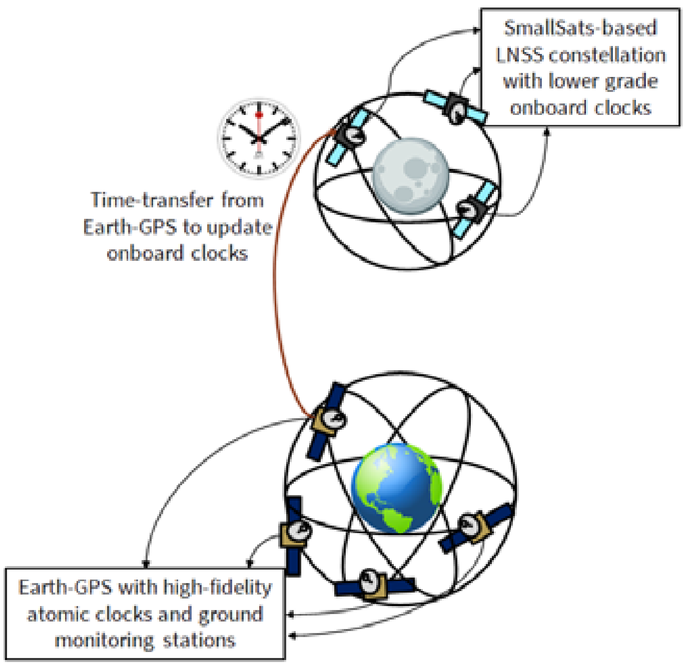
The proposed design alleviates requirements with regard to timing stability and, correspondingly, the size, weight, and power (SWaP) of the onboard clocks. By directly leveraging GPS signals (which are intermittently available when not occluded by Earth or the Moon), the need for additional ground infrastructure on the Moon to maintain LNSS services is eliminated.

Simulations of Lunar Navigation Satellite with a Chip Scale Atomic Clock

To test the theory, the designers performed high-fidelity simulations of a lunar navigation satellite with an onboard chip scale atomic clock (CSAC) for three cases of elliptical lunar frozen orbits (ELFOs). The lunar user equivalent range error (UERE) metric was quantitatively estimated, which characterizes the ranging accuracy of signals transmitted by a lunar navigation satellite. This demonstrated that a low lunar UERE value of <10 m, which is comparable in order of magnitude to that of Earth-GPS's UERE, can be achieved for all ELFOs, even with a lower-grade clock onboard (i.e., a CSAC). Through sensitivity analysis, a near-quadratic decrease in lunar UERE was demonstrated across all ELFOs as the broadcast ephemeris error of lunar satellites was reduced.

Current and Future Applications

The proposed work serves as a promising technique for maintaining precise timing onboard the future lunar PNT constellations, while abiding by the smallsat constraints and facilitating the lunar navigation satellites to function with clocks that are a thousand times cheaper than the atomic clocks on today's GPS satellites. This work further enables lunar navigation satellites to be smaller in size, perhaps as small as a shoe box, compared to terrestrial GPS satellites which are as large as a truck.



Additionally, this method can be utilized to provide insight on characterizing the use of Earth GPS signals in lunar navigation satellites that are equipped with low-SWaP clocks orbiting the Moon at different altitudes. Another use case of the proposed time-transfer-from Earth-GPS technique is to provide crucial insight for the PNT technologies utilized in various SWaP-constrained lunar missions being planned in this decade (e.g., NASA's LunaNet and the ESA's Moonlight).

On a broader scale, this methodology could be relevant to international space agencies and commercial space companies, particularly in the onboard PNT technologies of lunar satellites, which are an integral block in building a sustainable human presence on the Moon.

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

Bhamidipati, S., Mina, T., & Gao, G. (2022) Time transfer from GPS for designing a smallsat-based lunar navigation satellite system. *NAVIGATION,* 69(3). https://doi.org/10.33012/navi.535

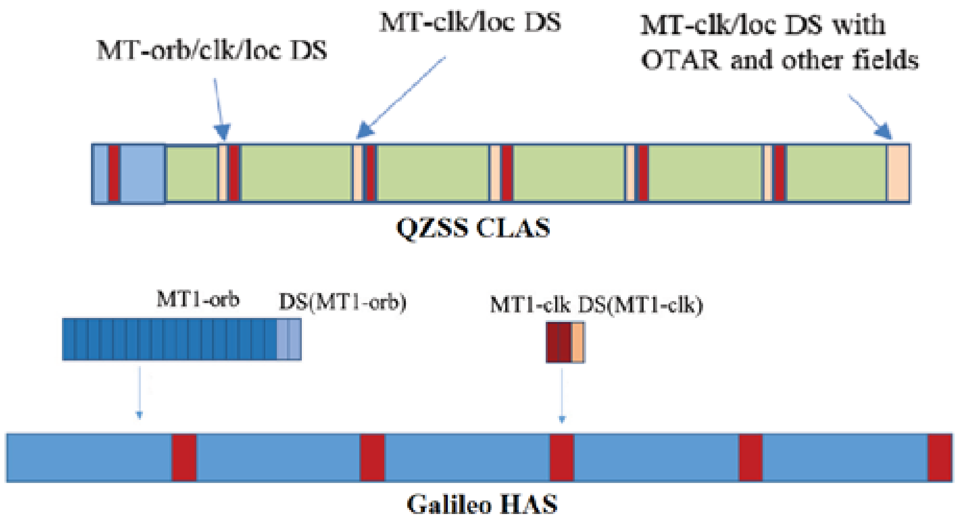
PPP-RTK Message Authentication

Ignacio Fernandez-Hernandez

Authentication of the broadcast GNSS ephemeris is maturing thanks mainly to Galileo OSNMA and GPS's CHIMERA. PPP/PPP-RTK services are also flourishing with QZSS CLAS and Galileo HAS, among others. However, not much has been said about the specifics of authenticating high accuracy data and the challenges this entails. This is particularly important for PPP/PPP-RTK data in a single message augmenting multiple constellations, as it may become a single point of failure if not authenticated.

In this paper, the authors propose and evaluate schemes for PPP/PPP-RTK message authentication that are compatible with existing satellite-based open PPP/PPP-RTK services. The schemes are implemented for Galileo HAS and QZSS CLAS but they can easily be extrapolated to other GNSS and services. This paper also analyzes post-quantum digital signatures and its adequacy for GNSS, particularly those pre-selected at the latest round of the NIST post-quantum cryptography standardization process.

Most authentication mechanisms proposed for GNSS are based on two schemes: standard digital signatures (DS) such as DSA or ECDSA, and delayed



disclosure (DD) protocols such as TESLA. In this work, both schemes are analyzed and compared under various simulated receiving conditions. This may be relevant for the PNT community, as it provides some first guidelines to designers of future PPP/PPP-RTK authentication features that may be implemented in the years to come and used by potentially millions of users.

The results show that degradation of the DS scheme is small, below two seconds in most conditions. DD degradation is also small, but under the condition that the receiver can use the clock corrections before they are authenticated.

Regarding post-quantum signatures, it is shown that Rainbow signatures can yield a performance close to ECDSA. However, it is premature to suggest a post-quantum signature at this stage, due to new attacks regularly discovered and variations in their security parameters. GNSS PPP/PPP-RTK providers might propose mixed schemes with both pre-quantum (ECDSA) and post-quantum (e.g., Rainbow) implementations as a risk-mitigation measure.

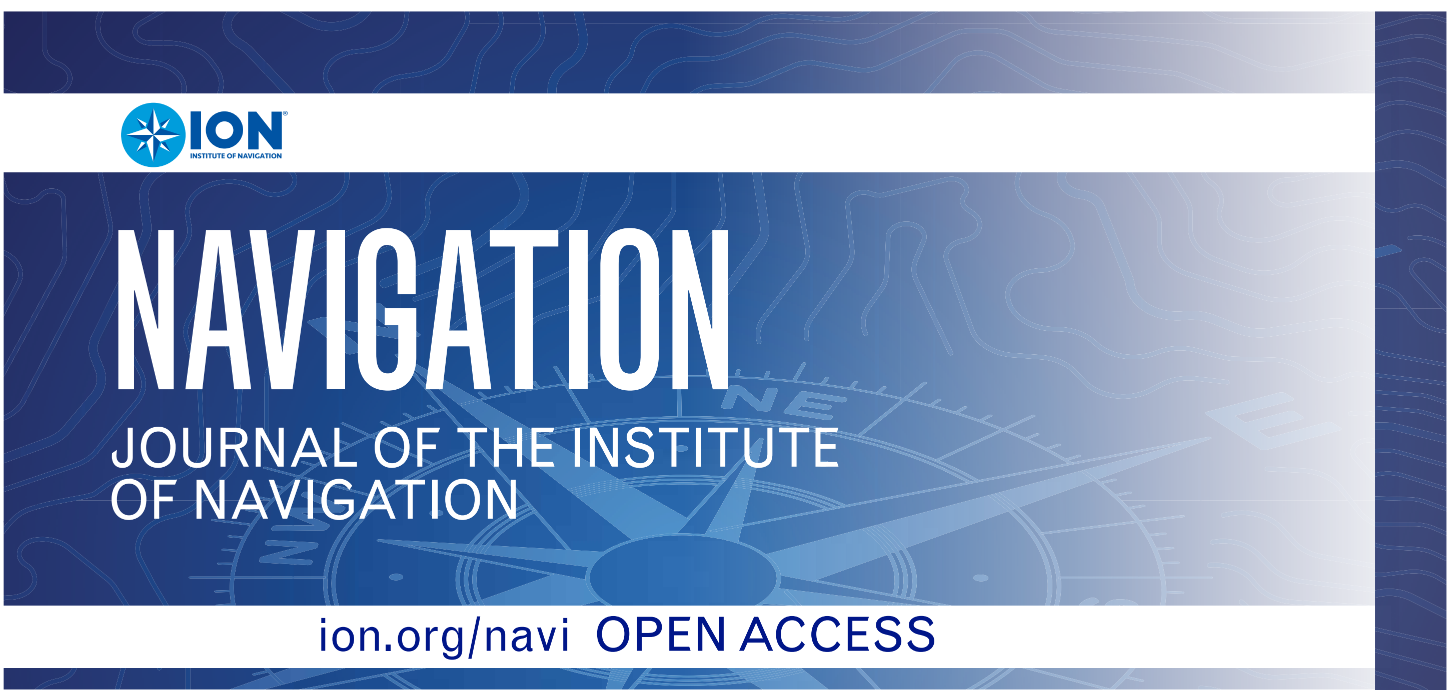
The schemes analyzed in this paper are a first proposal, but they are expected to serve as a basis for message authentication of PPP/PPP-RTK to be operational within a few years, at least for Galileo and QZSS.

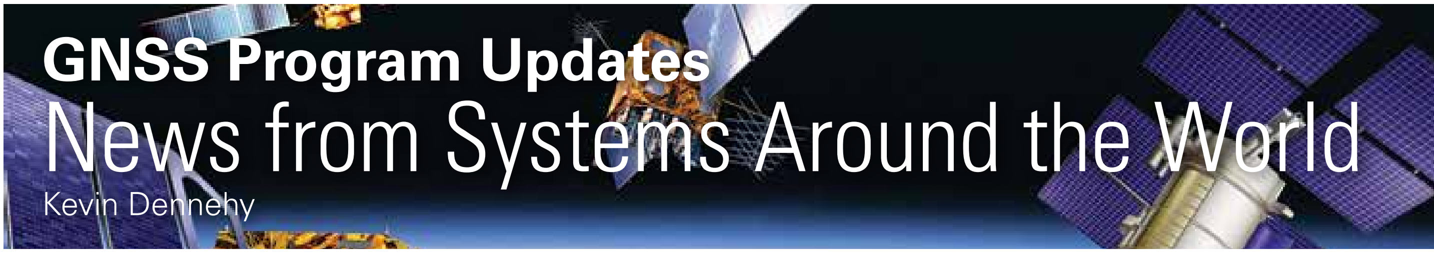
PPP/PPP-RTK message authentication is planned to be introduced in satellite-based open PPP/PPP-RTK services such as QZSS CLAS (PPP-RTK) and Galileo HAS (PPP). The application of PPP/PPP-RTK services includes road (autonomous driving), agriculture (farm machinery positioning), and drones.

Open PPP/PPP-RTK is now applied for safety-critical applications such as Automatic Driving Assistance Systems (ADAS). However, it is still vulnerable against spoofing attacks. The proposed message authentication schemes will raise the security bar for open PPP/PPP-RTK services.

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

Fernandez-Hernandez, I., Hirokawa, R., Rijmen, V., & Aikawa, Y. (2023). PPP/PPP-RTK message authentication. NAVIGATION, 70(2). https://doi.org/10.33012/navi.579





GNSS Program Updates
News from Systems Around the World

Kevin Dennehy

QZSS

In published reports, Japan announced plans to increase the number of its Quasi-Zenith Satellite System (QZSS) navigation satellites from four to 11. The announcement, made by the country's space policy committee, allows Japan to operate its QZSS without relying on the U.S.-based GPS, according to Nikkei Asia.

While no launch timetable was publicly revealed for the additional satellites, in a December 2022 space policy document, Japan called for a seven-satellite constellation to be launched in fiscal years 2023 to 2024, depending on the status of the H3 launch vehicle.

Japan's QZSS to expand to 11 satellites
National Space Policy SecretariatTrimble

Currently, the QZSS satellites are in geosynchronous orbit above Japan and Australia. In the previously announced seven-satellite configuration, the constellation will consist of one quasi-zenith satellite, a geostationary satellite and one quasi-geostationary satellite to increase the range where QZSS signals can be received.

In other QZSS news, the U.S. Space Systems Command completed the final delivery of the second U.S. Space Force-hosted payload to Japan. The two payloads were developed by MIT Lincoln Laboratory.

NavIC

India launched a satellite in late May to enhance its Indian Regional Navigation Satellite System, or NavIC. The satellite, dubbed NVS 01, was the first generation of upgraded regional navigation satellites that are interoperable with other GNSS.

India launched nine first-generation satellites from 2013 to 2018—with a smaller launch vehicle. NavIC currently has eight satellites—four in geostationary orbit (GEO) and four in inclined geosynchronous orbit (IGSO).

BeiDou

China launched its most recent BeiDou satellite in May onboard a Long March 3B carrier. The country has launched a total of 60 BeiDou satellites since 2000.

In 2020, the final satellite that completed BeiDou's third-generation network was launched at the Xichang launch port. According to published sources, there are currently 46 BeiDou satellites in operation.

Galileo

The European Space Agency (ESA) recently announced that the main procurement batch of Galileo Second Generation, or G2, satellites has been finalized. ESA said the system is ready for its on-orbit validation development operations.

There are 28 Galileo satellites in orbit, with 10 more scheduled to be launched—including G2 satellites with enhanced capabilities—in the next few years. ESA named ION members Thales Alenia Space, Airbus Defence and Space and Thales Six GTS as companies that will provide engineering support for the newest generation of satellites.

GPS

In a GPS modernization report, the Government Accountability Office (GAO) said that the U.S. Space Force needs to assess the number of GPS satellites necessary to meet operational needs. The report said that while the Space Force "seems well situated to achieve its approved requirement of keeping 24 M-code capable satellites in operation," the service's own analysis indicates that 27 satellites are necessary to meet real-world needs

While not on the list of formal recommendations, GAO took a shot at the delays to the GPS Next Generation Operational Control System (OCX) program. "While Space Force has not finalized a new schedule for the program, officials acknowledged that the expected delays reflect slower-than-expected progress, and there are still risks to the program. If testing reveals additional deficiencies or any other unexpected issues arise, the program may delay the delivery further because little margin remains in the proposed schedule," the report said.

Kevin Dennehy has been writing about GNSS for 30 years. He is editor of Location Business News, http://locationbusiness-news.substack.com.

Calendar of Upcoming Events

SEPTEMBER 2023

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

11-15: ION GNSS+ 2023, Hyatt Regency Denver at Colorado Convention Center, Denver, Colorado
Contact: ION
ion.org

JANUARY 2024

22-25: ION International Technical Meeting (ITM) & ION Precise Time and Time Interval (PTTI) Meeting 2024, Hyatt Regency Long Beach, Long Beach, California
Contact: ION
ion.org

MARCH 2024

20-22: Munich Satellite Navigation Summit 2024, Alte Kongresshalle, Munich, Germany
Contact: Munich Satellite Navigation Summit
https://www.munich-satellite-navigation-summit.org/

APRIL 2024

15-18: ION Pacific PNT, Hilton Waikiki Beach, Honolulu, Oahu, Hawaii
Contact: ION
ion.org

JUNE 2024

3-6: ION Joint Navigation Conference (JNC) 2024, Northern Kentucky Convention Center, Greater Cincinnati Ohio Area
Contact: ION
ion.org

SEPTEMBER 2024

16-20: ION GNSS+ 2024, Hilton Baltimore Inner Harbor, Baltimore, Maryland
Contact: ION
ion.org

OCTOBER 2024

28-31: International Association of Institutes of Navigation (IAIN) 18th World Congress, Beijing, China
Contact: IAIN
https://www.iainav.org

Defemse Matters
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and assets in the event of disruption and manipulation of PNT systems."

Additionally, at the most recent PNT Advisory Board meeting held on May 3, 2023, a Department of Transportation presentation titled DOT System-of-Systems Interference, Detection, and Mitigation referred to the Defense Innovation Unit's Harmonious Rook project involving the use the billions of distributed, networked GNSS devices as sensors to generate an accessible common operating picture to detect and locate GNSS disruptions.

Both initiatives support the need for further civil/military cooperation on interference testing planning and execution that may result in the sharing of approved test events that will benefit both national security objectives, e.g., 1) train the warfighter; and 2) strengthen national PNT resilience for civilian critical infrastructures such as transportation. One can only hope that the obvious benefits to both can be achieved.

Historian
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proach to relativistic issues; rather than waiting for the theoreticians to have a consensus on the formulations, they marched ahead based on the ultimate GPS position solutions being accurate.

(3) What about the effect of Earth's rotation during the approximate 40-milliseconds of signal transit time from the GPS satellite to the user equipment on or near the Earth's surface? I began to study this effect and pondered whether it was part of relativity. I learned that this effect was called the Sagnac effect. I furthermore learned that this phenomenon was named after Georges Sagnac (b. 1869-d.1928), a French physicist who was an ardent anti-relativist, perhaps as a concession to the rising tide of antisemitism in France. I pondered if the Sagnac effect was part of the Doppler effect, special, or general relativity and contemplated if and how the SSG should account for the Sagnac effect.

When my personal involvement with the SSG ended in 1994, I never was sure that relativistic and/or Sagnac effects were correctly implemented, and I was only sure that I would not be the one to prove or disprove their validity.

On a somewhat more positive note, I recently did find an outstanding person, who unlike Willie Mays or Albert Einstein, I could at least strive to emulate. He or she will be the subject of the next newsletter article.

The following references and links were used in the preparation of this article:

Ashby, N. (2004). The Sagnac effect in the global positioning system. In: Rizzi, G., Ruggiero, M.L. (eds) Relativity in Rotating Frames. Fundamental Theories of Physics, Vol 135. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-0528-8_3

DiEsposti, R., Fliegel, H., GPS and relativity: An engineering overview, Proceedings of the 28th Annual Precise Time and Time Interval Systems and Applications Meeting, December 3-5, 1996

Ashby, N., and M. Weiss, "Global positioning receivers and relativity," NIST Technical Note 1385, U. S. Government Printing Office, Washington, D.C., March (1999)

The Sagnac effect and its interpretation by Paul Langevin - ScienceDirect

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