Volume 34 No 2 **Spring 2024**

Quarterly Newsletter

ION®
INSTITUTE OF NAVIGATION

A HISTORY

# GNSS Software Defined Receiver Metadata Standard

Dr. Thomas Pany

*A recent paper published in the Spring issue of NAVIGATION: Journal of the Institute of Navigation outlines the work conducted by the global navigation satellite system (GNSS) software-defined radio (SDR) working group during the last decade, and summarizes the history of GNSS SDR development.*

Receiver development has always been an integral part of satellite navigation, ever since early studies were conducted for the U.S. Global Positioning System (GPS). The very first receivers were huge devices, enabling a correlation of received satellite signals with internally generated code and carrier replicas by a mixture of digital and analog electronics (Eissfeller & Won, 2017). Advances in semiconductor technology soon enabled signal processing on dedicated chips. This technology was complex to handle and was primarily located within the U.S. industry. Despite the success of GPS and its Russian counterpart globalnaya navigazionnaya sputnikovaya sistema (GLONASS), internal receiver technology was barely accessible to the broader research com-

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RESCUING THE NEXT GENERATION SPACE EXPLORERS

# GNSS and Other Technology for Lunar Search and Rescue

Kevin Dennehy

The same NASA search and rescue technologies that saved thousands of lives on Earth will be enhanced to safely return astronauts in future Moon and Mars missions. NASA's Search and Rescue (SAR) office is developing systems and incorporating GNSS to support Artemis Moon missions.

Going to the Moon, landing, and returning requires that search and rescue capabilities always be available. Because of distance and uncertainty, this means that a combination of GNSS and other geolocation technology must be available to find and rescue astronauts in very challenging environments, said Cody Kelly, NASA Search and Rescue Office's National Affairs Mission Manager, at the ION's International Technical Meeting in January.

"On the [International] Space Station, you are not more than a 90-minute rocket ride home. However, the Moon is three days away," he said. "Mars is 21-minutes away by any communication, and so it becomes even more vital that Mission Control on Earth can locate you throughout your mission duration."

Kelly, who heads all Human Spaceflight SAR operations activities and supports SpaceX, Boeing and Artemis/Orion missions, already provides dedicated search and rescue data for locating crew capsules and astronauts following landings from low Earth orbit (LEO).

When astronauts begin operating on the Moon, search and rescue will be extremely demanding because of the jagged terrain, Kelly said. "During the first Apollo landings, astronauts did not venture far from their landers in relatively gentle, sloping terrain. However, emerging technology plans feature a Winnebago-like rover that will traverse well beyond a landing area to include the massive region of the lunar South Pole," he said.

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**The Institute of Navigation**
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Manassas, Virginia 20109

PRESIDENT'S COLUMN | DR. SHERMAN LO

# ITM/PTTI a Resounding Success

ION hosted a combined 360 in-person participants, from 27 nations, for the ION's International Technical Meeting (ITM) and Precise Time and Time Interval (PTTI) Meeting, held January 22-25, 2024, in Long Beach, California. In addition to the 185 technical presentations, 21 organizations displayed their products and services in the exhibit hall. PTTI organized a full day of pre-conference tutorials on clocks, time, and quantum networks. The plenary session's keynote addresses were particularly interesting, and shared NASA's satellite-aided search and rescue for the Artemis program, and quantum-enhanced clock synchronization. Both of the ITM/PTTI keynotes are hosted on the ION's YouTube channel.

Many networking opportunities were made available during the week of ITM/PTTI, but near and dear to my heart are opportunities for student networking. Providing the opportunity for students to interact with each other, and with ION as a professional organization, helps ensure the future vitality of the organization by growing programs focused on the generation entering in the PNT community. Specifically, it ensures that students and young professionals are embraced by ION, experience a sense of community and welcoming therein, and find a place at ION for professional development, mentorship, and growth.

As part of ION's current student-focused initiative, the ITM program committee organized a student social event where students attending ITM could easily meet each other. Some fun and relaxed "getting to know you" games allowed participants to learn about each other's research, PNT interests, and goals for their week in Long Beach. Holding this event at the beginning of the week also ensured that everyone had the opportunity to make new friends from around the world. My thanks to the program committee for organizing the event, and to QuNav for their event sponsorship.

*ION President, Dr. Sherman Lo (second from left), pictured with students from Hong Kong Polytechnic University following the ITM/PTTI Student social event.*

*As part of the ITM/PTTI Student Social, students each deposited one of their shoes in the middle of the room. Later, each took a random shoe and went to find the shoe's owner as part of a "getting to know you" activity.*

*ITM/PTTI 2024 Program Committee: Dr. Josef Vojtech, PTTI Tutorials Chair; Dr. Daphna Enzer, PTTI Program Chair; Dr. Sherman Lo, ION President; Dr. Andrey Soloviev, ITM General Chair; and Dr. Sabrina Ugazio, ITM Program Chair*

*ITM/PTTI Student Social Event*

ION INSTITUTE OF NAVIGATION

**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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## ION Council Convened January

The ION Council met in person on January 22, 2024, with several members also joining virtually. Actions taken by the ION Executive Committee in the preceding months were reviewed. The most notable among these actions was that the ION Executive Committee had approved the declaration of October 23 (10.23) as International GNSS Day. Additionally, the ION's annual award winners were approved and ION's 2024 Fellows were inducted.

Additionally, during the Council meeting, the ION's fiscal year 2022-23 audited financial statements were approved and the Council approved a transfer from the ION's Operating Fund back to the ION's Reserve Fund. The Council approved the 2024-25 budget.

Minutes from the January Council meeting, with supporting information, are available for viewing at ion.org.

## Joint Navigation Conference Projected to be a Record Setter!

If the record number of abstracts, exhibit booth bookings, and early hotel reservations are any indication, the Military Division's 2024 Joint Navigation Conference (June 3-6, 2024, in the Greater Cincinnati area) is going to set records! The technical program has been expanded this year to six full tracks of technical presentations; and the SECRET session, returning on the last day, will host a series of carefully curated relevant and timely presentations (speakers and topics are by invitation only this year). Those of you planning to attend, I encourage you to get your clearance in early and make your hotel reservations now. This is an event that those of you in the U.S. DOD community will not want to miss!

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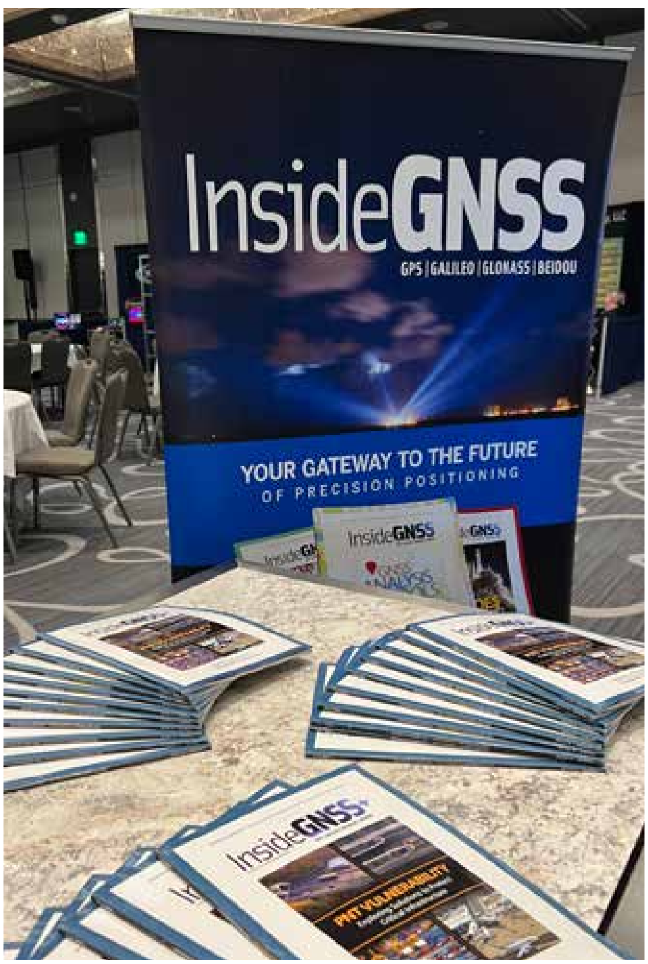



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# Congratulations ION 2023 Annual Award Recipients

**PER ENGE EARLY ACHIEVEMENT AWARD**

Given in memory of Prof. Per Enge, a brilliant engineer and teacher, who used his cheerfulness and enthusiasm to inspire others through education, advising, and mentorship. This award recognizes an individual early in their career who has made an outstanding achievement in the art and science of positioning, navigation, and timing.

## Dr. Tyler Gerald René Reid

For outstanding innovations in the development of low Earth orbiting satellites for providing an enhanced global positioning service

**SUPERIOR ACHIEVEMENT AWARD**

For outstanding accomplishments as a practicing navigator

## Captain Laura D. Norton

For leadership and professionalism while executing two short notice casualty evacuations; and developing international combat search and rescue training

**DR. SAMUEL M. BURKA AWARD**

To recognize outstanding achievement in the preparation of a paper advancing the art and science of positioning, navigation, and timing

## Dr. Daniele Borio

For his paper published in the Winter 2023 issue of *NAVIGATION: Journal of the Institute of Navigation:* "Bicomplex representation and processing of GNSS signals"

**PTTI DISTINGUISHED SERVICE AWARD**

To recognize outstanding contributions related to the management of precise time and time interval systems

## Francine M. Vannicola

For major contributions to GPS system time synchronization and GPS atomic frequency standard performance analysis; and for contributions to the success of the annual PTTI meetings

**CAPTAIN P.V.H. WEEMS AWARD**

For continuing contributions to the art and science of navigation

## Paul C. Manz

For outstanding contributions and exceptional technical leadership in the development and delivery of "resilient and survivable PNT" for assured precision weapons and munitions

**TYCHO BRAHE AWARD**

To recognize outstanding contributions to the science of space navigation, guidance and control

## Dr. Luke Winternitz

For outstanding development of receivers and filtering algorithms that enable GNSS cislunar navigation and pulsar-based deep-space navigation

**NORMAN P. HAYS AWARD**

In recognition of outstanding encouragement, inspiration, and support contributing to the advancement of navigation

## Chad E. Pinkelman

For enduring contributions to Global Positioning System (GPS)-based programs, including significant contributions to an open architecture for multi-sensor integration, delivering assured PNT capabilities

**COL. THOMAS L. THURLOW AWARD**

In recognition of outstanding contributions to the science of navigation

## Dr. Jiyun Lee

For significant contributions that guarantee the safety of satellite-based navigation systems for aviation

# ION's 2024 Fellows

The Fellows designation 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.


## Dr. Keith McDonald

For contributions to navigation warfare testing and PNT situational awareness; and for sustained thought leadership and management impact in military positioning, navigation, and timing

## Dr. Susan Skone

For sustained contributions to the advancement of geospace studies using GNSS and related subjects; and for her selfless services to the broader community

## Dr. Sanjeev Gunawardena

For contributions to the innovation, education, standardization, and proliferation of satnav software-defined receiver tools and technology

ION® INSTITUTE OF NAVIGATION

CALL FOR NOMINATIONS

# The Johannes Kepler Award

Nominations Due: June 30

Presentation of the Johannes Kepler award takes place at the Satellite Division's Annual ION GNSS+ in September. The purpose of the Kepler Award is to honor an individual for sustained and significant contributions to the development of satellite navigation. All members of the ION are eligible for nomination. A special nominating committee determines the winner of the award, which is presented only when deemed appropriate.

ION members are encouraged to submit nominations for deserving individuals. For complete nomination instructions/to submit a nomination, go to ion.org/awards, and click on "Kepler" in the left hand menu. Nominations must be received by June 30.

For a complete list of previous winners, visit ion.org/awards/kepleraward.cfm.

*Dr. Todd Humphreys, 2023 Kepler Award winner, for sustained contributions to the art and science of navigation signal processing; and for increasing the public awareness of the vulnerabilities of GNSS*

# The Confusing Tale of NITRO

Dana A. Goward

## An Uncomplicated Beginning

In many ways this should have been a fairly simple story.

In 2021 the National Guard recognized that it would have a difficult time operating in areas where GPS was either denied or, worse, being manipulated. The threat was real. They had seen it overseas, after all, and disruptions at home had also been observed. The Guard's Counterdrug Task Force had already had a mission fail, for example, when positioning, navigation, and timing (PNT) data from multiple sources did not match.

Adding to the imperative was a 2020 Presidential Executive Order to use additional and diversified PNT sources to avoid GPS being a single point of failure.

Of particular concern was timing. Not only is timing the basis for location determination, navigation applications, and common operating pictures, but it is also needed by land mobile radios and for the operation of almost every IT system.

Analyses showed that difficulties operating without GPS time and timing, and the proliferation of disparate alternatives to GPS, created 11 operational gaps for the Guard. So, like good soldiers, they set out to close those gaps and ensure their ability to serve the nation.

The solution was the Nationwide Integration of Timing Resilience for Operations (NITRO) project.

Executed under the Department of Defense's (DOD) Rapid Prototype and Fielding authority, NITRO is a federal-state partnership. The federal part is led by the National Guard Bureau in Washington, D.C., developing architecture and standards, ensuring coordination and connectivity, accessing authoritative sources of time, and ensuring the system is malware-free.

States are responsible for connecting to the system, distributing time to their first responders, and at their discretion to localities, critical infrastructure, and other applications or users governors think important.

Designed to be executed in several phases, NITRO receives multiple time signals from diverse sources and transmits an authenticated time message free from malware. When complete, the project is intended to:

- serve the landmass of all 54 U.S. states, territories, and the District of Columbia,
- provide immediate notification and geolocation of GPS anomalies anywhere in its service area,
- deliver time via broadcast, wireless, and fiber at <20ns relative to the National Institutes of Standards and Technology (NIST) UTC, and
- enable GPS-independent location and navigation applications.

As of this writing NITRO has been deployed to nine states/territories, serves 318+ organizations, and 37 million Americans.

NIST describes disruption of PNT information as a cyber problem. The DOD sees GPS disruptions through the varied lenses of navigation warfare, electromagnetic interference, and cyberspace/cybersecurity.

Over-dependence on GPS in the United States is so serious that a member of the National Security Council has called GPS "a single point of failure" for the nation.

Chronic GPS disruptions across the globe, along with revelations about China's cyber infiltration of infrastructure and applications within the U.S. should have alarm bells ringing at their loudest. China, America's "pacing threat" according to DOD, is in the final stages of construction of its high-precision, ground-based timing system to ensure it is not over-dependent on signals from space.

A fully implemented, perhaps an even more expanded, NITRO would seem to be the answer to a wealth of American vulnerabilities and needs.

Yet, despite broad recognition of our national vulnerability and need, there is a good chance the project will be terminated this year and the system dismantled.

## Whose Job is It?

How could this possibly be? – The reasons are many and varied, having little to do with the kind of straightforward analysis and practicality most Institute of Navigation members are accustomed to in their daily work.

According to congressional staff familiar with the issue, the proximate cause of NITRO's potential demise seems to be that authorities at the DOD have decided NITRO is a civil defense, not a national defense, project and therefore not appropriate for the DOD budget. This is despite NITRO protecting the American industrial complex, supply chains, and critical infrastructure that the DOD depends upon for its daily operations.

The same congressional staff observed that civil defense is a core mission for the National Guard and NITRO was funded in the DOD budget for two years without any problem. The question is, what has changed? Also, while funding for the National Guard flows through DOD, it is a relatively independent, mostly state-based entity operating under Title 32 of the U.S. Code. The remainder of DOD operates under Title 10. This has caused some in Congress to question whether the process should be changed so that Guard budgets are considered separately.

Regardless, if the project addresses a national need, especially one recognized by the National Security Council (NSC), identifying how it should be funded and led could be resolved fairly simply at the White House level. Another, more appropriate, organization or entity could be directed to fund and lead the project. Or it could remain with the National Guard and the DOD could be directed to include funding in its  budget.

Yet, in my experience, the NSC is frequently more of a forum for various federal departments and agencies to come together and reach a consensus, rather than a decision-making body. And even when consensus is achieved and decisions are made, they can be overridden or changed before actual progress emerges. In the PNT-world this happened in 2009, and again in 2015, when a consensus decision to build a terrestrial backup for GPS (endorsed by the deputy secretaries of Defense and Transportation) was negated by civil servants in the Executive Office of the President.

What this seems to have meant for NITRO is that either the departments were not able to reach a consensus, or a decision to proceed was again overruled by someone at the White House level. Considering the clear and present cyber and operational threats to the U.S., how either of these situations could be is anyone's guess.

Perhaps it is that, since the U.S. has not had a major GPS outage or cyber-related incident, there is little motivation to fix something that, to the uninformed, does not appear to be broken.

For those who do recognize the threats and vulnerabilities, it could be that there are just too many other seemingly more urgent demands upon their time and attention.

Alternatively, some retired senior leaders at the PNT Advisory Board have opined that for PNT "no one is in charge." The deputy secretaries of Defense and Transportation are responsible for making joint recommendations to the Executive Office of the President, but they have not met on PNT issues in almost ten years. And when they have made recommendations, many have gone unaddressed, and some have been overridden. Who, exactly, the recommendations have gone to and how and why they have been overridden is not at all clear.

Engineering and building PNT systems to protect the nation is difficult. Yet it involves linear, solvable problems that, with hard work and funding, can be overcome.

Policy and politics, though, involve peoples' ingrained beliefs, prejudices, and emotions. These are complex, non-linear problems that are more difficult to address. They are the biggest challenges to advancing complementary and backup PNT systems to protect the nation. They continue to place America at risk.

*Mr. Dana A. Goward is president of the Resilient Navigation and Timing Foundation and a member of the President's Space-based Positioning, Navigation, and Timing Advisory Board. In 2021 he received ION's Norman Hayes Award for inspirational leadership.*

MPLS, MN
AUTONOMOUS SNOWPLOW COMPETITION 2024

JANUARY 19–20, 2024
HOSTED BY DUNWOODY COLLEGE OF TECHNOLOGY

# ION Satellite Division and ION North Star Section Sponsors The Fourteenth Annual Autonomous Snowplow Competition

The Autonomous Snowplow Competition (ASC) is held annually and designed to challenge university and college students to design, build, and operate fully autonomous snowplows to remove snow from a designated path. This competition encourages participants to employ state-of-the-art navigation, guidance, and control technologies that can enable their machines to rapidly, accurately, and safely clear a path of snow.

This year's competition was hosted by Dunwoody College of Technology, January 19-20 in Minneapolis, Minnesota, with the support of the Institute of Navigation's Satellite Division and the Institute of Navigation's North Star Section. This was the second consecutive year that the competition was completely in-person and in its original format since the beginning of the COVID-19 pandemic, which forced much of the program online.

The overall competition followed a similar format to past years, with the preliminary design reviews taking place on a video-conference call in late 2023 and the in-person competition events beginning Friday morning, January 19. While volunteers worked to set up the snowplow fields and event venue, competitors and judges participated in vehicle safety inspections to ensure each snowplow was in good condition and ready to compete. On Friday evening, teams attended a welcome reception and presented their poster exhibits to judges and attendees. On Saturday, January 20, teams participated in two snowfield snow removal events. Awards were held Saturday evening to honor the winning teams.

### The Competitors

Nine teams from five different universities and one high school across the Midwestern United States registered to compete in the 2024 competition. Of those nine, eight were able to compete in the in-person events and put their vehicles to the test. Teams traveled to Minneapolis from North Dakota, South Dakota, and Iowa, along with teams from local universities in the Twin Cities area in order to participate in the events. The full list of 2024 competitors:

- Case Western Reserve University ("OTTO")
- Dunwoody College of Technology 1 ("Ice Hawk")
- Dunwoody College of Technology 2 ("Road Salt")
- Dunwoody College of Technology 3 ("Snow Devil")
- Iowa State University ("Snow Clone")
- Lake Area Technical College 1 ("Frostbite")
- Lake Area Technical College 2 ("Avalanche")
- North Dakota State University ("Hyflex")
- Saint Thomas Academy

As in past events, additional teams expressed interest but were unable to compete or attend due to logistical issues. This year,


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teams from Laval University, Canada, and the University of Stuttgart, Germany both attempted to join the 2024 events but needed to withdraw for multiple reasons. Both teams have stated that they hope to return for the next competition year.

### The Technical Competition

On Friday, January 19, all eight teams attending participated in vehicle safety inspections and final qualification reviews to ensure that each snowplow met the required safety standards and was ready for competition the following day.

Used for the first time at last year's ASC in 2023, the T-shaped snowfield course was again utilized in the 2024 events. This field is notably complex for vehicles to navigate, which allows for better simulation of real-world conditions where the snowplows may be used. The T-shaped field was designed to replicate a driveway leading to a sidewalk and requires vehicles to make an immediate turn after leaving the garage and rotate or reverse at the end of the course to plow toward the other end. This challenging field also demands that teams exercise precise navigation and coordination, the overall theme for the 2024 competition.

Similar to last year, each team was given two 20-minute opportunities to plow this snowfield, once in the morning and again in the afternoon on Saturday, January 20. For each team, final results were calculated with the best score they earned out of the two plow attempts.

Scores for plow attempts were calculated based on many factors. Teams were judged based on the amount of snow their plows were able to remove from the T-shaped field. Points were deducted if a vehicle did not autonomously return to the designated garage area, if the team requested to restart the round, and if the vehicle went past designated field boundaries. Participants were also able to earn extra points for timely completion if their vehicle was able to plow fifty percent or more of the course.

Like past years, two stationary posts were present on the snowfield for each attempt. These posts simulated signposts and trees that a snowplow may encounter in real-world applications and allowed judges to evaluate the obstacle detection and avoidance strategies of each vehicle. The locations of the posts within the snowfield were randomized and decided by ASC staff on the day of the competition, to ensure each vehicle was able to detect them entirely autonomously.

The event was live-streamed to YouTube with real-time commentary to allow family, friends, and fans to watch the competition from a distance (and stay warmer). Adam Robinson kept viewers engaged again this year with his upbeat banter, knowledgeable comments, and sense of humor to make the competition even more fun and interesting. Many sponsors attended the event in person for the purpose of meeting and recruiting the excellent students who participated and demonstrated their engineering talents.

An unusual detail for this year's competition involved a complete lack of snow in the Twin Cities, almost unheard of during a Minnesota winter. Pressure hoses were running continuously for days in advance of the events, making snow from thousands of gallons of water. This man-made snow was still adequate for the vehicles to plow, due to the determination and efforts of Dunwoody personnel. It was also bitterly cold on the weekend of the competition, with a high temperature on Saturday of just 6°F, but fortunately, only a light wind.

### Vehicle Designs in 2024

The 2024 ASC featured vehicles with diverse state-of-the-art navigation technology. Like past years, many vehicles utilized compact designs with significant mass in order to remove the snow, a feature that would be sought after in future commercial plows. Some vehicles also demonstrated significant improvements in battery life, such as North Dakota State University's Hyflex, which can operate for 32 continuous hours before need-

## 2024 ASC Competitors

| University/Affiliation | Snowplow Vehicle Name |
| --- | --- |
| Case Western Reserve University | OTTO |
| Dunwoody College of Technology 1 | Ice Hawk |
| Dunwoody College of Technology 2 | Road Salt |
| Dunwoody College of Technology 3 | Snow Devil |
| Iowa State University | Snow Clone |
| Lake Area Technical College 1 | Frostbite |
| Lake Area Technical College 2 | Avalanche |
| North Dakota State University | Hyflex |
| Saint Thomas Academy | n/a |


ing another charge.

Dunwoody College of Technology's Snow Devil utilized a magnetic strip track placed around the field in order to navigate the course, detected by a sensor arm on the plow. Dunwoody's Road Salt vehicle also featured this technology as an alternative strategy for use in low-visibility conditions, but relied primarily on machine vision and retro reflective sensors for obstacle detection. Machine vision systems were also utilized by Dunwoody College of Technology's Ice Hawk, and Lake Area Technology's Frostbite and Avalanche. Unfortunately, the sunny conditions during the competition caused some interference and shadows for plows relying on machine vision. Iowa State's Snow Clone navigated the course with LIDAR sensor technology.

### Results and Awards

The Awards Ceremony took place following the snow removal events on Saturday evening, January 20. Teams were scored on a combination of the Preliminary Design Reviews (5%), Final Student Poster Presentation (10%), and performance in the Single T-shaped Snow Path Competition (85%). Separately, teams were also evaluated on their sportspersonship throughout the event.

Dunwoody College of Technology's Ice Hawk received First Place with the highest overall score and highest Single-T field score. Dunwoody College of Technology's Road Salt came in second. The highest Preliminary Design Review score and the highest Poster Presentation score went to Case Western Reserve's OTTO.

The First Place winner received a cash prize of $3,000 with Second and Third Place winners receiving $2,500 and $2,000, respectively. The Fourth and Fifth Place winners also received cash prizes. The overall standings for 2024 are as follows:

| | |
| --- | --- |
| 1st Dunwoody College 1: Ice Hawk | $3,000.00 + First Place Award |
| 2nd Dunwoody College 2: Road Salt | $2,500.00 + Second Place Award |
| 3rd NDSU: Hyflex | $2,000.00 + Third Place Award |
| 4th Iowa State: Snow Clone | $1,500.00 + Fourth Place |
| 5th Dunwoody College 3: Snow Devil | $1,000.00 + Fifth Place |
| 6th Case Western Reserve: OTTO | Sixth Place |
| 7th Lake Area Tech 2: Avalanche | Seventh Place |
| 8th Lake Area Tech 1: Frostbite | Eighth Place |
| 9th Saint Thomas Academy | Ninth Place |

The Golden Shovel Award for the best student Poster Presentation was given to Case Western Reserve University's OTTO along with a $500 cash prize.

The Dr. Nattu Golden Smile Award, named after the late advisor to the University of Michigan-Dearborn robotics team, goes to the team exhibiting the best sportspersonship and spirit in the competition. This award was given to North Dakota State University's Hyflex team along with a $500 prize.

First place in the Single T-Snowfield category was awarded to Dunwoody College of Technology's Ice Hawk snowplow. Second place was awarded to Dunwoody College of Technology's Road Salt snowplow. Third place was awarded to North Dakota State University's Hyflex snowplow. Trophies were presented to teams in the top five places in the Single-T Snowfield event.

For more information, please visit www.autosnowplow.com



## GNSS Software Defined Receiver Metadata Standard

*continued from page 1*

munity for a long time, as it seemed to be impossible to realize global navigation satellite system (GNSS) signal processing on low-cost computers. Even in 1996, a key receiver design pioneer expressed skepticism that general-purpose microprocessors were, or would ever be, a suitable platform for implementing a GNSS receiver (Kaplan, 1996).

The situation radically changed when the algorithms of a GPS receiver were first implemented as MATLAB software on a desktop personal computer (PC) and estimates of digital signal processor (DSP) resources required to run the algorithms in real time were encouraging (Akos & Braasch, 1996; Akos, 1997). Soon after, real-time processing was demonstrated, even on conventional PCs, and the widespread use of software radio technology took off with exponential growth. Interestingly, software radio technology did not replace existing hardware receivers usually realized as one or more application-specific integrated circuits (ASICs), but complemented these receivers, allowing researchers to easily implement and test new algorithms or to develop highly specialized receivers with reasonable effort. Today, this is a well-established approach for military, scientific, and even commercial applications, as described by Curran et al. (2018).

As different research groups developed their own software radios, they used different data collection systems to sample GNSS signals. Whereas the data format of digital GNSS signal streams is comparably easy to describe, the widespread use of software radio technology made it necessary to introduce a certain level of standardization, which was finally achieved by a group of researchers, as documented by Gunawardena et al. (2021). The result was the so-called Institute of Navigation (ION) software-defined radio (SDR) Standard (ION SDR Working Group, 2020).

As technology evolved further, new GNSS software radios emerged, and some deficiencies of the ION SDR Standard became apparent (Clements et al., 2021). These conditions prompted the NAVIGATION paper, whose contributions are four-fold. First, it presents the first history of GNSS SDR development (Section 2). Second, it offers a detailed description of select GNSS SDRs (Section 3). Third, it overviews recent front-end developments (Section 4). Finally, it summarizes the history of the ION SDR Standard and proposes an update thereto (Section 5).

For the full paper copy of the ION GNSS Software Defined Received Metadata Standard see:

Pany, T., Akos, D., Arribas, J., Bhuiyan, M. Z. H., Closas, P., Dovis, F., Fernandez-Hernandez, I., Fernández-Prades, C., Gunawardena, S., Humphreys, T., Kassas, Z., López-Salcedo, J. A., Nicola, M., Psiaki, M. L., Rügamer, A., Song, Y-J., & Won, J-H. (2024). GNSS software-defined radio: History, current developments, and standardization efforts. *NAVIGATION,* 71(1). https://doi.org/10.33012/navi.628

*continued from page 1*

Kelly said NASA is in the process of assessing all technologies and processes to ensure that astronauts won't have to rely on Earth-based solutions to figure out technical problems such as where they are during hazardous operations. "What happens if an astronaut breaks a leg in a crater? These craters are enormous—and very dangerous—some of the largest on the Moon," he said. "We have to create the conditions that enable an astronaut to seek help, transit resources to a scene, and provide life support systems to someone in distress until they can be recovered."

Kelly said that NASA is developing techniques to use LunaNet navigation data to provide distress location services for both crewed and robotic missions on the Moon's surface. "Of course, there is no infrastructure on the Moon yet. Therefore, we are working with private commercial and intergovernmental partners to develop LunaNet, a new Lunar-based communications and navigation system" he said. "This includes research and development on geolocation that is not dependent on Earth-based positioning, navigation, and timing services."

## NASA's Search and Rescue Evolved with GNSS

For nearly 42 years, NASA's SAR office has assisted the international Cospas-Sarsat Program to develop search and rescue technologies. GPS and GNSS technology aided in saving more than 50,000 hikers, boaters, pilots, and others during that time.

"We've worked to put GNSS receivers into [our rescue systems] since the early 2000s. Now they've become smaller and more capable," Kelly said. "We've increased survival rates for pilots that use [Emergency Locator Transmitters] in small aircraft. We worked with the Federal Aviation Administration and the National Transportation Safety Board to ensure the person who buys a Cessna has the proper systems in place."

One of the big search and rescue devices, for both Earth and potential future space rescue capabilities, is the 406 MHz frequency beacon. GPS signals are relayed to the Cospas-Sarsat network to alert first responders to initiate a rescue.


*NASA's search and rescue technologies enable hundreds of lives to be saved in 2022.*
NASA

The personal locator beacons helped in 51 rescues in 2023, NASA said. About 255 rescues came from emergency positions indicating a radio beacon at sea, and 44 for emergency locator transmitters in the air, according to the National Oceanic and Atmospheric Administration (NOAA).

"NOAA runs the day-to-day operations at various ground stations. It's a global effort as 42 countries work together to ensure standards are interoperable," Kelly said. "That means if someone in Sierra Leone needs to be rescued, elements have to be in place for local SAR forces to find them."

For Moon exploration, the evolution of GNSS has been evolving into robust interoperability with other similar systems, Kelly said. "How we use the GPS beacons continues to evolve. We are now using two-way communications spearheaded by the European Union with the Galileo system," he said.

## Timing Plays a Big SAR Role

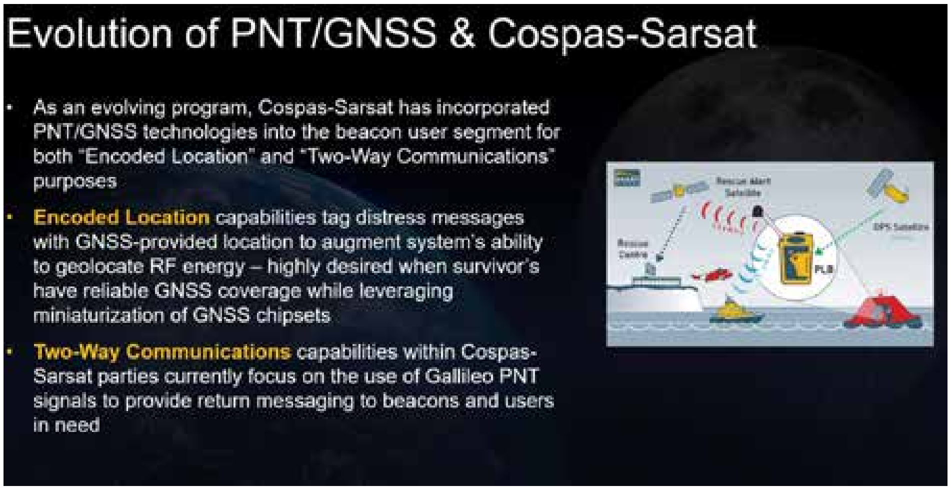
In terms of precision time and timing for the Cospas-Sarsat space segment, Kelly said that while search and rescue capabilities will operate in all orbital regimes, each plays a different role. In LEO, the space segment uses onboard time knowledge for the search and rescue receiver, or SARR. SAR receiver processing, or SARP, takes the 406 MHz frequency and stores and forwards it to ground stations in view.

*Cody Kelly holding search and rescue beacons.*
NASA

"It all requires precise timing. We don't have a rubidium clock sitting on the surface of the moon—what we utilize, the [astronauts] have to put on their backs," Kelly said. "Some really smart guys designed these systems back in the 1980s and we are putting to use some of their lessons to save many lives. The big element to this is the miniaturization of time and frequency oscillators."

In mid-Earth orbit, the space segment uses timing to timestamp received signals in view through the "bent pipe" concept of operation, while ground processing for Time Delay of Arrival and Frequency Delay of Arrival geolocation occurs. In geostationary orbit, satellites operate in a bent-pipe relay role to pass GNSS-encoded locations to ground stations, NASA said.

NASA's SAR office's time and timing research areas include chip-scale atomic




*NASA's search rescue technologies have evolved with GNSS.*
NASA

clock frequency references for user handsets; single-sensor geolocation algorithm development; emerging Kalman filtering techniques; and novel modulation schema and message compression to allow for higher data rates in space.

### Current Testing and Lunar SAR's Future

Just getting to the Moon is a challenge for search and rescue personnel, as Artemis launches use a nearly due-east trajectory from the launch at Kennedy Space Center, Kelly said. These challenges include covering a vast area of the Atlantic Ocean for the first seven to nine minutes of flight.

Physical effects of spaceflight on astronauts produce unique rescue scenarios that require specialized training for SAR forces when astronauts return from space. "We don't want the astronauts to be bobbing up and down for any lengthy period of time in a rough ocean. They've ridden a roller-coaster for 14 days and we want to minimize the time needed for location, rescue, and recovery," Kelly said.

Last summer, the SAR office tested Advanced Next-Generation Emergency Locators (ANGEL) on astronaut's life preservers, and installed location beacons on the Orion space capsule—to test out in real-world conditions off the California coast. The ANGEL beacon, which is a palm-sized device, allows NASA to locate astronauts very quickly in the event of a launch abort or landing outside the specified splashdown area.

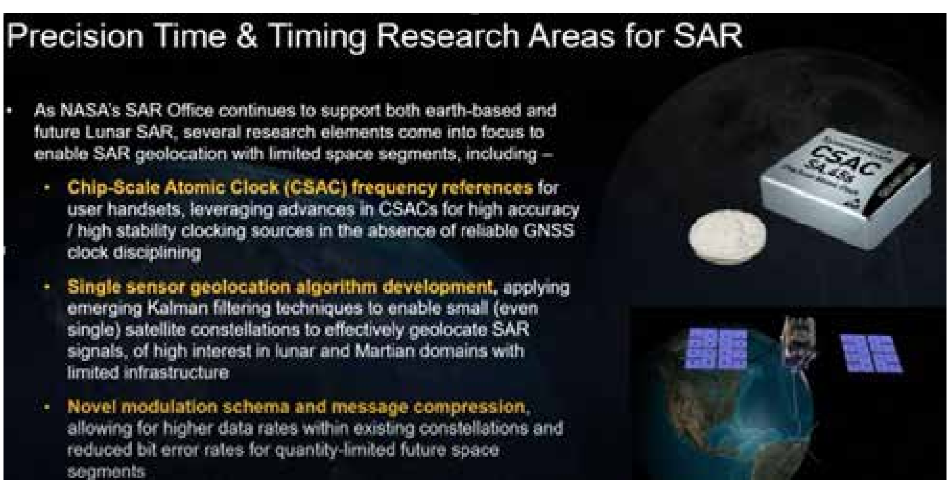
"We replicated conditions with a Navy support team, working with our astronauts off the coast of San Diego. We tested the Artemis survival suit in real-world ocean conditions, and in a Shreveport, Louisiana, pool that was used as a set for the movie, *The Guardian,*" Kelly said.

In the future, Kelly said that NASA will support current aviation locator beacon programs and how they could apply to Artemis missions. "We are working in concert with private and commercial industry on six parts of search and rescue. These parts are the big Orion capsule, building the beacons that go on it, how it flies on the Space Launch System, how they work with ground systems during launch, and supporting landing operations," he said.

Kelly said that NASA is evaluating future lunar architecture options, such as what combination of ground-based towers on the Moon's surface as well as potential satellite systems. "These could be 5G or 6G emergency data services. [Satellite and ground] are two very competing camps," he said. "So there is a high probability that for safety and redundancy, we will be utilizing a hybrid mix of ground- and satellite-based systems. Our continued efforts to develop LunaNET so that SAR is a key component that will play an important role."

NASA's SAR office is testing systems that are independent of PNT—and those that augment it. "In the near term, securing 406 MHz frequencies to the Moon, and S-band allocation for distress tracking is a big win. We are seeing first-hand how hard it is to get dedicated spectrum, especially on the Moon," Kelly said.

The work of the NASA SAR office at Goddard Space Flight Center is already shaping the future of space rescue capabilities, said James Miller, a NASA Headquarters sponsor of the SAR initiates. "The team works the ground, space, and user segments as a cohesive whole. They were successful in getting Orion and our commercial space partners such as SpaceX and Boeing to equip with SAR beacons for human rated space vehicles," he said. "Now they are going way beyond to see how similar equipment can be utilized on space suits and space infrastructure yet to come. Remember that their pioneering work putting SAR on GPS set the stage for all similar GNSS constellations to do the same. Now we all work to ensure that these same life-saving initiatives are available to all humankind beyond our pale blue dot of Earth."




*Timing and Timing Research Areas for Search and Rescue*
NASA

Marvin B. May

# SR-71 Blackbird

The massive defense spending of the Cold War (1945-1991) led to the development of several exotic and secretive weapons. In May 1960, at the peak of the Cold War, an international diplomatic crisis erupted. The Union of Soviet Socialist Republics (USSR) shot down an American U-2 Dragonfly spy plane in Soviet air space and captured its pilot, Francis Gary Powers (b1929-d1977). Confronted with the evidence of his nation's espionage, President Dwight D. Eisenhower (b1890-d1969) was forced to admit to the Soviets that the U.S. Central Intelligence Agency (CIA) had been flying spy missions over the USSR for several years. The United States pledged to end flying spy planes over USSR airspace and accelerated other reconnaissance and intelligence gathering programs that were more resilient and covert. Two of those top-secret programs were the CORONA spy satellite series and the SR-71 Blackbird reconnaissance aircraft.

The SR-71 Blackbird was an aircraft developed in the early 1960's by Lockheed Martin's famed "Skunk Works" located in Burbank, California. Lingering over the SR-71 designer's decision processes was the importance of distinguishing it from the nearly contemporary U-2 Dragon Lady reconnaissance plane that had been in service since 1956. The Blackbird, operationally and technologically, had to be more invulnerable and covert than the Dragonfly.

*Blackbird in flight*
Wikipedia

## Ahead of its Time

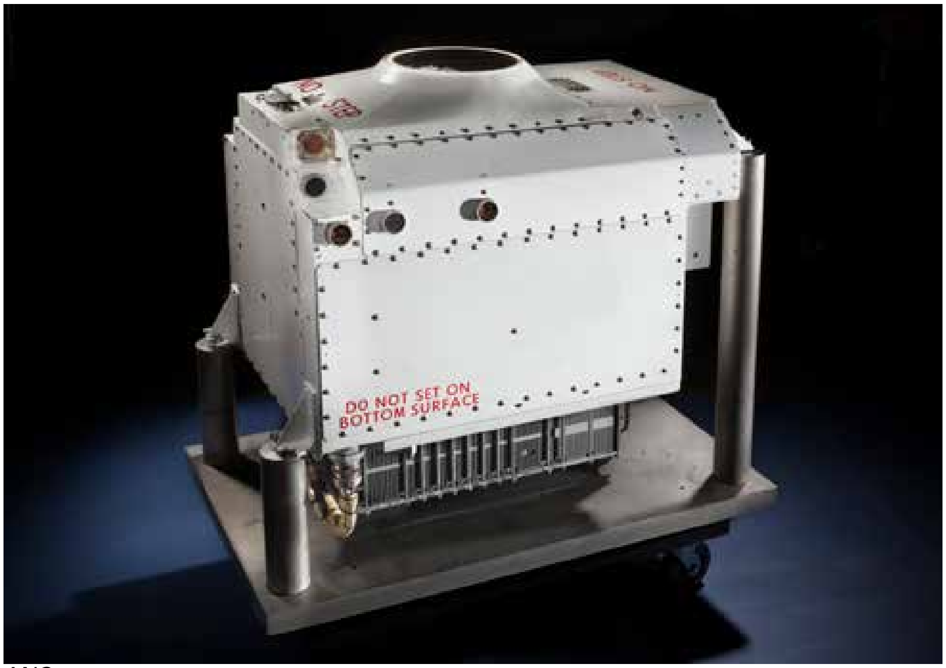
The Blackbird had performance and mission requirements that made it a technological marvel that was years ahead of its time. As a high-performance aircraft, it could fly at a record setting speed of Mach 3.2 (2061 knots) at an altitude of 85,000 feet for durations up to 12 hours. Featuring its original stealth technology that presented a radar cross section of less than 10 square meters, the Blackbird was nearly undetectable by an adversary and, even in the unlikely event of detection, its speed and altitude made it effectively invulnerable to hostile anti-aircraft systems. Although of questionable necessity, the equipment suite also included an advanced Electronic Counter Measure defensive system.

Its highly classified reconnaissance missions involved using its video, signals intelligence and/or electro-optical sensors located in the Blackbird's nose, to surreptitiously spy on adversary targets including those in Middle East, Vietnam, and North Korea, while skillfully avoiding flying into the prohibited airspaces of the Soviet Union and China. Of the many technical challenges facing the designers, providing accurate, undeniable, and covert navigation was critical. The value of the sensor information was largely dependent on being able to reconstruct the Blackbird's track thereby registering the images geographically.

> Few applications, if any, had as critical dependence on its navigation system for overall mission success as did the SR-71.

## Astroinertial Navigation System

Few applications, if any, had as critical




*ANS*

Long, E. (2012). SR-71 Astroinertial Navigation System (ANS). Smithsonian National Air and Space Museum, National Air and Space Museum Original Photography, NASM Acc. 2012-0026. https://airandspace.si.edu/collection-media/NASM-NASM2013-00439

dependence on its navigation system for overall mission success as did the SR-71. The navigation system was modeled after that of an earlier Cold War exotic weapon— the SNARK. The SNARK was an air-breathing, subsonic, unpiloted winged intercontinental missile built by Northrop Aircraft in the late 1950s. The Blackbird's navigation system was designated the Astroinertial Navigation System (ANS), and it filled the requirements of being highly accurate, reliable and without any dependency on inputs from sources subject to electronic jamming. The ANS, with its embedded Guidance Group, was central to most mission critical functions of the Blackbird. The ANS was an inertial navigation system tightly coupled to a star tracking system. At least two different stars had to be tracked for optimum navigation performance. As part of the SR-71's lengthy pre-mission setup, a 61-star catalog was loaded into the ANS computer. Selection of which star(s) to track was made by the ANS computer as a function of latitude, longitude, day of year, time of day, aircraft attitude and relative location of the sun. The computer selected a star by going through its star catalog, which was arranged by decreasing star brightness, until it found the star. A telescope-like star tracker searched for the stars in an expanding rectangular spiral search pattern. The ANS star-tracking window was located on top of the fuselage just forward of the air refueling door and consisted of a round piece of distortion-free quartz glass that allowed the star tracker to see through. At the extreme speeds that the Blackbird flew, along with the strict sensor requirements for path and attitude control, it was impossible for a pilot to fly the aircraft in a conventional sense. Instead, the ANS, in conjunction with the embedded Guidance Group, computed automatic tracking, guidance and avionics control, while continuously updating accounts of navigational status and coordinate values. The computer also stored instrument parameters and mathematical coefficients for predetermined data references that designated the stars and executed the mission flight plan. Software corrections to the stored data were provided for the supersonic shock-wave over the star-tracker window that refracted the star light, and for pressure and temperature gradients acting on the window causing optical lens distortions. For optimal sensor imagery, the aircraft was flown in autopilot mode with the ANS able to keep the Blackbird within 300 feet, once on course, of the desired track as laid out in the pre-mission plan.

Thirty-four years after its final retirement in 1990, the SR-71 Blackbird spy plane still holds the records as the fastest and highest-flying crewed aircraft ever. In 36 years of service with the CIA, the U.S. Air Force and NASA, the 50 SR-71's and A-12, FY-12 and M-21 variants flew reconnaissance missions over the Middle East, Vietnam, and North Korea and supported important research.

Thirty-four years after its final retirement in 1990, the SR-71 Blackbird spy plane still holds the records as the fastest and highest-flying crewed aircraft ever.

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## Defense Matters

# Congressional Oversight

### National Defense Authorization Acts – Limitations and Reporting Requirements

**Doug Taggart**
President
Overlook
Systems
Technologies, Inc.

Primary responsibilities of Congress include requirements to enact laws, raise and provide money for government functions and programs, oversee its proper expenditures, and provide oversight of the Executive Branch.

As I was preparing this column, Congress continues to struggle with the duty to prepare and present to the President the necessary appropriation bills to keep the Federal Government operating.

As of this drafting, it appears that the potential for a partial government shutdown, which was forecast to begin at midnight on March 1st, has been averted with two shorter-term Continuing Resolutions (CRs).

The first CR will extend the funding for Agriculture, Commerce-Justice-Science (including NASA and NOAA), Energy-Water, Interior, Military Construction-VA, and Transportation-HUD (including the FAA and its Office of Commercial Space Transportation) to March 8th.

The second CR will fund the Department of Defense (DoD), Financial Services-General Government, Homeland Security, Labor-HHS, Legislative Branch, and State-Foreign Ops until March 22nd.

With the senior leadership of the House and Senate Appropriate Committees announcing these bipartisan "deals", they also provided a forecast that a "deal in principle" to finalize individual appropriation bills for the federal government would be finalized and enacted prior to March 22nd.

In the nearly five decades since the current Congressional budgeting and spending process was put in place, Congress has only completed appropriations measures before a fiscal year (FY) begins four times. Those were: fiscal 1977 (the first year the current system was enacted), FY1989, FY1995, and FY1997. With this pitiful on-time track record standing, one should not place much in the hope in the promise to have appropriations in place by March 22nd, noting that we are already six months into the current fiscal year.

Under the normal Congressional process, authorization bills precede appropriations bills as the authorization bills limit and direct the use of the funds, which are then appropriated. Congress has a better record of passing authorization bills each year for the DoD through the annual National Defense Authorization Act (NDAA) process. Here again though, Congress is rarely on time in meeting the intended process with an average delay since 1977 of 42 days after the start of the fiscal year.

The NDAA for FY 2024 was passed in mid-December of 2023. Consistent with prior year NDAAs, it places requirements on the DoD to submit reports on various areas impacting the Global Positioning System (GPS) and broader initiatives focused on providing diverse positioning, navigation, and timing (PNT) capabilities for national security purposes.

A back-of-the-envelope tally of NDAAs dating back to the FY 2011 NDAA reveals that there have been over 40 different requirements placed on the DoD, and in some cases on other agencies or departments, involving limitations on the use of funds, as well as numerous requirements for status reports to the House Armed Services Committee (HASC), the Senate Armed Services Committee (SASC), or both, on a variety of GPS and other PNT related matters.

Examples of a few of these taskings includes a FY2011 NDAA limitation on the use of funds to only acquire M-code capable user equipment after FY2017, with the exception that the Secretary of Defense (SecDef) may waive the requirement if M-Code equipment is not available or if a determination is made that such equipment is not required for the particular mission or platform in question.

In the FY2014 NDAA, there was a limitation placed on the construction within U.S. territories of GNSS ground monitoring stations by "certain foreign governments." The requirement provided for a waiver by the SecDef if it was determined that such an action was "in the vital interest of the national security of the United States" with the added stipulation that such actions "do not reduce or compete with the advantages of GPS technology for users."

The FY2015 NDAA continued to poke

at the issue of M-Code fielding with a requirement for providing reports to the HASC and SASC on progress being made for M-Code development with added language requiring the Air Force to provide recommendations on "how to make the program more successful in delivering M-code capability."

This same NDAA also noted that it was the sense of the HASC that if GPS is unavailable due to malfunction or jamming, that the "committee encourages the DoD to review potential technologies to improve the military's ability to address this challenge." The FY15 statute also inquired about the GPS Block-III schedule, replenishment risks, and updates on the progress being made on completing the next generation GPS ground control network, OCX.

The FY2017 NDAA placed a requirement on the DoD for major defense acquisition programs to be designed with a modular open system approach (MOSA) to enhance competition and innovation to reduce costs and schedule, accommodate upgrades, and increase interoperability.

This same NDAA also assigned to the DoD Chief Information Officer (CIO) the responsibility for "policy, oversight, and guidance for matters related to precision navigation and timing…". It is notable that during this time, the DoD PNT Enterprise strategy was being developed which itself incorporates MOSA as a central tenet. In the time since the PNT Enterprise Strategy was signed by the DoD CIO in 2018, MOSA has become the PNT Strategy cornerstone that will enable U.S. and allied military forces to achieve and maintain PNT dominance in the future electronically challenged PNT battlespace.

The FY2017 NDAA also placed prohibitions of use by the DoD of certain non-allied PNT systems, i.e., BeiDou and GLONASS. The NDAA also required that a report be provided to the HASC & SASC on the risks of using these systems, and any potential impacts of harmful interference to GPS.

In the spirit of addressing national security matters, the FY18 NDAA tasked the SecDef, the Secretary of Transportation, and the Secretary of Homeland Security to jointly develop a plan for carrying out a backup GPS capability demonstration. The authority to carry out the demonstration was provided as an 18-month window following the enactment of the NDAA on January 3, 2017. The demonstration was ultimately completed with DOT and DHS taking the lead in 2019 and early 2020, with some delays due to the pandemic, and the final report was issued in January 2021.

The FY2021 NDAA addressed a number of activities underway within the DoD and other agencies, e.g., U.S. Coast Guard, to include reports on the impact (costs) if the FCC were to approve the Ligado spectrum application, a requirement for the DoD CIO to conduct an assessment of timing variability across DoD information technology networks, and for the Commandant of the Coast Guard to submit to the House Committee on Transportation and Infrastructure a report on the training and qualifications for Coast Guard deck watch officers with a focus on basic navigation.

The FY22 NDAA made some adjustments to prior year NDAAs based on the standup of the Space Force. Section 1604 placed additional responsibilities on the Oversight Council for the PNT Enterprise to include alternate methods to perform PNT capabilities. The NDAA also directed a briefing be prepared by the Secretary of the Air Force on a prototype program for multinational GNSS (see Defense Matters – PNT for the Warfighter (Let the DoD tend to its knitting) - Spring 2019).

Most recently, the FY2024 NDAA has two sections (1685 and 1686) that impact GPS.

Section 1685 requires the DoD to prepare quarterly briefings on the implementation of M-Code compliant receivers. The specific language tasks the co-chairs of the Council on Oversight of the DoD PNT Enterprise, to provide a briefing on the status of the implementation of M-Code compliant GPS receivers through the Military GPS User Equipment (MGUE) program, including the status of Increments 1 and 2, and details regarding expected dates of M-Code compliance for all sea-, air, and land-based terminals across the various platforms of each of the Services. The requirement for these quarterly updates will continue until all platforms have reached full operational capacity.

Section 1686 requires the DoD to establish requirements to ensure electronic protection of military sensor, navigation, and communications systems against jamming, spoofing, and unintended interference from military systems of the United States and foreign adversaries. It tasks the SecDef to develop and approve requirements for every radar, signals intelligence, navigation, and communications system to ensure such systems and subsystems are able to withstand threat-realistic levels of jamming, spoofing, and unintended interference, including self-generated interference.

The Section places requirements to test such systems at least once every four years on test ranges that provide threat-realistic electronic warfare attacks against the systems, with the first set of highest priority systems to be tested by no later than the end of fiscal year 2025.

Clearly the almost daily reports of GPS jamming in the on-going war in Ukraine, and the Israel-Hamas conflict in Gaza, have raised awareness that PNT is a warfighting capability that must be preserved.

For now, let's hope that Congress is as interested in finding ways to navigate the political challenges of both authorizing and appropriating vital PNT-related funding for the departments and agencies as it is in telling the DoD how to manage its own PNT capabilities to support the warfighter.

## Bicomplex Representation and Processing of GNSS Signals

Daniele Borio

Winner of the 2023 Burka Award

All communication systems relying on electromagnetic waves operate on the basis of a simple yet elegant formula: a radio frequency (RF) signal can be represented as the product of a complex baseband component and a carrier, which conveys the signal through the communication channel. This formula is also at the heart of the RF and signal processing stages of a global navigation satellite system (GNSS) receiver, which needs to recover the baseband signal, the carrier and the different parameters introduced by the communication channel on these two components. The delays introduced on the received baseband signals, namely the code components, are converted into pseudoranges, whereas Doppler shifts and phase measurements are estimated from the carrier terms. When signals from different frequencies are considered, a receiver can either estimate their parameters independently, i.e., treating each frequency separately, or adopt a receiver architecture that benefits from the commonalities and relationships between different frequency components.

In this paper, the standard RF signal representation formula is generalized to the dual-frequency case by using bicomplex numbers, which are characterized by four real components and find applications in physics and quantum mechanics.

Using bicomplex numbers, it is shown that two different RF signals can be jointly represented as the product of three terms: a bicomplex code, a carrier and a subcarrier component. The carrier up-converts the two signals to a common centre frequency whereas the subcarrier splits them to the final targeted RFs.

This new representation formula has significant implications for the design of dual-frequency algorithms and leads to triple-loop receiver architectures where a delay lock loop (DLL) is used to track a common bicomplex code component. A phase lock loop (PLL) and a subcarrier phase lock loop (SPLL) are adopted to track the carrier and subcarrier terms, respectively. The derived representation formula and bicomplex numbers are used to generalize concepts, such as the cross-ambiguity function (CAF), which are the basis of standard single frequency GNSS acquisition and tracking algorithms. In this respect, the above-mentioned triple-loop tracking architecture is a direct generalization of standard dual-loop single frequency processing schemes.

Theoretical results have been supported by experiments involving the wideband Galileo alternative binary offset carrier (AltBOC) modulation and the joint processing of the Beidou B1I and B1C components. The AltBOC combines two side-band components, the E5a and E5b signals, from nearby frequencies and can be considered, together with the joint Beidou B1I/B1C modulation, an example of GNSS meta-signals.

In this respect, the theory developed provides an innovative and elegant solution for the processing of GNSS meta-signals. The experimental analysis supports the effectiveness of the acquisition and tracking solutions developed using bicomplex numbers. An example of the results discussed in the paper is provided in Figure 1, which shows the

## ION's AE's Top Picks from 2023

Ever wonder what the ION's associated editors (AE) of *NAVIGATION* are reading? These were their "top picks" from articles published in 2023:

**ION's 2023 Burka Award Winner:**

- **Borio, D. (2023). Bicomplex representation and processing of GNSS signals. *NAVIGATION,* 70(4). https://doi.org/10.33012/navi.621**
- Wen, W., Bai, X., & Hsu, L. (2023). 3D Vision aided GNSS real-time kinematic positioning for autonomous systems in urban canyons. *NAVIGATION*, 70(3). https://doi.org/10.33012/navi.590
- Antic, J., Maliet, O., Trilles, S. (2023). SBAS protection levels with Gauss-Markov k-factors for any integrity target. *NAVIGATION,* 70(3). https://doi.org/10.33012/navi.594
- Bhamidipati, S., & Gao, G. (2023). GPS spoofing mitigation and timing risk analysis in networked phasor measurement units via stochastic reachability. *NAVIGATION,* 70(3). https://doi.org/10.33012/navi.574

All the excellent manuscripts are available open access at navi.ion.org.

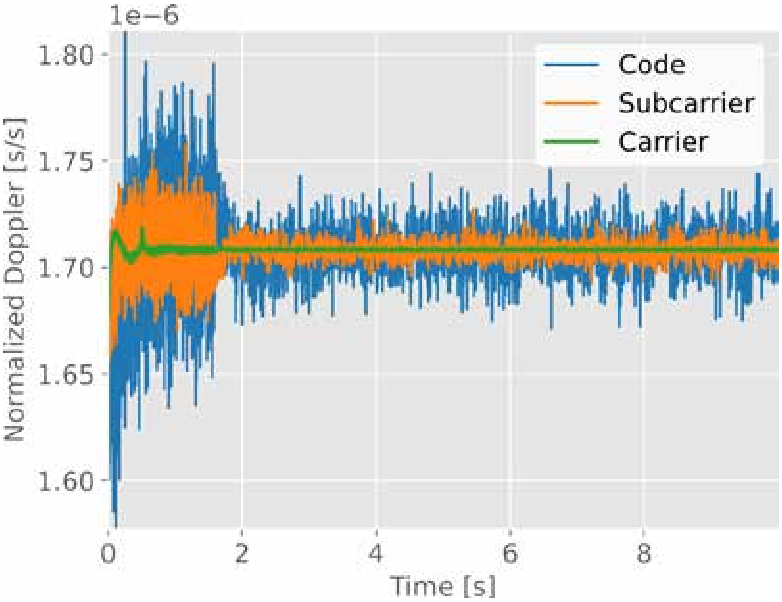



*Figure 1: Normalized code, subcarrier, and carrier Doppler estimates from the DLL, SPLL, and PLL in the triple-loop architecture implemented for processing the AltBOC signal.*

outputs of the filters of the three tracking loops implemented for the processing of the AltBOC signal. The code, subcarrier, and carrier Doppler estimates are provided after normalization by the corresponding nominal frequencies: the three components overlap, showing proper functioning of the loops and the possibility of aiding, for example, from the carrier to the other components.

The theoretical results provide a general framework for developing effective dual-frequency and meta-signal processing algorithms. Existing algorithms for the processing of the AltBOC and B1I/B1C can be described using bicomplex numbers resulting into a more compact and effective notation. Moreover, the solution proposed is also valid when considering meta-signals incorporating side-band components with different characteristics.

The methodology proposed has been extended to better exploit the relationships between the different signal components. For instance, a Kalman Filter (KF)-based triple-loop receiver architecture using bicomplex numbers has been presented at the 2023 ION GNSS+ conference ("Bicomplex Kalman Filter Tracking for GNSS Meta-Signals"). Tests were conducted under dynamic conditions using a Software Defined Radio (SDR) front-end. Views of the experimental setup are provided in Figure 2. Also, these tests confirmed the potential of the proposed approach on bicomplex numbers, which can be extended to support more than two frequencies.

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

Borio D. (2023). Bicomplex representation and processing of GNSS signals. *NAVIGATION,* 70(4). https://doi.org/10.33012/navi.621

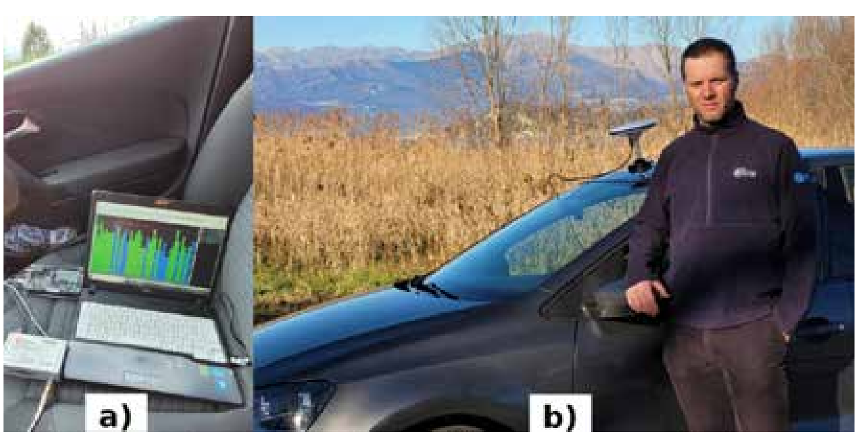



*Figure 2: Equipment used for the dynamic tests. a) Internal view of the vehicle with the laptop, reference receiver and front-end adopted for the data collection. b) External view of the vehicle with the multi-frequency antenna mounted on the roof.*

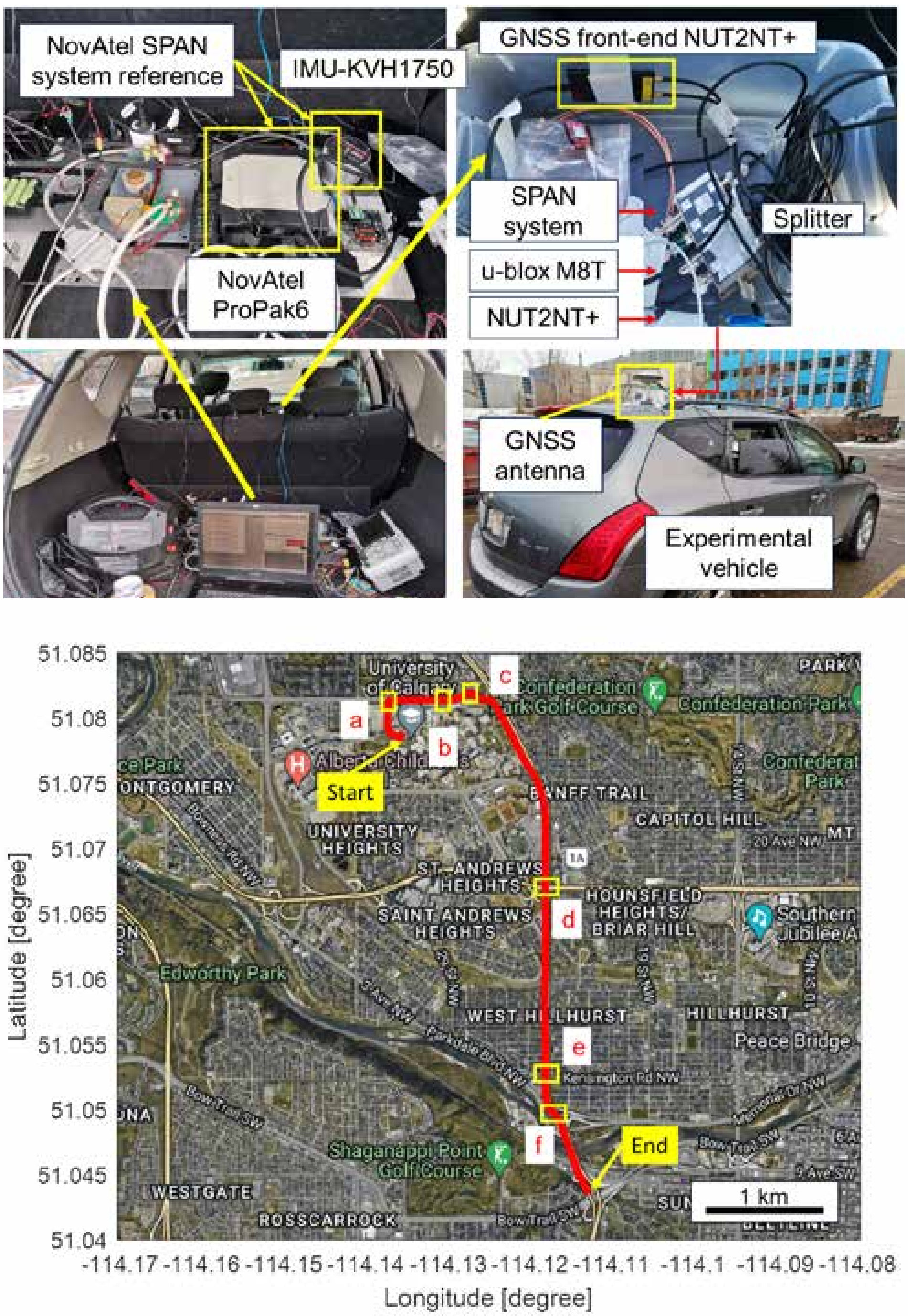
# A Baseband MLE for Snapshot GNSS Receiver Using Super-Long-Coherent Correlation in a Fractional Fourier Domain

Yiran Luo, Li-Ta Hsu, and Naser El-Sheimy

Instead of relying on traditional methods combining long coherent integration and non-coherent integration techniques, super-long coherent integration (S-LCI) approach was employed in conjunction with the proposed snapshot baseband maximum likelihood estimator (MLE). This approach demonstrates the potential to significantly reduce the root-mean-square error (RMSE) in Doppler frequency and code phase estimation, approaching the theoretical lower bound, the Cramer-Rao lower bound (CRLB). This implies that GNSS measurements can achieve top-tier performance even under weak signal conditions.

State-of-the-art GNSS measurement was introduced, the Doppler rate, which permanently enhances the degrees of freedom in GNSS navigation by one. For instance, the conventional GNSS receiver's output of absolute position, velocity, and timing (PVT) solutions is elevated to absolute position, velocity, acceleration/deceleration (calculated using Doppler rate measurements), and timing (PVAT) solutions.

This paper describes how we incorporated the snapshot baseband MLE technique from the NAVIGATION paper into a GNSS receiver prototype. This prototype undergoes ground-vehicle field testing involving GPS, Galileo, and BeiDou constellations. Notably, for the field test evaluation of our receiver prototype and the u-blox M8T, we employed single point positioning (SPP) alongside the Klobuchar and Saastamoninen models to compensate for ionospheric and tropospheric delay errors. The experimental set-up is shown in the figure below. Based on the statistical results and comparative analysis, the proposed GNSS receiver prototype demonstrates the potential to deliver navigation solutions, particularly in reducing random errors, that are on par with or even superior to the current commercial model in kinematic field tests. Notably, it exhibits exceptional sensitivity in consistently providing dependable navigation solutions, especially in challenging scenarios with severely attenuated GNSS signals, outperforming the u-blox M8T.




*Experimental set-up for the ground-vehicle field test.*

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

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

## Stochastic Reachability-Based GPS Spoofing Detection with Chimera Signal Enhancement

Tara Mina, Ashwin Kanhere, Shreyas Kousik, and Grace Gao

To be launched later in 2024, the Navigation Technology Satellite (NTS-3) will test the U.S. Air Force Research Lab's Chimera signal enhancement. Chimera will protect civilian GPS users from spoofing attacks by inserting a digital signature in the L1C navigation message and pilot channel, which users can periodically validate to authenticate their received GPS signal. The Chimera fast channel allows users to authenticate the received GPS signal once every 1.5 or 6-seconds, depending on the out-of-band source utilized for receiving the fast channel marker keys. However, moving receivers oftentimes rely on faster GPS measurement rates, at 1-20 Hz. To tackle this challenge, this paper derived a stochastic reachability-based filter and spoofing detector to provide continuously authenticated navigation solutions during the Chimera epoch. Our formal verification method leverages the previously authenticated set of Chimera measurements, in combination with conservative error models for the GPS and self-contained sensor measurements to update the receiver state and uncertainty at each time instant. Using stochastic reachability (SR) analysis, we further provably guarantee that our detector satisfies a user defined false alarm requirement in the presence of unknown, but bounded sensing biases. Once spoofing is detected, our SR estimator switches to relying only on the self-contained sensor measurements, while maintaining a conservative uncertainty model of the vehicle state, for the remainder of the Chimera epoch.

In order to probabilistically validate the derived bounds for our spoofing detector and state estimator, we ran Monte Carlo simulations for 1,000 sampled trajectories for two ground vehicle models. For the first, the vehicle dynamics are modelled as a double-integrator system with control inputs modelled as 2-D accelerations in the inertial frame of reference. For the second, we simulated the vehicle dynamics with model replacement from an IMU providing two-dimensional body-frame accelerations and yaw rate measurements. In both scenarios, we simulated bounded sensing biases and stochastic uncertainties and consider a 6-second fast channel implementation of Chimera. We examined the performance of our SR filter and spoofing detector under both authentic GPS conditions and simulated, trajectory drifting spoofing attacks. During authentic GPS conditions, we validated in both scenarios that the SR detector satisfies the user-defined false alarm probability requirement in the presence of bounded-bias and stochastic sensing uncertainties. At the same time, our detector recognized spoofing during the simulated spoofing attacks, once the GPS errors exceed the sensing errors during the Chimera epoch. We additionally demonstrated that our SR estimator and uncertainty models probabilistically bound the true vehicle state, during both authentic and spoofing conditions. In particular, during authentic GPS conditions, the Chimera SR filter utilizes both the self-contained sensor and real-time GPS positioning measurements for state estimation, along with conservative error models to probabilistically bound the true vehicle state. During spoofed GPS conditions, as the spoofing trajectory deviates from the true trajectory, because our detector recognizes the attack, the Chimera SR filter switches to the self-contained state estimate and continues to probabilistically bound the true vehicle state. These results demonstrate that our formal verification-based framework performs continuous and uncertainty-aware spoofing detection and secure state estimation with Chimera GPS. Correspondingly, once the Chimera signal enhancement for GPS is tested and becomes integrated within the L1C signal, this framework can be leveraged to ensure secure navigation with Chimera GPS.

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

Mina, T., Kanhere, A., Kousik, S., & Gao, G. (2023). Stochastic reachability-based GPS spoofing detection with Chimera signal enhancement. *NAVIGATION,* 70(4). https://doi.org/10.33012/navi.616

## Analytical and Empirical Navigation Safety Evaluation of a Tightly Integrated Lidar/IMU Using Return-Light Intensity

Ali Hassani and Mathieu Joerger

The unique aspect of this research is that it provides a means to bound the integrity risk of a tightly integrated landmark-based navigation system using lidar (light detection and ranging) and IMU (inertial measurement unit). Data fusion improves the accuracy and continuity of autonomous driving systems (ADS) position and orientation estimation. The incorporation of lidar return-light intensity further facilitates the process of matching sensed features with mapped landmarks. The method enables the evaluation of navigation safety risks that are neglected in other non-safety-critical applications. Theoretical analysis and experimental data to quantify the reduction in landmark association risks achieved using lidar intensity are used.

Covariance analyses and lab experiments were performed to evaluate the system's integrity performance. The system was tested under various scenarios including landmark occlusions and challenging landmark configurations. The results demonstrated a substantial reduction in integrity risk when incorporating return-light intensity to the integrated lidar/IMU system.

The paper addresses the challenging problem for an automated PNT system to self-assess the trust that can be placed in the information it is providing. The approach leverages GNSS-based aviation safety methods: it relies (a) on large amounts of experimental data for offline, a-priori sensor error modeling and (b) analytical methods for high-integrity online navigation. The intent is to bring these aviation safety methods to other sensors and other applications.

Navigation is a key functionality of mobile autonomous and robotic systems, which must provide safety guarantees when human lives are at risk. For a self-driving car, such guarantees cannot be solely provided by extensive experimental data (billions of miles would have to be autonomously driven to prove safety performance superior to a human driver). Probabilistic analytical methods, such as those developed in this paper, can help reduce the amount of experimental testing required to make the case for a safe autonomous vehicle.

The research methodology fills a gap in rigorous integrity evaluation for IMU/lidar-based localization. Current lidar point clouds are comprised of thousands of data points at high update rates. In this context, landmark-based methods can be used as an alternative or as a complement to computationally-expensive point-cloud matching methods: our risk bounds are currently used in academic research as a safety-based criterion to select the most reliable features in a point cloud.

Tightly integrated lidar and IMU algorithms are already implemented on automated vehicles in commercial autonomous ride-hailing services. The increased ability of autonomous systems to quantify trust in their navigation solution will further reduce the risk of crash and the rate of "disengagement", i.e., the rate of occurrence of the vehicle stopping or handing control back to a (remote) human operator. Enhancing trust in autonomous vehicles will increase acceptance and adoption by the general public, thereby facilitating the mobility of passengers and goods. In the military domain, quantifiably reducing the risks of navigation errors will improve the performance of unmanned vehicles and precision-guided systems. Overall, increasing trust in navigation will help achieve safer and more efficient transportation.

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

Hassani, A., & Joerger, M. (2023). Analytical and empirical navigation safety evaluation of a tightly integrated lidar/IMU using return-light intensity. *NAVIGATION,* 70(4). https://doi.org/10.33012/navi.623

*Dr. Ali Hassani (left) and Casey Smith (right) working on the next iteration of the integrity risk bounding of a tightly integrated lidar and IMU navigation system at the Virginia Tech main campus, Blacksburg.*

*Data acquisition platform installed on a car roof including time synchronized lidar, IMU and GNSS sensors.*

# The Business of GNSS

Kevin Dennehy

One of the big business announcements since our last column was ION member **u-blox's** new project awards with "major automotive customers" in the Asia-Pacific region. These new awards, scheduled to begin in 2026, could be worth more than $100 million.

*u-blox's automotive project wins could be worth $100 million, starting in 2026*
u-blox

While the company didn't name the automakers because of nondisclosure agreements, it said that upcoming vehicle models will incorporate u-blox's GNSS F9 platform for automated driving.

While the auto projects are long term, along with the expected revenue generated from them, u-blox believes the automated driving market will continue to grow as it is working with the leading companies in that segment, said Stephan Zizala, u-blox CEO.

In other u-blox news, the company and Nordian announced expanded coverage of the PointPerfect GNSS correction service in Brazil, a growing market for GNSS applications. The deal between u-blox and Nordian will allow such applications as high-precision agriculture, but also service robots, machinery automation, micro- mobility, lane-accurate navigation and telematics.

Another ION member, **HERE Technologies,** extended its partnership with Uber to enhance the rideshare company's mapping capabilities at the CES conference in January. The agreement calls for HERE to provide location-aware tools and functions to the Uber platform for accurate drop-off and pick-up points at locations, including airports and stadiums.

New HERE Technologies CEO Mike Nefkens, who said that the company had its best financial year ever in 2023, also announced it would be partnering with both Bosch and Daimler Truck advanced driver assistance system (ADAS) technology.

Also at CES, ION member **Qualcomm** unveiled a range of products based on its Snapdragon Digital Chassis platform to support generative AI digital cockpits, connected car technologies, connected services, ADAS and automated driving systems.

In maritime business news, ION member **GMV** is working with the European Commission on the navigation of autonomous vessels. The project, called AVIS, will use the European GNSS and Copernicus space systems.

## Big Acquisition Closes for BAE Systems

ION member **BAE Systems** won U.S. government approval to complete its $5.5 billion acquisition of Ball Aerospace. Ball Aerospace's 5,500 employees will remain in Colorado. BAE Systems also announced it had completed a Critical Design Review of its Military GPS User Equipment (MGUE) Increment 2 Miniature Serial Interface (MSI) program, which is part of a $247 million U.S. Space Force contract. The MSI includes a Next-Generation Application Specific Integrated Circuit that will provide security for M-Code technology.

## Recent Product Launches

Recent product announcements include the AntaRX-Si3, a GNSS/Inertial Navigation System smart antenna from ION member **Septentrio**, which is tailored for agriculture robots and other use cases. AntaRx-Si3 incorporates GNSS/INS FUSE+ technology.

ION member **Topcon Positioning Systems** launched its HiPer CR GNSS receiver designed for centimeter-level, real-time kinematic (RTK) accuracy. The unit is tailored for professionals in the surveying, construction, engineering, forestry, and mining industries.

*AntaRx-Si3 features GNSS/INS FUSE+ technology*
Septentrio

*Topcon's HiPer CR GNSS receiver*
Topcon

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

# GNSS Program Updates
# News from Systems Around the World

Kevin Dennehy

## KPS and KASS

**Korea Augmentation Satellite System Certified**

KASS has been certified by South Korean government.

Korea Aerospace Research Institute

The Korea Augmentation Satellite System (KASS), which was developed by Thales Alenia Space, has been certified by the South Korean government. The navigation system, now operational, is a collaboration between Thales, Leonardo, the Korea Aerospace Research Institute for the Korean Ministry of Land, Infrastructure and Transport.

Thales Alenia Space is delivering the ground infrastructure, which the company has worked on since 2020. The KASS system initially operated via a MEASAT-3d geostationary satellite, launched in 2022. The satellite will be supplemented by the KOREASAT 6A, developed by Thales Alenia Space for KT SAT, which will carry a satellite-based augmentation system (SBAS) payload.

KASS will initially focus on aircraft applications in accordance with the International Civil Aviation Organization (ICAO), the company said.

## Galileo

By using Galileo Signal-in-Space (SiS) capabilities, the European Space Agency (ESA), along with ION member GMV and Astroscale UK, have launched its Collision Risk and Automated Mitigation (CREAM) initiative. The partners will use SiS and its Galileo Return Link Service to assess the way satellites respond to potential collisions.

ESA plans to launch two more first-generation Galileo satellites in April, with a couple more to follow later this year. As we reported in our last issue, SpaceX has the contract to launch the satellites through a $192 million contract.

*KASS*

## GPS

Since our last column, published reports indicate that Russia is developing a space-based nuclear capability to attack satellites, including GPS. U.S. House Intelligence Committee Chairman Mike Turner of Ohio released a statement calling on President Joe Biden to declassify information regarding Russia's ability to use nukes in space as a national security threat.

This isn't the first time that Russia has threatened destruction of the GPS satellite constellation. In November 2021, Russia, on state TV, warned it could blow up the GPS constellation to render missiles useless.

In other constellation news, the U.S. Space Force's Space Systems Command (SSC), part of the United States Space Force, is seeking comment from the GNSS industry through a Request for Information (RFI) regarding GPS Rapid Prototype Demonstration. SSC's RFI is part of a strategic initiative to upgrade GPS capabilities to modernize and meet new space challenges.

Finally, the Next-Generation Operational Control System (OCX) is now facing a new delay of 16 months, according to the 2023 Annual Report of the Director of Operational Test & Evaluation (DOT&E). At the same time, a satellite is still on the slate to be launched this year, with the GPS III SV07 mission on target to launch in June.

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

# Calendar of Upcoming Events

**MAY 2024**

**22-24:** European Navigation Conference (ENC), ESA ESTEC, Noordwijk, The Netherlands

*Contact:* http://enc-series.org/2024

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

**JANUARY 2025**

**27-30:** ION International Technical Meeting (ITM) & ION Precise Time and Time Interval (PTTI) Meeting 2025, Hyatt Regency Long Beach, Long Beach, California

*Contact:* ION

ion.org

**APRIL 2025**

**27-30:** IEEE/ION Position, Location, and Navigation Symposium (PLANS) 2025, Marriott Salt Lake Downtown City Creek, Salt Lake City, Utah

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