Volume 33 No 2 **Spring 2023**

ION® INSTITUTE OF NAVIGATION

Quarterly Newsletter

ITM/PTTI 2023 RECAP

Prospectives and Challenges of Advanced Air Mobility and Standards Setting

ITM/PTTI 2023 was held January 23-26, 2023, in Long Beach, California with Dr. Andrey Soloviev from QuNav serving as the program chair for the International Technical Meeting (ITM)

Dr. Han Park, Deputy CTO and Head of R&D, Supernal

portion, and Dr. Daphna Enzer from Jet Propulsion Laboratory serving as the program chair for the Precise Time and Time Interval (PTTI) Systems and Applications Meeting. The meeting enjoyed a return to pre-pandemic numbers with more than 150 papers presented to more than 330 in-person attendees, and another 50 attendees participating virtually.

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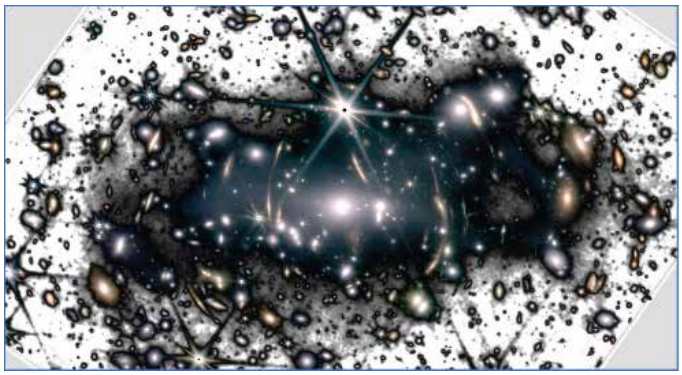
GOOD ENOUGH CLOCKS?

Shedding Light on Dark Matter

Dr. Demetrios Matsakis

Recently an article appeared in *Nature Astronomy* suggesting that dark matter could be detected by flying a clock near the Sun[1]. If it succeeds there will be something poetic about it, because the very discovery of dark matter came from observing the suns that make up our universe.



Dark Matter in the galactic cluster SMACS-J0723, as revealed by the James Webb Space Telescope.
NASA, ESA, CSA, STScI

But what exactly do we mean by dark matter? Believe it or not, the Moon is dark. It reflects only 7% of the sunlight that falls on it. But the kind of dark matter this article is about would reflect 0% of the sunlight. It isn't even made up of electrons or protons or quarks or anything that interacts with light. And it's probably streaming through all of us right now.

What do we know about it? Dark matter constitutes about 27% of the mass-energy of the universe, while dark energy [2] makes up about 68%, give or take. We don't know what dark energy is either, but that's a different problem. According to the Big Bang theory, ordinary non-dark matter can only make up 5% of the total mass-energy because otherwise the amount of helium would differ too much from what we see. Actually, we only see about half of that 5%, but that's another problem still.

We've suspected some kind of dark matter problem may exist for a long time. Poincare first coined the term in discussing speculations Lord Kelvin made in 1884, because according to Newton's laws there was too much gravitational pull given the number of stars. Newton showed that planets only move in stable orbits if their motion isn't fast enough to escape the Sun's gravity while not so slow as to be sucked into it. And because gravity gets weaker the further away you get, the outer planets have to move slower – they would escape if they had the same speed as the Earth.

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PRESIDENT'S COLUMN | DR. SHERMAN LO

Changing of the Guard

At the conclusion of ION's International Technical Meeting (ITM)/Precise Time and Time Interval (PTTI) Systems and Applications Meetings I accepted the ION's presidential gavel from outgoing president, Dr. Frank van Diggelen, and thanked him for his leadership of ION during the past two years – the majority of which was spent navigating the effects of the international pandemic, pandemic relief, and ION's recovery. I look forward to continuing to serve with Frank and all the members of the incoming Council for the next two years.

Goals

For the next two years, one of my primary goals will be to continue to ensure that ION maintains its healthy recovery from the impacts of the COVID-19 pandemic. I am happy to report that Dr. van Diggelen's outgoing president's report, conveyed that ION membership has returned to pre-pandemic levels. Additionally, the ITM/PTTI 2023 technical program and registration levels were also back to pre-pandemic levels, though we have noted the absence of our colleagues from some geographical areas of the world, and hope to welcome them back soon. Additionally, the Joint Navigation Conference (JNC) reported record attendance and program size in 2022. While ION GNSS+ 2022 (held in September 2022 in Denver, Colorado) was just shy of its former glory, we are hopeful registration will be back to normal in 2023. The ION GNSS+ 2023 program committee is planning for a full technical program, including Tuesday's pre-conference tutorials and a return this year to the popular free "masters short courses" taught by legends in the PNT community on Monday.

My second goal for my ION presidency will be to focus on ensuring the future vitality of the organization by growing programs focused on the generation entering in the PNT community – specifically, ensuring 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.

ION Council Convened January

The ION Council met in person on January 23, 2023, with several members also joining virtually. Outgoing president, Dr. Frank van Diggelen, reported on several actions that had been taken by the ION Executive Committee in the preceding months. The most notable among these actions was that the ION Executive Committee had approved a transfer from the ION's Operating Fund back to the ION's Reserve Fund, a step toward paying ourselves back for a loan we made to cover operating expenses during COVID-19. The Council also approved ION's prior fiscal year's audit report and next year's National Office budget.

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

Incoming President Dr. Sherman Lo accepting the ION's presidential gavel from outgoing president Dr. Frank van Diggelen

ION Convening at IEEE/ION PLANS this Spring

I look forward to greeting you at the IEEE/ION PLANS meeting, being held fully in-person April 24-27, 2023 in Monterey, California. The technical program will feature tracks on inertial sensing and technology; GNSS; integrated, collaborative, and opportunistic navigation; and applications to automated, semi-autonomous, and fully-autonomous systems. It is sure to be a full and exciting program – see you there!

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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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ION thanks the ITM/PTTI program committee for their service. Dr. Josef Vojtech, Tutorials Chair; Dr. Sven-Christian Ebenhag, PTTI General Chair; Dr. Daphna Enzer, PTTI Program Chair; Dr. Andrey Soloviev, ITM Program Chair; Dr. Juan Blanch, ITM General Chair; and Dr. Frank van Diggelen, ION President.

The conference plenary session hosted Dr. Han Park from Supernal (affiliate of Hyundai Motors Group) who presented an overview of perspectives and challenges of advanced air mobility applications (essentially, air taxis) with electrical take-off-and-landing vehicles (eVTOL) including battery design options, challenges of air traffic control, certification of artificial intelligence and navigation system requirements. Dr. Park was followed by Dr. Elizabeth Donley from NIST Time and Frequency Division who brought to life the years-long process for creating and/or updating IEEE standards. Dr. Donley reviewed what's new in the two recent updates she spearheaded: 1139 on noise in time and frequency measurements, and 1193 on environmental sensitivities. The amount of expertise and collaboration across the field that went into these updates was evident, and these standards will be a great resource for the community. Dr. Donley also reported on a working group formed to create a new Standard (1952) on Resiliency in GPS and PNT, which was described further in the week's technical sessions. These talks are available for free viewing on the ION's YouTube channel.

The technical sessions showed a continued strong interest in improving GNSS resiliency through sensor fusion, alternative navigation aids, and applications of advanced signal processing techniques. Two of the most popular ITM sessions (by the number of papers submitted to them, as well as people in attendance) were "Alternatives, Backups, Complements to GNSS" and "GNSS Integrity and Augmentation." In addition, there is a growing interest in interplanetary navigation applications, which resulted in an excellent session on "Extraterrestrial Navigation" with high-quality technical papers primarily focusing on lunar missions. Dr. Soloviev, ITM program chair, noted: "Overall, I was very pleased with the technical content and feel that the recent implementation of the peer-review process significantly strengthened the paper quality. It was also great to see colleagues and friends, and meet people who came for their first ION meeting. For me, ION conferences have always been a source of motivation and renewed energy and ITM/PTTI 2023 was no exception."

PTTI's clock sessions were characterized by many reports of smaller, more integrated, and more deployable packaging for high performing clocks and fiber combs. Even for laboratory-based systems, places like USNO report moving toward fiber-based lasers for their Rb Fountains to improve robustness and environmental sensitivities. There were also impressive reports on the lowest SwAP clocks with less stringent performance specifications. New devices such as metasurfaces and fiber coupled tantala waveguides appeared in several of these talks. Other talks spanned the topics of time transfer, LEO constellations, GNSS, environmental sensitivities, national metrology laboratories, and timescales/algorithms. Dr. Enzer, PTTI program chair, reported: "I was truly interest and excited to hear all the talks, but standouts for me included Judah Levine (NIST) asking the community to ponder big questions like should NIST's fiber-based time service be fee-based, as opposed to the old free time-services of the past? And who weighs the cost versus ease-of-use decisions that determine the type of systems offered? I also enjoyed the lively presentation from Vector Atomic about testing their new molecular iodine optical clocks at sea during the RIMPAC 2022 campaign; and was interested to learn in another talk that the Indian Space Agency built their own RAFS clocks, soon to be launched into their GNSS constellation."

ITM/PTTI 2024 will be held January 22-25, 2024, again in Long Beach, California.

Off to see the exhibits!

Congratulations ION 2022 Annual Award Recipients

COL. THOMAS L. THURLOW AWARD
In recognition of outstanding contributions to the science of navigation

Dr. Mathieu Joerger

For significant contributions to integrity and continuity assurance for safety-of-life navigation

PTTI DISTINGUISHED SERVICE AWARD
To recognize outstanding contributions related to the management of precise time and time interval systems

Dr. Demetrios Matsakis

For improving the U.S. Naval Observatory's Master Clock by a factor of five over two decades, while personally making many advancements to international timekeeping

SUPERIOR ACHIEVEMENT AWARD
For outstanding accomplishments as a practicing navigator

Major Bryan A. Singer

For leadership and outstanding instructional ability in the development of innovative training solutions for future combat search-and-rescue aviators

CAPTAIN P.V.H. WEEMS AWARD
For continuing contributions to the art and science of navigation

H. Logan Scott

For over 40 years of sustained contributions to GNSS assurance, including spectrum advocacy, invention of the Chimera authentication signal, and multiple resilient NTS-3 signal designs

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. Li-Ta Hsu

For outstanding research leadership and innovation in urban navigation and positioning

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

Elisa Gallon, Dr. Mathieu Joerger, and Dr. Boris Pervan

For their paper "Robust Modeling of GNSS Orbit and Clock Error Dynamics" published in the Winter 2022 issue of *NAVIGATION, Journal of the Institute of Navigation,* Vol. 69, No. 4

NORMAN P. HAYS AWARD
In recognition of outstanding encouragement, inspiration, and support contributing to the advancement of navigation

Deborah Lawrence

For significant leadership in the development and sustainment of the FAA's navigation programs

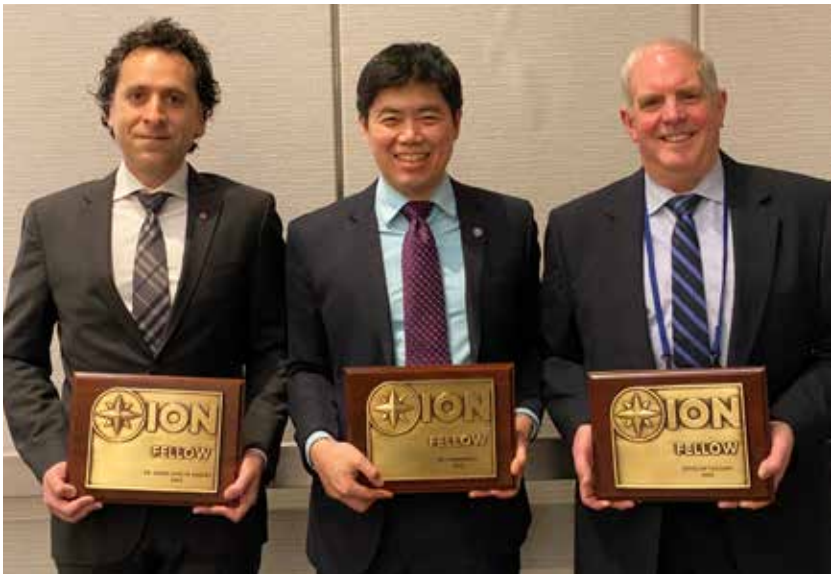
ION Distinguished Service Award

Dr. Frank van Diggelen

For extraordinary service to the Institute of Navigation

ION's 2023 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. Zaher M. Kassas

For groundbreaking contributions to the theory and application of navigation with terrestrial and extraterrestrial signals of opportunity, and for dedicated national leadership and scientific service

Dr. Sherman Lo

For sustained contributions to the development of methods to ensure secure and safe access to positioning, navigation, and timing under adverse conditions

Douglas Taggart

For distinguished and sustained technical and strategic contributions, leadership, and guidance in the use of multiple navigation systems

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The same kind of balance exists for "systems" of stars (or star clusters, galaxies, clusters of galaxies, even gas clouds - you name it). The mutual gravitational attraction between the components pulls them to the center of mass. But gravity is a force, so they speed up as they get sucked in. They could just pass through and go to the other side of the system so that nothing really changes. But too much gravity will bring about an overall collapse, and either their random motions will increase to attain a balance in a smaller volume or the whole thing will coalesce into a more condensed object, such as a black hole. Conversely, if the net gravitation is too weak the stars will move further out, where either gravity will slow them into stable orbits or they will escape the system. So for any stable system the velocity spread and the gravity will be in balance. It's called the virial theorem. And if you measure the velocity distribution, you know the total mass needed for gravity to hold the system together (Figure 1).

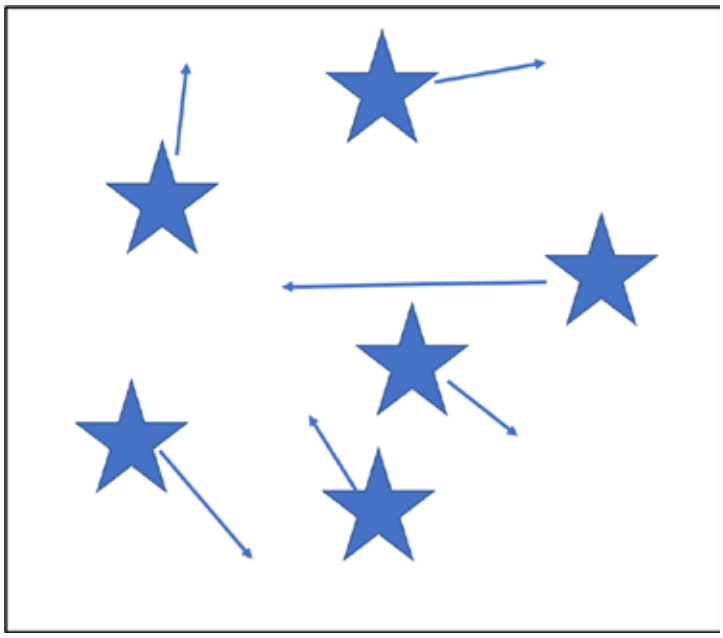

Figure 1. Stable systems of stars balance their mutual attraction against their random motions.

The problem is that every time somebody does the math for any system of stars, the total mass needed to hold it together is much more than the mass of the visible stars. And the larger the system is, the more the missing mass. In 1939 Horace Babcock observed this in the rotation in the Andromeda galaxy, the large spiral that will pass through us in 5 billion years - although he thought it was because dust clouds obscured the starlight. In 1933 one of my heroes, Fred Zwicky, photographed the Coma galaxy cluster and found it had only 1% of the mass needed to hold it together.

Things really went wild in the 1970's, when Vera Rubin and others started photographing galaxies big time. They found that instead of the orbital speed decreasing as you got farther out in galaxies, like it does with the planets of our solar system, the speeds of the stars and gas levelled off to a constant of about 200 km/s. That meant there had to be a lot more mass out there than was observed by starlight. In the solar neighborhood, the ratio of dark to ordinary matter is about 50-50.

Since then we've have found evidence of dark matter just about everywhere and in many ways – superclusters, gravitational lensing, and even anisotropies in the cosmic microwave background, which is the faint microwave glow left over from the Big Bang. Cosmologists have even discovered they need dark matter to correctly predict the parameters of the soap-bubble-like universe on the grand scale (Figure 2).

There are many theories as to what dark matter is. Solar-mass black holes, neutrinos, hypothetical elementary particles, and new physics have been proposed. There are even Modified Newtonian Dynamics (MOND) theories, in which the gravitational force doesn't get as weak at long distances as Einstein and Newton thought. All these theories have their advocates, but none have a large following among astronomers.

So why haven't we found it? Maybe because we don't have good enough clocks. The basic frequencies of the oscillators inside the clocks depend on fundamental constants of physics. If dark matter swished by them, the so-called weak force would perturb the energy levels of the atoms, and we would see a momentary change of frequency or maybe of the interaction constants. Many people have looked for such things. Me too, when I was director of the USNO's Time Service Department. Following a suggestion by Prof. Lord at the University of Washington, I rotated some cesium beam clocks so that if a stream of dark matter particles was coming from any particular direction it might selectively perturb the strength of the atomic forces and cause the phase lock loops in those clocks to work differently. Others have looked for correlated variations in the frequencies of the clocks on GPS satellites on opposite sides of the Earth; also by comparing clocks using different atomic species, which would have different sensitivities to a dark matter stream. If anybody had found anything interesting, we'd all know about it already.

Now back to the paper that inspired this article. What if dark matter is gravitationally trapped by the Sun? Its greater density there would make it easier to detect. So you might fly two or more clocks based on different atomic species as close as practical to the Sun, and see what happens to the ratio of their frequencies. It would be a test of many things. A null result would confirm general relativity far more accurately than similar tests on and near Earth, and it would serve to constrain the amount of dark matter of certain types. A differential variation of the two clocks would open a new window for exploring dark matter and the limits of relativity. It's a win-win.

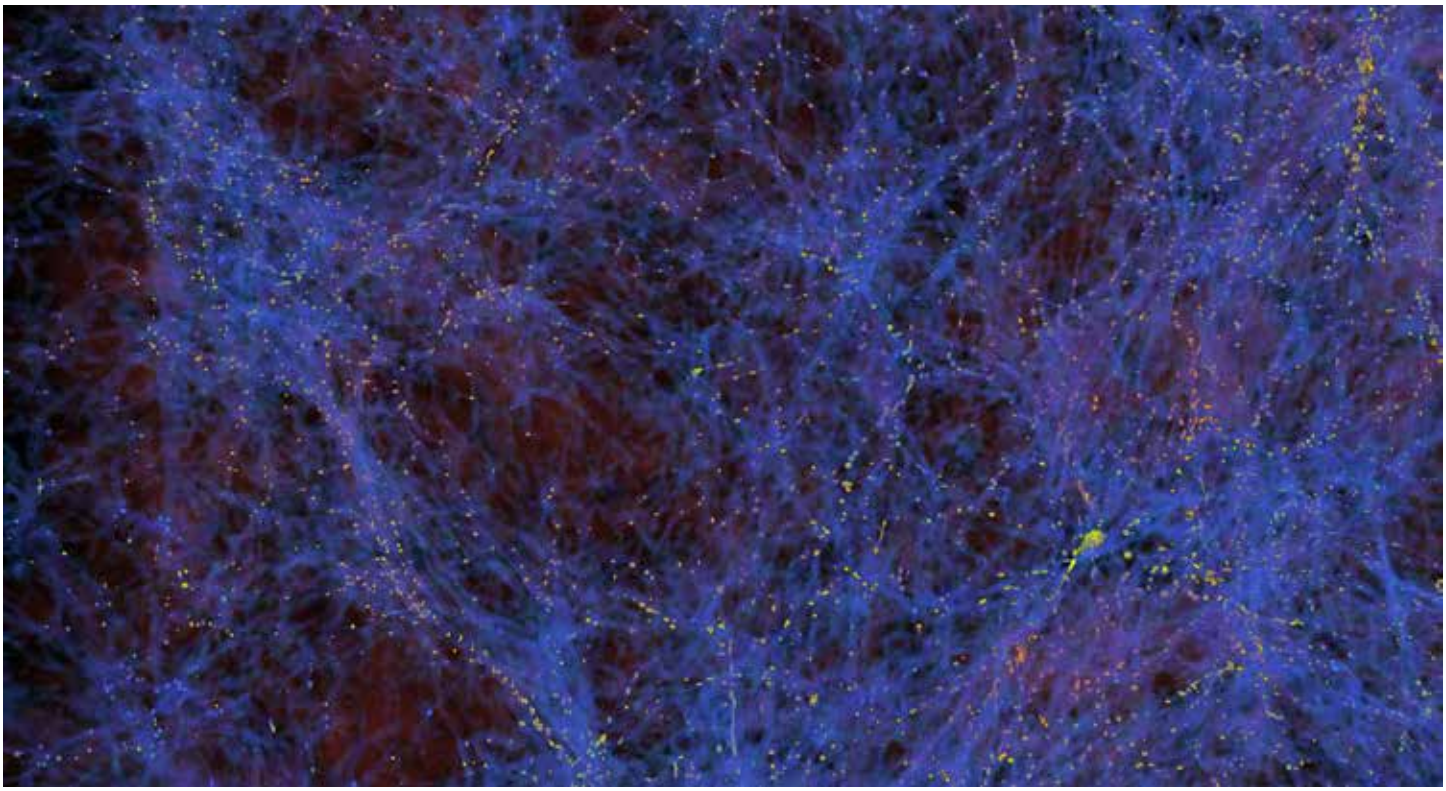

Figure 2. Simulation of the universe, showing density filaments in blue and galaxy formation in yellow.
Dr. Zarija Lukic, which appeared in https://nightsky.jpl.nasa.gov/event-view.cfm?Event_ID=64348

There are of course more than a few engineering challenges, including but far from limited to advancing clock technology. But history shows it can be done. Clocks based on optical atomic transitions are routinely attaining precisions of 18 decimal points; they can be space-hardened, with more reliable components. The Parker Space Probe made it ten times closer to the Sun than Mercury's orbit. We can do the same.

I once heard Jocelyn Bell, discoverer of pulsars, say that learning the nature of dark matter was on her bucket list. I mentioned this in a SciFi short story that suggests we enter the dark matter world after we die [3]. But I don't want to wait that long, so I hope NASA funds the proposed mission!

Dr. Demetrios Matsakis recently retired from being chief scientist for Time Services at the U.S. Naval Observatory where he worked on most aspects of precise timekeeping for 40 years.

[1] Yu-Dai Tsai, Joshua Eby, and Marianna S. Safronova, "Direct detection of ultralight dark matter bound to the Sun with space quantum sensors", Nature Astronomy, 5 December 2022, https://www.nature.com/articles/s41550-022-01833-6.epdf?sharing_token=2MDOLkHmzyE88wl6-zV-lpNRgN0jAjWel9jnR3ZoTv0MqIEd-W7Hc8W_VwTN2IJYXAQ22IrunQM-LE9Pi04oY4rLj2gki957D-tZs3EYYD55d-0ecr9MOH65wlyu09t4sZiDL0cd3wN5qk-BR_aXby6QWC1j_qI_AK9xqwUHd9b7G Orrm9MIpzqHtzFjYvNr7_1P61sGc3uO0d IBT1MikTaWDGYYVyJo0UtsilKfT7HAW ssc%3D&tracking_referrer=www.space.com

[2] Dark energy is the reason the universe is expanding faster and faster over time, rather than expanding less fast or even slower over time.

[3] D. Matsakis, "Beyond", Altered Reality, http://www.alteredrealitymag.com/beyond-by-demetrios-matsakis/, 2018

Case Western Reserve University Wins First Place

For the first time since the start of the COVID-19 pandemic, the Autonomous Snowplow Competition returned to Dunwoody College of Technology in Minneapolis, Minnesota. The Autonomous Snowplow Competition is designed to challenge university and college students to design, build, and operate fully autonomous snowplows to remove snow from a designated path. The 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.

Following the 12th annual competition, which was hosted in separate parts over two years, the 13th annual competition featured a single-year, single-vehicle, fully in-person snow removal event in January, 2023. The theme of the 13th Annual Autonomous Snowplow Competition was *Precise Navigation and Coordination.*

The 13th Annual Autonomous Snowplow Competition was held with the support of the Institute of Navigation (ION) Satellite Division and the ION's North Star Section. This year's preliminary design reviews took place via video conference in mid-December 2022. The final qualification review, vehicle demonstration, safety inspection, and poster presentations were held at Dunwoody College of Technology on January 20th, followed by the snow removal portion of the competition on January 21st.

Teams were scored on a combination of the preliminary design reviews (5%), poster presentation (10%), and performance in the single-T snowfield competition (85%). Separately, teams were also evaluated on their sportspersonship throughout the event.

Teams

Eleven teams hailing from seven universities across the Midwest and Canada participated in this year's competition. Unfortunately, due to several last-minute hardware component issues, the team from the University of Ottawa was unable to participate in the dynamic competition, although they were still able to take part in the preliminary design reviews.

Iowa State University returned to the competition this year debuting their new snowplow, "Snow Clone." North Dakota State University also debuted a new snowplow, "Hyflex" as did Minnesota State University with their new snowplow, "Bad Chicken."

Snowplow Courses

In contrast to the single-I and triple-I courses in past competitions, a new single, straight T-shaped field was debuted at the 2023 event. This required vehicles to plow a more complicated path than in prior years, as the T-shaped field simulated actual conditions such as a driveway leading to a sidewalk. This new field also required vehicles to make an immediate turn after leaving the garage, and to completely reverse at the end of the course to plow toward the other end. To accomplish these objectives, a maneuvering zone was built into the field on both ends of the "T." These new aspects of competition in the snowfield challenged teams to refine their navigation and locomotion strategies.

Each team had two opportunities to

Autonomous Snowplow Competition teams hosted at Dunwoody College of Technology, January 2023

2023 First place winners from team "OTTO", Case Western Reserve University

2023 Autonomous Snowplow Competition Teams

University/Affiliation	*Snowplow Vehicle Names*
Case Western Reserve University	"OTTO"
Dunwoody College of Technology	"Snow Devil;" "Wechuge;" "Wendigo"
Iowa State University	"Snow Clone"
Lake Area Technical College	"Bad Max;" "Fluffy;" "Torque;"
Minnesota State University	"Bad Chicken"
North Dakota State University	"Hyflex"
University of Ottawa	"Caribou"

attempt to clear the snowfield. Teams were judged on the amount of snow their vehicle was able to remove from the path within 20 minutes. Teams were penalized if their vehicle did not autonomously return to the designated garage area. Teams also had the opportunity to earn extra points for timely completion, if their vehicle was able to successfully plow at least 50% of the course.

Two stationary posts were placed on the course to test the vehicles' obstacle detection and avoidance strategies. These stationary posts simulated signposts and trees that a snowplow might encounter in a real-world application. The locations of the posts were not revealed to competitors ahead of time, ensuring the vehicles had to detect them autonomously.

Snowplow Design and Navigation Systems

Each of the teams used a variety of state-of-the-art navigation technology – including lidar, optical navigation systems, inertial instruments, magnetic sensors, ultra-wideband radio reflectors, visual odometry, and even GNSS. The vehicles continue to get more advanced each year, with feature designs that will likely result in a commercial autonomous snowplow product in the future.

The University of Ottawa's Caribou, Lake Area Technical College's vehicles, as well as the three vehicles from Dunwoody College of Technology all featured compact body configurations. Still supporting significant vehicle mass, the smaller designs are a positive step forward toward future commercial applications. Dunwoody College of Technology's "Snow Devil" also featured a magnetic-strip track placed around the snowfield detected by the vehicle to aid in navigation. Dunwoody's "Wendigo" snowplow utilized machine vision and fiducial targets to orient itself.

North Dakota State University's "Hyflex" uniquely articulating snowplow featured state-of-the-art technology and was significantly updated from their vehicles in prior years. Minnesota State University's "Bad Chicken" featured new and improved systems, giving the team more advantages than their previous designs. Lake Area Technical College's "Torque" gave an impressive demonstration this year, with a very smooth manual override capability and lots of power, built and operated by a single student, who showed significant determination and resolve, despite eventual difficulties.

For more information and a complete list of competition winners and scores, please visit www.autosnowplow.com

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Winners and Awards

1st Place:	Case Western Reserve University "OTTO"	$3000 + 1st Place Award
2nd Place:	Dunwoody College of Technology "Wendigo"	$2500 + 2nd Place Award
3rd Place:	Dunwoody College of Technology "Snow Devil"	$2000 + 3rd Place Award
4th Place:	Dunwoody College of Technology "Wechuge"	$1500 + 4th Place Award
5th Place:	Iowa State University "Snow Clone"	$1000 + 5th Place Award
6th Place:	Minnesota State University "Bad Chicken"	$500 + 6th Place Award
7th Place:	North Dakota State University "Hyflex"	
8th Place:	Lake Area Technical College "Bad Max"	
9th Place:	Lake Area Technical College "Torque"	
10th Place:	Lake Area Technical College "Fluffy"	
11th Place:	University of Ottawa "Caribou"	

The Golden Shovel Award, given to the team with the best student poster presentation was presented to Case Western Reserve University's "OTTO" with a cash prize of $500.

The Dr. Nattu Golden Smile Award, which is named after the late University of Michigan-Dearborn advisor, Dr. Narasimhamurthi "Nattu" Natarajan, went to the University of Ottawa's Caribou in recognition of their phenomenal team spirit and sportspersonship.

Investigation of Potential GPS Interference Events in Texas

Zixi Liu, Juan Blanch, Sherman Lo, and Todd Walter

A recent interference event affected air traffic in the general area of Dallas-Fort Worth International Airport (KDFW) on October 17 and 18, 2022, causing widespread disruption. This incident resulted in multiple aircraft reporting their GPS position solutions as unreliable within a 40-NM radius of the airport. Further, one of the active runways could no longer be used as its instrument landing system (ILS) was temporarily out of service and had been using GPS for approach procedures up to that point. The event caused a significant rerouting of air traffic and led to many flight delays and cancellations. The users' reporting impact were primarily aircraft; there were no other known significant public reports of ground infrastructure being impacted during this event.

nals were noticed near San Antonio and Del Rio. These areas appear to regularly experience some form of interference, but only on normal weekdays—not on weekends or holidays, or even outside of normal business hours.

To investigate these events further, ADS-B data was collected from a broad region around Texas with a focus on data centered around Dallas. To identify the affected regions, Stanford GPS Lab used the Navigation Integrity Category (NIC) data from the ADS-B reports to estimate the quality of GPS reception. The NIC describes the size of an integrity containment radius that the current horizontal GPS position is guaranteed to be within with a 99.999% probability. According to the ADS-B equipment performance requirements, under normal circumstances, the aircraft's NIC value should be 7. Therefore, when observing low NIC values, especially NIC = 0, it is often inferred that the aircraft has been severely affected by some interference source(s).

For the Dallas event, an area of 300–460 NM centered at Dallas-Fort Worth and extending North towards Wichita and South towards Austin, was investigated. Within the selected area, ADS-B reports from October 16, 2022, to October 20, 2022, were collected. This time range covered the entire duration of the interference event with some normal days before and after. For potential interference events in Southern Texas, a separate investigation area of 180–250 NM, enclosing San Antonio and Del Rio, was examined. The ADS-B reports for this region from December 10, 2022, through December 25, 2022, were collected. These weeks of data were used to investigate the regular occurrence of aircraft reporting low NICs on workdays but not weekends. In addition to the regular occurrence in Southern Texas, it was noticed that, for the October interference event that happened in Dallas, there were other regions outside of the main affected area that had low NIC values. Specifically, there were three other regions that contained position points with low navigation accuracy (see Figure 1). Low NIC values were observed in these regions both before and after the main interference event near DFW.

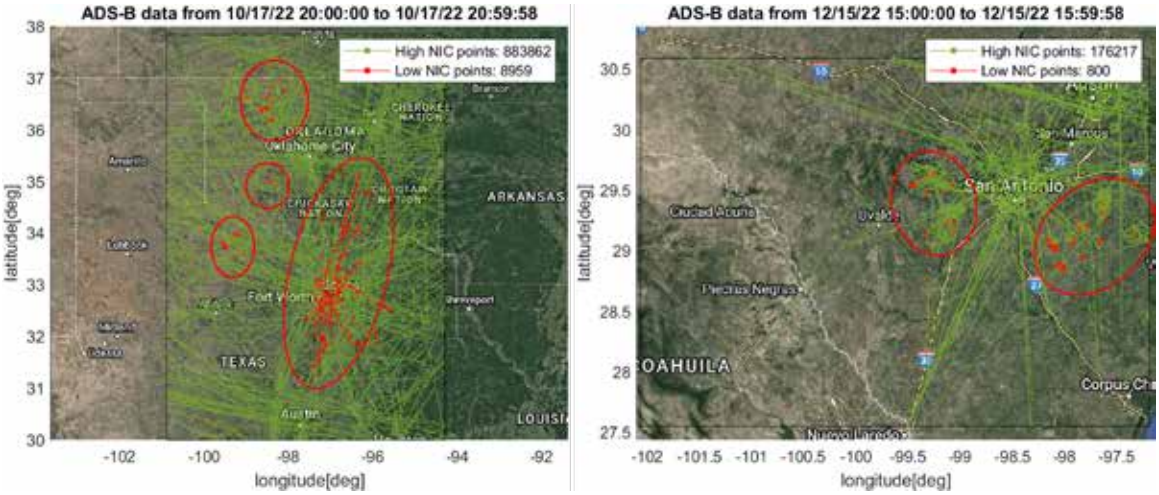
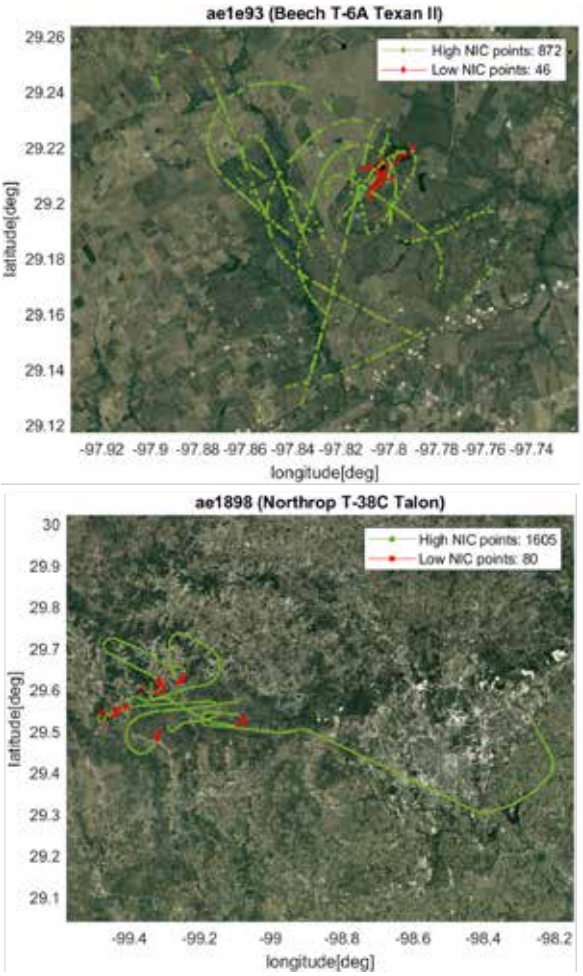


Figure 1. Flight trajectories over 1 hour: Red indicates low navigation accuracy (low NIC value) and green indicates normal navigation accuracy (high NIC value).

Automatic Dependent Surveillance – Stanford Researchers Examine the Broadcast Reports

Data collected from the Automatic Dependent Surveillance—Broadcast (ADS-B) system provides one of the best measures on the effect of a radio-frequency interference (RFI) event like the October 2022 Dallas event. ADS-B periodically broadcasts GPS-derived aircraft position information, and each message includes parameters that indicate the integrity and accuracy levels of the reported GPS measurements. Stanford's GPS Lab monitored the ADS-B reports collected from Texas and the surrounding area, and regular interference of GPS sig-



https://upload.wikimedia.org/wikipedia/commons/thumb/d/d8/T-6A_Texan_II.jpg/300px-T-6A_Texan_II.jpg

https://upload.wikimedia.org/wikipedia/commons/thumb/3/3f/T-38_Talon_over_Edwards_AFB.jpg/300px-T-38_Talon_over_Edwards_AFB.jpg

Figure 2. Two of the most common types of observed military trainer aircraft and their sampled flight trajectories

Investigation Results and Conclusions

Each aircraft's flight trajectory, ICAO identification number, aircraft models, as well as when and where each flight reported low NIC values, were examined. It was discovered that the regular occurrence of aircraft reporting low NICs in Southern Texas, and in the three other regions outside the main affected area in DFW, were all from aerobatic military trainer aircraft. These aircraft were doing unusual and rapid flight maneuvers such as tight turns with high bank angles; the reported low NIC values were not a result from interference affecting GPS signals, but rather a result of aircraft maneuvering. High bank and high dynamic maneuvers can typically lead to a loss of GPS signal on the aircraft. This intermittent loss of track on GPS signals can cause the onboard ADS-B system to report low NIC values. In addition, those low NIC values were aircraft specific; other commercial airplanes flying nearby were all reporting high NIC values, showing no evidence of the existence of interference. Therefore, even though low NIC values are often inferred as resulting from GPS interference, in this case, the reports from military trainer aircraft were not associated with interference. It is important to identify such cases of low NIC values, as they can be misleading for interference detection.

The above information not only solved the mystery of the strange recurring sequence of low NIC reports from Southern Texas, but also improved the understanding of the Dallas interference event, both in terms of timeline and impact region. By filtering out those military trainer aircraft, rather than four different areas, there was only one affected region centered at the Dallas-Fort Worth airport. In terms of timeline, according to public sources, air traffic was disrupted for 44 hours. However, the actual interference lasted for only 24 hours, and within that interval, there was a 5-hour gap when all ADS-B reports were showing high NIC values.

Identifying Future Sources of Disruption

The source of this disruption has still not been identified, and work is still being done to better identify potential locations for the disruption source. Applying Stanford's localization algorithm to this event identified characteristics from the potential jamming source. There can be a significant variation of the most-likely jammer location depending on the assumed broadcast antenna characteristics. (For details on the algorithm's design, please see the full paper presentation at the ION's 2023 International Technical Meeting; citation information follows the end of this article.)

Rapid detection algorithm design and accurate localization of GNSS interference sources continue at Stanford's GPS Laboratory. Using the algorithm, the Stanford GPS Lab plan to rapidly detect the existence of a GPS interference event, identify the most-likely location of the interference source, and provide an error bound. By narrowing the ground search area, authorities will be better able to quickly locate and disable jamming sources. This service will help protect the safety of aviation from GPS interference events and limit widespread disruption like the event that happened in Dallas.

For the full manuscript please see: Liu, Zixi, Blanch, Juan, Lo, Sherman, Walter, Todd, "Investigation of GPS Interference Events with Refinement on the Localization Algorithm," *Proceedings of the 2023 International Technical Meeting of the Institute of Navigation,* Long Beach, California, January 2023, pp. 327-338. https://doi.org/10.33012/2023.18627

Securing PNT for Highly Automated Transportation Systems

Zak M. Kassas

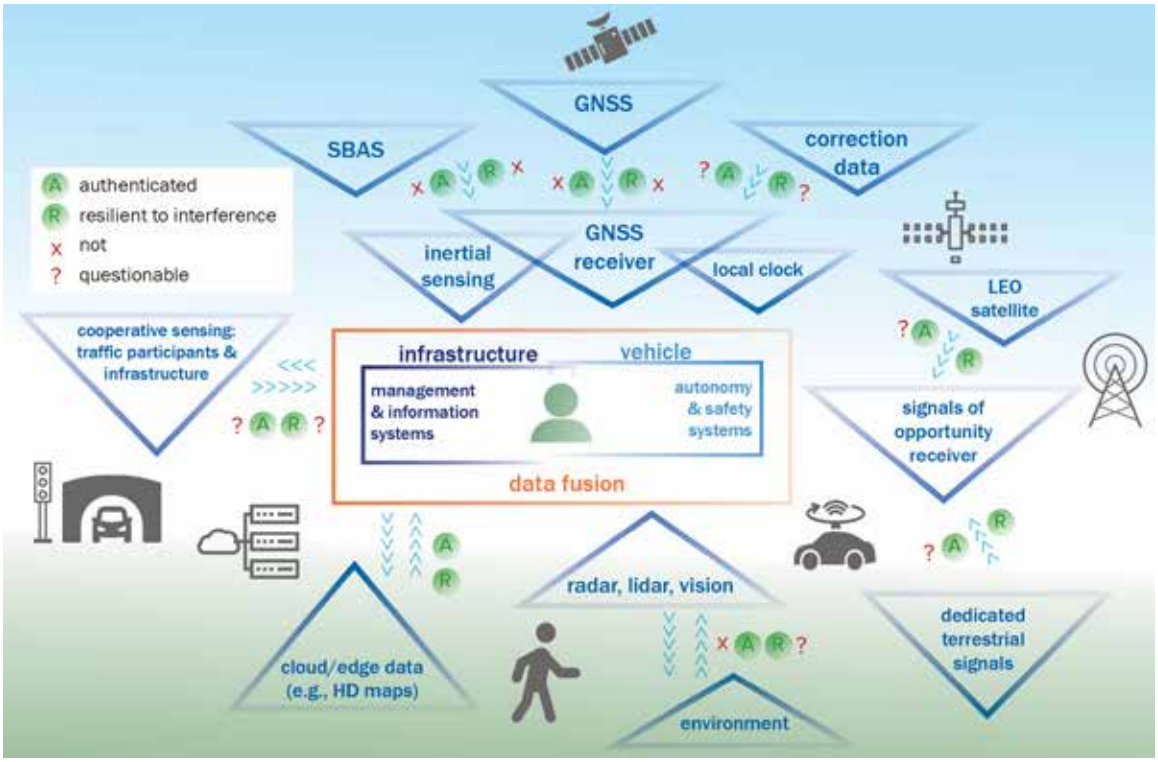
Transportation systems are undergoing the automation revolution. From urban air mobility to self-driving cars, integrating these highly automated vehicles into our daily lives will have astounding societal and economic impacts.

Highly automated transportation systems (HATS)–whether ground, air, or maritime; rely on a steady stream of signals and information from external sources for localization, route planning, perception, and general situational awareness. This includes reliance on positioning, navigation, and timing (PNT) information: Location is essential both for short-range driving control and long-range navigation and planning; and accurate timing is a precondition for on-board sensor fusion, cooperative planning and control, and management based on information from other vehicles or the infrastructure.

Current HATS are too trusting of such external information, and too fragile in the face of loss or attenuation of vital PNT and communications links.

There is a global trend of increasing interference, whether accidental or deliberate, in radio bands crucial for HATS. GNSS jamming and spoofing have evolved from a hypothetical threat, to an experimentally-verified vulnerability, to an emerging public safety hazard. The obvious risk for highly automated vehicles is loss of ability to produce an accurate, sustainable position, velocity, and time solution in a global map with sufficiently high integrity. The risks for vehicle networks and transportation management systems are increased traffic congestion and collisions due to inadequate or misleading situational information.

Despite encouraging progress over the past decade, the vulnerability of externally-sourced information vital to PNT



CARMEN UTC Vision: Human transportation participants (center) depend on vehicles and infrastructure that fuse data from a host of external sources. Many of the vital links to these sources lack authentication (A) or resilience (R). The CARMEN UTC identifies, develops, and validates PNT sensing techniques for HATS that are both resilient to unusual natural or accidental events and secure against deliberate attack.

CARMEN UTC proving grounds at OSU: (a) Skyview of the Transportation Research Center; (b) an autonomous vehicle at the Center for Automotive Research, (c) anechoic chamber at the ElectroScience Laboratory, and (d) OSU Airport

and to situational awareness remains an open problem for HATS. Yet a solution must soon be found: interference cannot be allowed to paralyze a city's transportation network. Vehicle manufacturers, suppliers, fleet operators, and human drivers/pilots have some knowledge of the threats to HATS PNT, but they do not fully appreciate the threats' scope and seriousness. They tend to rely on security and resiliency schemes that address bare minimum requirements, leaving serious weaknesses exposed.

US DOT CARMEN

In March 2020, the US Department of Transportation (DOT) announced a competition to establish Tier 1 University Transportation Centers (UTCs) in four topic areas. The competition was fierce, with 67 consortia applications. The Ohio State University (OSU) led a consortium comprising The University of Texas at Austin (UT); University of California, Irvine (UCI); and University of Cincinnati, that was awarded a UTC in the area of HATS.

This UTC, named CARMEN: Center for Automated Vehicles Research with Multimodal AssurEd Navigation, is squarely focused on four main objectives:

1. Gather and systematize existing knowledge and identify gaps in knowledge/practice related to GNSS/PNT threats to HATS
2. Carryout risk identification studies to understand the impact of PNT threats on HAVs
3. Develop new PNT lapse mitigation strategies for HATS, which are (i) robust in the face of unusual natural or accidental events and (ii) secure against deliberate attacks
4. Complement existing methods for cyber resilient PNT receiver testing, develop new mitigation methods, and propose standards and create "best practices" documents and guidelines

Led by Prof. Zak Kassas, the CARMEN UTC comprises a blue- ribbon team with complementary expertise in (i) PNT: Zak Kassas, Dorota Grejner-Brzezinska, Todd Humphreys, Charles Toth, and Teh-Hong Lee; (ii) Automotive: Keith Redmill, Qadeer Ahmed, Alfred Chen, Giorgio Rizzoni, and Kelly Cohen; and (iii) Transportation: Chandra Bhat, Umit Ozguner, Stephen Ritchie, and Craig Rindt.

OSU, the CARMEN UTC lead institution, possesses unparalleled facilities being utilized to validate the UTC's research outcomes: (i) Transportation Research Center (TRC, Inc.): North America's largest multi-user automotive proving ground; (ii) Center for Automotive Research (CAR): 30-plus years of experience in the research and development of intelligent transportation systems and highly automated vehicles (sensing, control, communication systems, embedded systems, cybersecurity, testing, and deployment); (iii) Electroscience laboratory (ESL): world-class research center in electromagnetic scattering, antennas, propagation, remote sensing, signal processing, and photonics, housing the largest active academic anechoic chamber in the world; and (iv) OSU airport: one of three airports owned by top-tier research universities nationwide with three runways and a control tower supporting over 80,000 aircraft operations annually.

Future Outlook

In February 20223, DOT announced the selection of the CARMEN+ UTC, from among 169 UTC proposal applications, as one of its 20 new Tier 1 UTCs. Building on CARMEN's success and expanding its scope, CARMEN+ will receive $15M over the next five-years to address DOT's research priority of cybersecurity. Led by Kassas, CARMEN+ will involve 20 PIs from OSU (lead institution), UT, UCI, and NC A&T.

Zak M. Kassas is a Professor of Electrical and Computer Engineering at The Ohio State University and Director of the US DOT CARMEN UTC. His emails is: kassas.2@osu.edu

Regiomontanus

Marvin B. May

After enduring the ravages of the Dark Ages for several centuries, Mongol and Turk invasions, and the Black Death, the beginning of the 15th century marked a turning point for western civilization. From a navigation perspective, it was the Portuguese, under the leadership of Prince Henry the Navigator, (see Historian Newsletter Articles from Winter and Spring 2009-2010) that led the reawakening of European creativity with explorations of newly found territories in the Atlantic Ocean beginning in the 1420's.

From a broader perspective, the invention of the movable type printing press in 1452 by Johannes Gutenberg (b.1400-d.1468) of Mainz, Germany, was the epochal event of the second millennium. The combination of movable type, mechanical molds, and oil-based ink led to a practical system that allowed the mass production of printed books, and was economically viable for publishers and readers alike. This invention has been universally heralded as introducing the era of mass communication, which permanently altered the structure of society. In 1997, *Time–Life* magazine picked Gutenberg's invention as the most important of the second millennium.

Two years after the printing of The Gutenberg Bible, mathematical and astronomical prodigy Johann Müller of Königsberg, Germany, was awarded a master's degree from the University of Vienna. The Latin version of Königsberg (meaning King's mountain) is Regio Monte or, as he later became referred to as Regiomontanus. Regiomontanus was appointed to the faculty at the University of Vienna where he specialized in mathematical astronomy and cosmology.

Collaborating with his mentor, Georg Von Peuerbach (b.1423-d.1461), himself an accomplished astronomer, they compiled an edited and expanded version of Ptolemy's 2nd century AD *Almagest.* The *Almagest*, originally written in Greek, is an astronomical manual that served as the basic guide for Islamic, and later European, astronomers until the late 15th century. The Peuerbach-Regiomontanus epitome of Ptolemy's great work was invaluable as a reference for Renaissance astronomers. This edition was almost certainly the text which provided Nicolaus Copernicus (b.1473-d.1543) with his knowledge of the Ptolemaic system, which had formed the basis of astronomy for more than a millennium. Copernicus went on to lay the foundations of modern astronomy with his revolutionary heliocentric system, contradicting the Ptolemaic geocentric worldview engrained in Christian theology.

Regiomontanus realized the potential value of printing multiple copies of scientific texts, which could be carefully edited with accurate diagrams. At Nuremberg, Germany, only 140 nautical miles from Mainz, Germany, he set up a printing press in his own house, and in 1471-1472

Regiomontanus, royal astrologer of the late Middle Ages
Smithsonian

Manuscript copy of the Calendarium and Ephemerides as published by Regiomontanus in 1474. Kislak Center for Special Collections, Rare Books and Manuscripts, LJS 300. Lambach?, Austria, 1500
Penn Libraries Catalog

printed a prospectus announcing his detailed plans for publishing many carefully edited mathematical, astronomical, and geographical texts. He thus became the first publisher of this type of scientific literature, which included ancient, mediaeval, and modern works.

Regiomontanus's first publication was *New Theory of the Planets,* authored by his former teacher Peuerbach, followed by his publication of his own calendar *Kalendarium* in 1474, and then his *Ephemerides.* He wrote the seminal treatise on solving spherical triangles, a fundamental necessity for utilizing celestial navigation. These books were reprinted many times and had great influence; for example, both Italian explorers Christopher Columbus (b.1451-d.1505) and Amerigo Vespucci (b.1454-d1512) used Regiomontanus's Ephemerides to measure longitudes in the New World.

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The following web sites were among those used in the preparation of this article:

https://mathshistory.st-andrews.ac.uk/Biographies/Regiomontanus/

https://en.m.wikipedia.org/wiki/Johannes_Gutenberg

Regiomontanus (1436 - 1476) - Biography - MacTutor History of Mathematics (st-andrews.ac.uk)

The Navigation Hall of Fame nominations reported on in recent ION Newsletter articles, are periodically being updated. Based on the research done for this article, Regiomontanus will be added to the Navigation Hall of Fame. I solicit the readership to provide further nominations.

Defense Matters

National Cybersecurity and National PNT

Are we getting closer? Not really.

Not a day seems to pass without a new report in the news about data breaches, cyber-attacks, and what we need to do to protect ourselves from being hacked, having our identity stolen, and our privacy compromised. These endless reports highlight our constant struggle to block threats from those with bad intentions.

As we march to the drumbeat of absolute reliance on the Internet for nearly everything we do, our smartphones have become the most important item we carry. To leave home without your phone can make for a distressing, frustrating day. Phones are essential for communicating, keeping track of our e-mails, accessing our bank accounts, and knowing where we are and where we are going.

More and more applications are employing password policies that increase the password's strength, with requirements governing password length, required or prohibited character types, and how often a user must change a password (ever more often, it seems). Many applications are implementing a secondary piece of electronic security - multi-factor authentication, which makes our phones even more critical to have with us in order to gain access to our data.

National Cybersecurity Strategy

On 2 March 2023, the Biden Administration released the *2023 National Cybersecurity Strategy.* This strategy replaced the Trump era, *2018 National Cyber Strategy.*

The 2023 strategy was noted to be in development for nearly two years and involved more than 20 government agencies and consultations with a large number of private sector organizations. [Note: In that regard, its developmental duration nearly paralleled the creation of the National PNT Architecture between early 2006 and mid-2008, an effort involving over 30 agencies.]

Development of the Cybersecurity Strategy was initiated by the Biden Administration's May 2021 *Executive Order on Improving the Nation's Cybersecurity.* This Executive Order indicated that the Federal Government must lead by example for the prevention, detection, assessment, and remediation of cyber incidents to protect the nation's digital infrastructure, which is essential to national and economic security.

On page 2 of the Strategy's *Introduction,* under the heading of *Emerging Trends,* there is a discussion on the "deepening digital dependencies" of systems where next-generation interconnectivity is "collapsing the boundary between digital and physical worlds, and exposing some of our most essential systems to disruption."

This passage goes on to state, "Our factories, power grids, and water treatment facilities, among other essential infrastructure, are increasingly shedding old analog control systems and rapidly bringing online digital operational technology."

Missing the PNT Point

It is here that positioning, navigation, and timing (PNT) gets a brief nod in the form of "…space-based assets – including those enabling positioning, navigation, and timing for civilian and military uses…will accelerate this trend, moving many of our essential systems online and making cyberattacks inherently more destructive and impactful."

Unfortunately, the point being made is not that over-reliance on GPS as a source of PNT is the problem, but rather that the emergence of space-based technologies such as GPS are simply creating more digital systems that are PNT reliant.

The assumption that a shift toward such space-based technologies, rather than the explicit reliance on them alone, is making essential infrastructure systems more vulnerable to cyberattacks is the flawed reasoning that skirts the issue.

It is unfortunate that the Administration has missed an opportunity to elevate the need to invest in alternate sources of PNT to address the overreliance on GPS as the single source of PNT. Clearly the phrase PNT as used in this Strategy is just another way of saying GPS; and the bad actors that may seek to disrupt those essential infrastructure systems know that GPS is vulnerable.

Reading further, the 2023 Strategy is built around five pillars: defend critical infrastructure; disrupt and dismantle threats by malicious cyber actors; shape

Doug Taggart
President
Overlook Systems Technologies, Inc.

market forces to drive security and resilience; invest in a resilient future; and forge international partnerships to pursue shared goals.

Those five pillars line up well if the intended focus can be broadened to developing alternate sources of national PNT capability as a way to achieve the desired security and resilience.

It is asserted that for the nation to address these five pillars, two fundamental shifts in the roles, responsibilities, and resources in cyberspace must occur.

The first is that stewardship of the digital ecosystem must shift away from individuals, small businesses, and local governments, and toward organizations that are best positioned to address wider-reaching security and resilience.

The second is characterized as a rebalance of incentives and investments between building a secure and resilient foundation for the future digital ecosystem and defending ourselves against urgent threats of the day.

Again, the "fundamental shift in roles" lines up well if the intended focus of the strategy is to develop alternate sources of national PNT capability.

Looking back on the Trump era 2018 Cyber Strategy, which demonstrated a commitment to a significate agenda on space issues, there was a single reference to PNT (on page 10) where it states, "The Administration is concerned about the growing cyber-related threats to space assets and supporting infrastructure because these assets are critical to functions such as positioning, navigation, and timing (PNT)…" but that mention of GPS reliance was not made in the context of identifying alternatives, but simply recognizing that attacks on GPS were concerning from the perspective of the cyber world.

How the DoD is Proceeding

Looking to the defense side of developing a more robust and resilient PNT capability for the warfighter, a key purpose of the DoD PNT Enterprise strategy released in 2019, is to meet national objectives for improving U.S. global military effectiveness through DoD-wide implementation of not only GPS modernization, but also new integrated PNT applications to augment GPS. The strategy is specifically intended to encourage DoD PNT application designers to use modular, open-system approach techniques to integrate a diverse mix of PNT sources within individual DoD systems based on the operational environments each will be required to face.

Challenges Remain

National defense spending as a percentage of GDP has dropped from 5.8 percent in 1985, the height of the last global competition, to 3.2 percent in 2021.

In addition, in 13 of the past 14 years, the Defense Department has operated under a continuing resolution for part of the year, preventing the new starts essential for modernization. The 2024 White House Funding request for $842 billion in defense funding is noted to be 3.2 percent above the 2023 budget, which is unfortunately still beneath the rate of current inflation. Further, we are in a marketplace where fundamental good practices must compete for resources with shiny new add-ons and the latest features. Instead of using sound engineering principles to build strong, resilient systems, the majority of the money and attention has gone to adding yet another layer of patches and extensions on top of fundamentally broken technologies. Despite those realities, the DoD is paying additional attention to equipage of key Joint Force platforms with modernized GPS equipment and integrated complements using diverse sources of PNT information that ensure functionality should GPS be disrupted.

For the DoD, the PNT end state is straightforward: ensure that our warfighters have robust and resilient PNT-enabled platforms, services, and technologies to maintain operational superiority, never engaging any competitor on an even technological basis.

ION SATELLITE DIVISION

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+ meeting 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 instructions, or 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.

To view a complete list of previous Kepler Award winners, please visit ion.org/awards/kepleraward.cfm.

Dr. Boris Pervan, 2022 Kepler Award winner. For his pioneering contributions to high-integrity GNSS-based aviation navigation and his dedication to education.

The Business of GNSS

By Kevin Dennehy

Since our last column, big news came from ION member HERE Technologies when it launched UniMap, which provides up-to-date and unified map content for automated driving, logistics and enterprise markets.

While mapping updates used to take months, UniMap allows customers to have unified maps that are refreshed in seconds, said Giovanni Lanfranchi, HERE's senior vice president and chief product and technology officer.

"This a transformation we started three years ago. We said, let's really unify all the pipelines we have into one single end-to-end automated pipeline," he said. "From there, we can feed use cases from classic car navigation, search places, [SAE] Level 2-3 autonomous driving and navigation on demand."

UniMap uses AI models to automate 500 million kilometers of vehicle probe and sensor data every hour, extract map features such as 2D and 3D positioning of road signs, validate speed limits, and to build missing road geometry, the company said. HERE has been developing the technology with such automotive companies as BMW Group. UniMap is set for a rollout to select customers this year before being available to all company customers in 2024.

In other GNSS business news, ION Member Trimble announced a deal with Nissan Motor Co. to use its RTX technology as the positioning source for the ProPILOT Assist 2.0 driver assistance system. ProPILOT, available on the 2023 Nissan Ariya, features Trimble's RTX that enables consistent lane-level positioning, the company said.

Trimble's RTX positioning technology can provide decimeter-level accuracy in seconds, making it an ideal solution for autonomy applications, the company said.

Nissan's Ariya has ProPILOT Assist with Trimble's RTX
Nissan

PointPerfect GNSS Augmentation Service Expands to Canada

GMV and ION member u-blox [UBXN] recently partnered to combine u-blox's GNSS receiver hardware with GMV's safe correction service, sensor fusion and positioning engine for the automotive industry.

Starting this summer, u-blox will commercialize the solution. Both companies will provide integration service and certification support for advanced driver-assistance systems (ADAS) 2+ and up to full vehicle autonomy, the companies said.

Thalwil, Switzerland-based u-blox also announced that the coverage of the PointPerfect GNSS augmentation service was expanded to Canada. The expansion includes both L-band satellite and mobile internet IP service and is available up to 12 nautical miles off coastlines, the company said.

PointPerfect is available through Thingstream, u-blox's IoT service delivery platform. PointPerfect is the first PPP-RTK (Precise Point Positioning, Real-Time Kinematic) high-precision positioning solution commercialized in the region, the company said.

U-blox's worldwide PointPerfect coverage
U-blox

Topcon Provides GNSS Correction Services for California Emergency Response

ION member Topcon Positioning Systems offered free access to its GNSS correction services network to emergency response agencies and personnel in designated California disaster areas earlier this year.

"During major disaster response and recovery, local utilities and municipalities, local FEMA and Army Corps of Engineers, essential emergency services such as utility and construction companies have to go out and find out what's broken, what's been wiped out,

and they need the ability to utilize positioning technology," said Jason Killpack, director, business development, emerging business, Topcon Positioning Systems, in a statement.

The company also launched a GNSS option for its MC-Mobile compact machine control solution. The GNSS option allows contractors to integrate their compact machines into fleets already powered by location technology, the company said.

Another company, Safran Electronics & Defense, which purchased ION member Orolia last summer, has consolidated its positioning, navigation, and timing (PNT) technology and another unit into one called Navigation & Timing.

The new Navigation & Timing unit will include inertial measurement technologies and control; systems, algorithms, and architectures for interference detection and mitigation; sensor fusion and update technologies; GNSS technologies, including simulation; and clocks and timing.

JAVAD GNSS' T3-NR GNSS Network Rover
JAVAD

In Other Company News:

ION member JAVAD GNSS' new T3-NR is a small and light GNSS Network Rover, with an integrated MEMS IMU, designed for a full day of field work, the company said.

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

Multi-Frequency Simulation of Ionospheric Scintillation Using a Phase-Screen Model

Fernando Nunes and Fernando Sousa

Ionospheric scintillation constitutes a major source of degradation of global navigation satellite system (GNSS) signal quality: it may lead to carrier cycle slips, navigation bit errors, and may even prevent the receiver's operation. It is important to have tools to evaluate the receiver's robustness in ionospheric scintillation scenarios. In general, it is difficult to gather large amounts of experimental data in those scenarios because they depend on solar activity and may be collected only on certain occasions in places near the equator or the poles. This means that reliable and computationally efficient simulation tools are welcome.

This paper proposes a new fast Monte-Carlo technique to simulate the amplitude and phase effects of equatorial ionospheric scintillation on satellite transmitted signals, which is useful for assessing the performance of GNSS receivers. The method uses a single-layer phase-screen model of the ionosphere in which it is assumed that a train of plasma total electron content (TEC) irregularities drift eastward with constant velocity. The TEC depletion for each electron density irregularity is chosen randomly using, for instance, a uniform distribution generator. The shape of the irregularities is made triangular in the x-direction, allowing for easy determination of the ionospheric scintillation random process. This process is expressed analytically by the

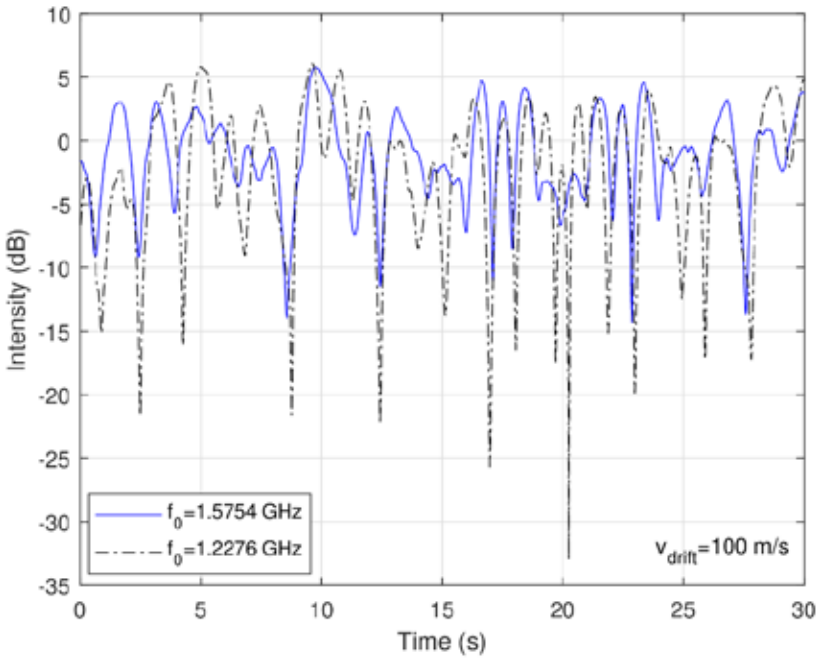


Figure 1. Fading intensities generated by a common scintillation process for different carrier frequencies (bands L1 and L2)

Huygens-Fresnel complex integral, which can be computed by a sum of Fresnel cosine and sine integrals, thus avoiding the use of lengthy numerical integrations and making the computation fast. The model of the plasma density irregularities is characterized by a small number of parameters including the drift velocity of the irregularities, their size, the maximum TEC depletion, and the separation between them. These parameters may be freely adjusted, aiming to simulate different scintillation scenarios. Contrary to some popular simulation methods that separately generate the amplitude and phase sequences (time-series) of faded signals and resort to independent models, the proposed methodology allows us to simultaneously obtain sequences in a consistent way.

Values of scintillation index S4 up to approximately 1.3 can be obtained, encompassing the weak, moderate, and strong classes of scintillation strength. The distributions for the amplitude and phase of the disturbed signals versus S4 were calculated and it was shown that, in general, the amplitude of the fading process is difficult to characterize in terms of known distributions (it was suggested that it could be characterized as a finite mixture of distributions). However, for strong scintillation scenarios, it was verified that the amplitude is well approximated by the generalized gamma (or alpha-mu) distribution, as it happens in real scenarios. The argument of the Huygens-Fresnel integral was utilized to generate unwrapped phase sequences that are useful to evaluate the performance of phase-locked loops in GNSS receivers. Several statistics were calculated for signals generated with the proposed technique, including fading duration and depth, separation between fades, peak-to-peak phase change, and maximum phase change rate. It was verified that the power spectral density function of both

phase and intensity follows an inverse power-law distribution and depends on the drift velocity of the electron density depletion regions. Results obtained for the L1, L2, and L5 bands have shown good agreement with the results provided by experimental data.

A significant advantage of the synthesized intensity time-series over the experimental ones is that time-series with constant scintillation statistical characteristics and an arbitrarily long duration can be generated, in contrast with real signals whose characteristics are typically non-stationary over intervals longer than a few minutes. With experimental data, some configurations for the parameter S4 and the plasma irregularity drift velocity may not be available. Another convenient feature of the proposed Monte-Carlo simulation technique is the ability to simultaneously generate fading processes for different bands using a common ionospheric scintillation model with a plausible physical justification, as shown in Figure 1. This is useful, for instance, to assess the performance in multi-band receivers.

Monte-Carlo simulation tools that generate synthetic data simultaneously affected by amplitude and phase disturbances in various equatorial scintillation scenarios are advantageous. The proposed methodology may be used to statistically evaluate the performance of existing GNSS receiver architectures in military and commercial applications as well as to develop and test new receiver architectures able to withstand large intensities of ionospheric scintillation. Another possible application is the development of new algorithms for scintillation detection.

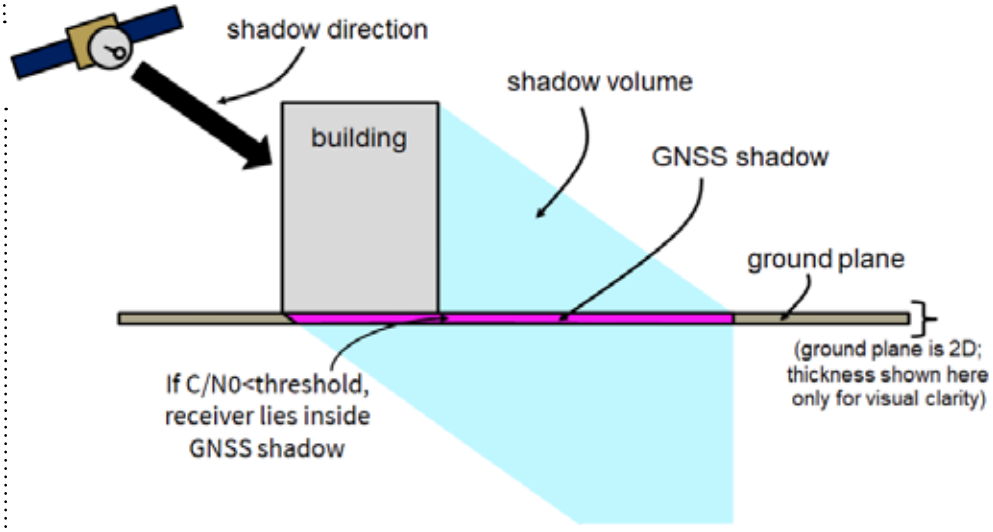
For the full article, and accompanying data and figures, please see:

Nunes, F. D., Sousa, F. M. G., & Marçal J. M. V. (2022). Multi-frequency simulation of ionospheric scintillation using a phase-screen model. *NAVIGATION*, 69(4), https://doi.org/10.33012/navi.545

Set-Valued Shadow Matching Using Zonotopes for 3D-Map-Aided GNSS Localization

Grace Gao

Zonotope shadow matching (ZSM) enables an exact set-valued localization estimate in urban areas, unlike prior methods which create either point estimates or coarse set representations (e.g., confidence ellipsoids) that cannot capture the true multimodal, geometric nature of urban localization.



The key experiment in the paper compared ZSM against conventional shadow matching. ZSM produced a more accurate and precise localization estimate by avoiding the coarse gridding of the urban environment. Critically, the runtime of our algorithm is not excessive, meaning this technology has high potential for practical deployment.

In terms of PNT, the ZSM results provide a new, set-valued way of thinking about the position component of PNT, which is directly useful in safe motion planning and control for autonomous urban systems. This also highlights the broader impact of this technology: ZSM provides a bridge between the navigation and robotics/control communities to enhance safety and performance in future technologies such as autonomous driving and urban drone delivery.

It is anticipated that future ZSM technology will directly integrate with autonomy stacks (i.e., perception, planning, and control) to provide a safety-aware representation of a mobile system's state. For example, ZSM can provide an autonomous car both its position and associated uncertainty in a way that directly takes advantage of the car's surroundings. In the longer term, the underlying mathematical techniques used to enable this method may also have applications outside of shadow matching to solve other problems in PNT, such as multipath detection.

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

Gao, G., Bhamidipati, S., & Kousik, S. (2022). Set-valued shadow matching using zonotopes for 3D-map-aided GNSS localization. *NAVIGATION*, 69(4). https://doi.org/10.33012/navi.547

Winner of the ION's 2022 Samuel M. Burka Award recognizing outstanding achievement in the preparation of a paper advancing the art and science of positioning, navigation, and timing

Robust Modeling of GNSS Orbit and Clock Error Dynamics

Elisa Gallon, Mathieu Joerger, and Boris Pervan

This paper contributes to providing GNSS-based navigation safety guarantees. While overbounding theory establishes high-integrity error models of measurements at one instant in time, this paper answers the question of how to robustly account for error dynamics over time.

To ensure navigation integrity, the models of the navigation error must bound the actual errors. The term overbounding is used when referring to error distributions. In safety-critical applications, particularly in aircraft en-route and vertical guidance, snapshot positioning techniques are employed. However, more and more applications are shifting towards recursive techniques including Kalman filters (KFs) which can provide higher accuracy than snapshot approaches. Recursive techniques require models that account for the time correlation of the errors. These models must be bounding if they are to be used in safety-critical applications. No such error models are available in the literature. In this paper, a methodology is outlined and error models are developed for the orbit and clock errors of GPS and Galileo satellites.

Three years (from 2018 through 2020) of reference and broadcast satellite positions were used to generate orbit and clock errors of the GPS and Galileo satellites. These errors, and the impact of the satellite clock on ranging errors, were analyzed and evaluated. Separate bounding models were derived through power spectral density bounding for each of the two clock types of each constellation: Rubidium/Cesium for GPS and RAFS/PHM for Galileo. These time-correlated bounding error models can be used in applications requiring high integrity and measurement filtering.

New error models are currently evaluated in multi-frequency, multi-constellation advanced receiver autonomous integrity monitoring (ARAIM). They are tested in receiver algorithms and analyzed offline to evaluate the potential of combining GPS and Galileo in future aviation navigation applications. The circumstances under which ARAIM can safely guide an aircraft towards a runway, and how close it can be guided to that runway, are currently being determined.

The scope of applications for overbounding theory includes safety-critical navigation for aviation, autonomous ground vehicles, and rail and harbor transportation. The methodology implemented in this paper could have generic applications when filtering out noisy measurements, and the models apply to both GPS and Galileo data. The methodology and models facilitate the integration of GNSS and INS measurements in a KF for aviation applications.

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

Gallon, E., Joerger, M., & Pervan, B. (2022) Robust modeling of GNSS orbit and clock error dynamics. *NAVIGATION*, 69(4). https://doi.org/10.33012/navi.539

Modified CEMIC Scheme for Multiplexing Signals Over Single Frequency Band

Vijay S. Bhadouria, Dhaval J. Upadhyay, Parimal J. Majithiya, and Subhash Chandra Bera

Satellite-based navigation provides open, restricted, and commercial services across one or more carrier frequencies. Multiple navigation services on the same carrier frequency need each navigation satellite to transmit multiple signals. It needs onboard multiplexing of navigation signals over the single carrier frequency before satellite transmission. Signal multiplexing techniques provide a constant envelope waveform to avoid nonlinear distortion from an onboard

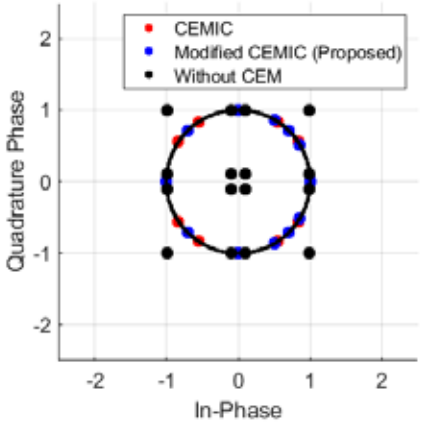


Figure 1: Constellation diagram of the signal generated by the original CEMIC and modified CEMIC scheme

high-power amplifier (HPA) operating at saturation. Operating onboard an HPA under saturation conditions provides maximum power efficiency and better performance, which is desirable for satellite design and operations.

The GNSS community has conducted extensive research to reduce the multiplexing loss caused by the multiplexing method. In literature, various amplitude and phase-domain optimization iterative methods have been proposed to generate constant envelope composite signals. Unlike phase-domain processing, amplitude-domain processing

provides an accurate analytical expression that is representative of the composite signal. This information is needed to predict intra- and inter-system interferences for coordination with other GNSS service providers. Constant envelope multiplexing using intermodulation construction (CEMIC) is a state-of-the-art method to multiplex more than three signals over a single frequency efficiently.

Modified CEMIC Scheme: A Technique to Support Signal Diversity With Backward Compatibility

Navigation receiver architecture depends on signal type, power, and transmission phase relative to other signals on the same frequency band. A multiplexing scheme must account for the signal structure of operational navigation services. The proposed solution adds backward compatibility to the CEMIC scheme cost function. Simulations demonstrate that the modified CEMIC technique meets backward compatibility requirements and has better multiplexing efficiency than the existing CEMIC scheme, as shown in Figure 2 and Figure 3.

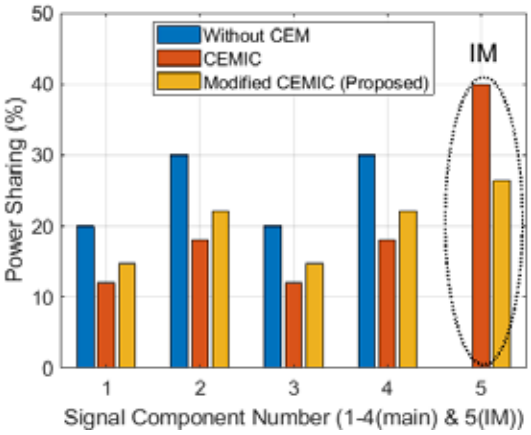


Figure 2: Multiplexing efficiency comparison between the original CEMIC and modified CEMIC scheme

The Importance of the Modified CEMIC Scheme to PNT

GNSS service providers are introducing many commercial, upgraded, restricted, and interoperable open navigation services. They propose these new services in existing navigation satellites on the available carrier frequency, which is currently broadcasting existing service signals, or on a new carrier frequency depending on onboard resources and frequency coordination with other GNSS service providers. The added signal should not affect the existing signals. Backward compatibility requires preserving the transmitted power and phase of operational navigation signals for a service. Our paper presents a modified CEMIC-based multiplexing approach to minimize existing signal structure changes and maximize efficiency.

Usage and Future Scope of the Modified CEMIC Scheme

In the full paper, a case study to multiplex an additional signal with the current Indian Regional Navigation Satellite System (IRNSS) L5 and S-band signals using the modified CEMIC scheme to illustrate its practical efficacy is presented. However, the scope of the scheme is not limited to multiplexing over a single frequency and binary coded sequence (BCS) type signals. It can be easily extended to the other multi-level and multi-frequency signals. The modified CEMIC scheme spans a multitude of service dimensions like PNT services, safety-of-life services, and high-precision messaging services, as shown in Figure 3.

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

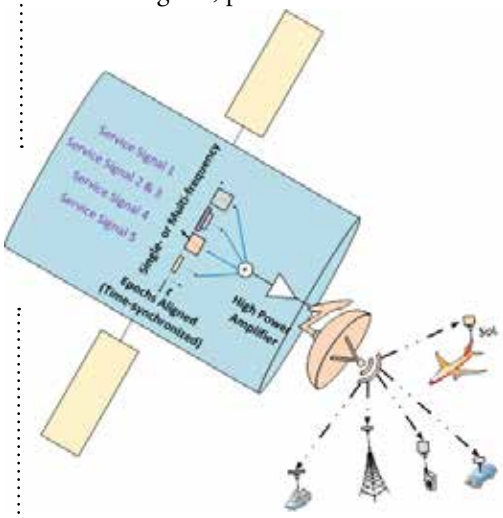


Figure 3: Onboard signal constant envelope multiplexing and usage

Bhadouria, V., Upadhyay, D., Majithiya, P., & Bera, S. (2022). Modified CEMIC scheme for multiplexing signals over single frequency band. *NAVIGATION,* 69(3). https://doi.org/10.33012/navi.528

GNSS Program Updates
News from Systems Around the World

By Kevin Dennehy

GPS

Since our last GNSS update, the U.S. Space Force launched a GPS III satellite aboard a SpaceX Falcon 9 spacecraft on January 18, 2023. The satellite, GPS-III-SV06, was placed into medium Earth orbit (MEO).

Maybe even bigger news was the recent announcement by the Space Force that it is pausing new orders of GPS satellites as there are several in storage waiting to be launched. At a Pentagon press conference, Maj. Gen. Michael Greiner, deputy assistant secretary for budget for the Department of the Air Force, said two GPS 3F satellites from last year's budget, worth about $250 million each, won't be included in the 2024 version.

Two GPS 3F satellites pulled from 2024 Pentagon Budget
Lockheed Martin

The 10th and last GPS 3 satellite, manufactured by ION member Lockheed Martin, was recently delivered to the company's Colorado facility for storage until a launch date becomes available. The company is now manufacturing the GPS 3F under a 2018 contract worth $7.2 billion for as many as 22 satellites.

In its yearly budget request, the Space Force did request $1.2 billion for the GPS Enterprise, which consists of $980 million in research and development and $280 million for procurement. This includes development of the GPS 3F satellites.

Some of the funding includes transition from the Operational Control Segment to the next-generation Operational Control System (OCX). In addition, testing and integration of receivers from the Military GPS User Equipment (MGUE Increment 1) were included in the funding request.

QZSS

Since our last update, the Space Force has delivered two hosted payloads to Japan for the Quasi-Zenith Satellite System (QZSS). Japan will integrate the payloads into two satellites it plans to launch—increasing the constellation from five to seven satellites. The payloads are designed to monitor spacecraft and dangerous debris in geosynchronous orbit.

The primary payload developer, Massachusetts Institute of Technology's Lincoln Laboratories (MIT/LL), will travel to Japan to help with the payload's integration and testing. Overall, the Space Force's Space Systems Command is managing the program.

Galileo

The European Space Agency has made two major announcements about the constellation's signal this year. The first was that a satellite was reconfigured to emit signals optimized for low-end receiver devices and Internet of Things (IoT) applications.

The new test signal component, in the E5 band, is intended to enable streamlined position fixes without any effect on the E1 and E6 bands, ESA said. One of the Galileo satellites, GSAT0202, has been reconfigured to transmit the new signal component in tests, ESA said. The agency also announced that Galileo is the first GNSS to provide free, high-accuracy Precise Point Positioning (PPP) correction, now available through its E6-B signal and the Internet.

GLONASS

Not much has been publicly revealed about the Russian constellation since we reported that a Soyuz rocket launched the last GLONASS-M in November. However, there have been numerous media reports about GLONASS-compatible chips being found on shot-down drones in Ukraine.

ION member u-blox issued a statement to say it not only condemns Russia's invasion of Ukraine, but acknowledged that certain GNSS modules had been found on Russian drones. The company said that its products must not be used in weapons, including target identification.

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.

Galileo satellite in orbit
European Space Agency

Corporate Profile

PNI Sensor
PNICorp.com

PNI SENSOR CORPORATION

PNI is an American navigation product & technology company that specializes in providing highly accurate, precise position and navigation data when GPS is compromised or unavailable.

Unique in the industry, PNI's prowess in magnetic sensing and expertise in fusing complex sensor data with proven proprietary algorithms and Edge AI into usable navigation data is unmatched. PNI's products, in use by many major UAV stakeholders, deliver reliable navigation data for use in unmanned vehicles in the air, on the ground and under water.

For more information on corporate membership in the Institute of Navigation, please contact Beth Lathrop at 703-366-2723 extension 1004

Calendar of Upcoming Events

APRIL 2023

24: AFRL/ION Magnetic Navigation Workshop
Contact: ION
Web: ion.org/magnav

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

MAY 2023

31-2 June: European Navigation Conference (ENC) 2023, Noordwijk, The Netherlands
Contact: European Group of Institutes of Navigation (EUGIN)
https://www.enc2023.eu/

JUNE 2023

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

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

APRIL 2024

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

ION News and Notes

January, 2023, Dr. Dorota A. Grejner-Brzezinska (ION Fellow, past president, and current Satellite Division vice chair) was appointed a member of the U.S. National Science Board (NSB) by U.S. President Joseph Biden. The National Science Board was created by the National Science Foundation (NSF) Act of 1950, which created the NSF, to pursue the goals and function of the NSF, including the duty to "recommend and encourage the pursuit of national policies for the promotion of research and education in science and engineering."

In addition, the National Science Board has two important roles. First, it establishes the policies of NSF within the framework of applicable national policies set forth by the President and the Congress. In this capacity, the Board identifies issues that are critical to NSF's future, approves NSF's strategic budget directions and the annual budget submission to the Office of Management and Budget, and approves new major programs and awards. The second role of the Board is to serve as an independent body of advisors to both the President and the Congress on policy matters related to science and engineering and education in science and engineering. In addition to major reports, the NSB also publishes occasional policy papers or statements on issues of importance to U.S. science and engineering.

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