Volume 33 No 1 **Winter 2023**

Quarterly Newsletter

ION®

INSTITUTE OF NAVIGATION

Space Weather Lessons Learned in Very Low Earth Orbit Operations

Delores J. Knipp and Vishal Ray

Low Earth orbit (LEO) satellite mega-constellations are providing global phone and internet communications as well as space-based imaging services—and more are on the way. The space community stands to learn much about operating in the LEO environment as these constellations complete their configurations. For example, with an eye toward building a LEO constellation comprised of thousands of spacecrafts, Starlink mission designers use a combination of boosting and electric orbit-raising to elevate constellation spacecraft to operational altitudes. In early February 2022, this seemingly proven approach had a rough encounter with space weather, creating a "lessons-learned" situation for the space industry.

Prior to 2022, SpaceX had launched more than 30 clusters of Starlink satellites to test and form the backbone of the Starlink constellation. The pre-2022 launches occurred during the minimum of solar and geomagnetic activity between solar cycles (SCs) 24 and 25. The 3 February 2022 Starlink launch supplements took place during the fitful start of SC 25 when neutral density in Earth's

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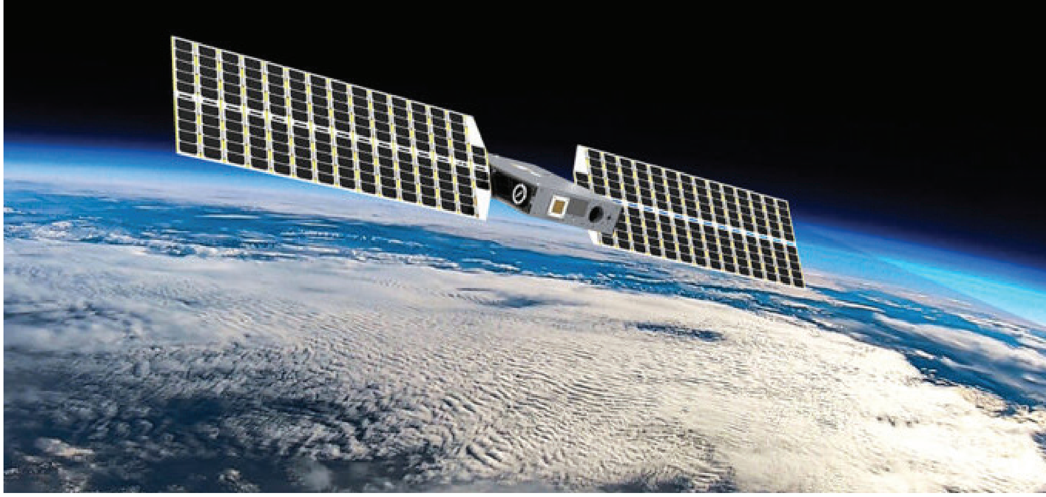
Is LEO PNT the Next Big Thing?



Artist impression of a Xona Space Systems' LEO satellite

Kevin Dennehy

Many companies are developing low Earth orbit (LEO) systems and equipment to augment GPS and other GNSSs for such commercial applications as autonomous vehicles, drone delivery services, critical infrastructure, and other markets. While GNSSs that operate in medium Earth orbit (MEO) are the dominant positioning, navigation, and timing (PNT) satellite constellations, industry experts say their signals are weak, subject to interference, and expensive to augment.

LEO PNT proponents advocate that LEO constellations have increased signal strength, enhanced security, offer worldwide coverage, 2D and 3D positioning, and precise timing, and are much closer to the Earth than MEO GNSSs. By operating in a much lower orbit, LEO PNT accuracy can be more than 10 times that of GPS.

Advocates of GNSS augmentation systems, many of whom presented at the National Space-Based Positioning, Navigation, and Timing (PNT) Advisory Board meeting in November, also point to recent GPS outages in Denver and Texas, where aircraft Automatic Dependent Surveillance–Broadcast (ADS–B) and Traffic Alert and Collision Avoidance System (TCAS) were compromised.

"GPS signals are extremely vulnerable, and with rising international tensions, it is only a matter of time before we see a serious GPS interruption. With a specially built PNT system, LEO satellite signals can be used opportunistically to significantly reduce the drift of an inertial navigation system during complete GNSS outages," said Joshua

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PRESIDENT'S COLUMN | DR. FRANK VAN DIGGELEN

Reflections

At the end of January, I pass the ION's presidential gavel to incoming president, Dr. Sherman Lo. I am delighted that the ION will continue under Sherman's capable leadership. The transition has also offered me the opportunity to reflect on the past two years.

When I took office in 2021, we were nine months into COVID lockdown. One of my immediate goals was to get the ION's programs back to normal as quickly as possible post-vaccine. I was proud of how quickly and adeptly ION transitioned our events to a virtual environment. And, like many of you, I am also aware of the great value, sense of community, collaboration, and fun at our in-person ION events. And so, we have focused on bringing back physical ION conferences.

ION Back to Pre-Pandemic Operations

As of 2023, ION's events are fully back on track with in-person conferences at near pre-pandemic attendance levels, in some cases exceeding them! Additionally, ION membership numbers have also returned to normal, and ION's journal, NAVIGATION, has a robust selection of manuscripts for publication. Thank you to all the many leaders and volunteers who made this possible.

Thanks also to those who helped us stay connected with our membership through the ION's popular webinar program. We dramatically ramped up our webinar game to bring ION to you. ION's YouTube channel, youtube.com/@ionavigation, carries video abstracts for NAVIGATION, conference keynotes, and substantive webinars. Two of my favorites, among many, are Navigation to Mars and Insect Dead Reckoning. It's also a thrill for me to see ION content prominently displayed on my Smart TV suggestions alongside Stephen Colbert, Trevor Noah, and the latest sports videos. Subscribe and settle down to an educational and fun webinar or keynote tonight!

Dr. Frank van Diggelen demonstrating how to access raw measurements from a smartphone in Morocco.
F. van Diggelen

ION Accelerates Efforts for Inclusivity

I am proud of our efforts to improve diversity within our organization. Our goals include broader representation of all of our membership and gender equity in leadership roles on the Council and the ION's program committees. For the last five years, the ION and conference organizers have proactively built and tracked a new-talent pool to draw from with candidates coming from member recommendations, volunteers, and outstanding speakers in our sessions. With this, alongside other initiatives, we've steadily increased the representation of women chairs at ION GNSS+ from 15% in 2017 to 25% in 2022. If you are organizing ION conferences, tracks, or sessions, please contact me to access this resource so you can keep this trend going in the right direction.

Additionally, this past year, the Council adopted inclusive language best practices for the ION. These guidelines are now provided to all ION authors from our ION Author Conference Resource Centers to encourage inclusive and respectful language in writing. Finally, we have also seen a welcome increase in participation and influence of our younger members; this is something I hope we will actively pursue to ensure the future of the ION.

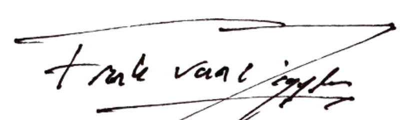
African Highlight

One of the highlights of my ION life has been the opportunity to teach GNSS as part of ION's Africa Outreach Program. Last year this was in Rabat, Morocco. I taught a class on accessing raw GNSS measurements from smartphones alongside my ION and Google colleague, Dr. Mohammed Khider, who taught students how to build apps that use GNSS measurements. There is an article on the Africa Outreach program later in this newsletter.

F. van Diggelen

Thank you

It has been a pleasure to serve you as ION President for the last two years. Our Institute is comprised of a wonderful group of members and an incredibly capable team of full-time professionals that keep it running and thriving. I anticipate long and fulfilling involvement with the Institute for many years to come, and look forward to seeing you in-person at ION GNSS+ in Denver this year and at other ION conferences.



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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 Satellite Division's
Africa Outreach 2022

Sponsored by the Boston College Institute of Scientific Research (ISR), the Satellite Division supported two programs to promote the sustainable use of GNSS in Africa in 2022. As part of this program, Satellite Division technical experts lend their talents to this program by volunteering to teach various aspects of GNSS with the goal of building a knowledgeable and sustainable GNSS workforce in third-world countries, especially those in Africa, that can use GNSS/space technology for socio-economic transformation and integration into the world economy.

The March 2022 program was held in Rabat, Morocco, and led by the late Patricia Doherty, program founder. The Morocco workshop hosted a suite of courses on the ionosphere, space weather, GNSS, and related courses. Highlights included a European Space Agency monitor project that instructed students on current ionospheric scintillation variability over Africa and real-time ionospheric sounding over Kenya. Additionally, a day of practical labs were led by Dr. Frank van Diggelen and Dr. Mohammed Khider of Google. The labs provided instruction on using mobile phones for ionospheric measurements and gave students the hands-on opportunity to create applications on mobile phones that could access GNSS raw measurements. Several ION member instructors taught virtually.

The October 2022 African Capacity Building Workshop on Space Weather Effects on GNSS took place at the International Centre for Theoretical Physics (ICTP) in Trieste, Italy. As with many previous GNSS events aimed at enhancing the knowledge and research capacity of young scientists, especially from Africa, the late Patricia Doherty was a key organizer of the workshop. ISR's Keith Groves, who also helped organize the event, served as a meeting director. Several other ISR scientists gave lectures and tutorials on aspects of GNSSs, how space weather affects their signals, and how those affected signals can be used for studies of the ionosphere. ION Satellite Division instructors (Dr. James Garrison, Dr. Jade Morton, Dr. John Raquet, and Dr. Frank van Diggelen) also provided lectures covering GNSS fundamentals, reflectometry, ionospheric monitoring, and propagation effects. Over 125 participants, both in person and online, from 28 different (mostly African) countries attended the lectures and tutorials, and took part in projects to learn analytical techniques for using GNSS data for their own ionospheric investigations. The Women's Dinner, a favorite event started by program founder Patricia Doherty, was organized and hosted this year by Dr. Jade Morton from the University of Colorado, Boulder, and Yenca Migoy-Orue of ICTP with the support of Boston College.

K. Groves, Y. Migoy-Orue, and J. Morton

ATACNAV

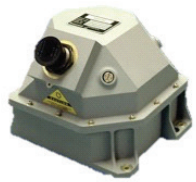
ADVANCED TACTICAL NAVIGATOR

A combat-proven, Alt-PNT solution demonstrated in denied environments providing mission assurance

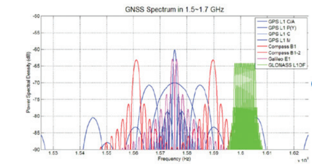
COMPLETE THE MISSION

AUTOMATIC SYSTEM REDUNDANCY – CONTINUOUSLY OPTIMIZING NAVIGATION ACCURACY FROM A SUITE OF POSITIONING TECHNOLOGIES

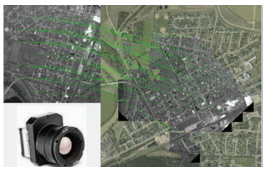
M-code
TRL 9, combat proven GPS solution



Best in Class IMU
High accuracy, low drift INS with flexible alternatives



Full Spectrum/Jam Resistant GNSS
Unique defense software utilizing complete GNSS spectrum



Vision Based Navigation
Provides position in full RF denied environments

LEO SATCOM Position Tracking
Alternate frequency band using high powered satellite constellations

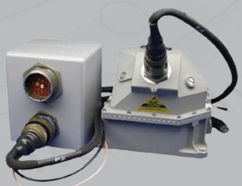
SEAMLESS INTEGRATION

- Update and future proof legacy navigation systems to meet emerging threats
- Simulated GPS signal – Plug and play
- Common and customizable digital interfaces to emulate existing I/O

SMALL, FLEXIBLE, AND RUGGED

ATACNAV Micro; Designed for small UAVs and munitions

Configurable and modular solutions to meet unique application requirements



Since 1993 ASEI has been ensuring that our customers complete their missions. From integrating next level GPS/INS technology into munitions to continuing to pace threats in theater on multiple weapon platforms and launchers with the US Army and USSOCOM, we drive innovation. Providing tactical integrated navigation solutions, custom engineering services and testing at our facilities in Florida and Arizona, ASEI stands ready to support you in completing your mission.

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ION Partners with NSF/ERVA and AFIT

This past November, the ION partnered with the National Science Foundation's Engineering Research Visioning Alliance (ERVA) to co-host the Sustainable Transportation Networks virtual event.

Recognizing that innovative and sustainable transportation modes and infrastructure networks are required to support a vibrant society, the event focused on the importance of resilient and safe transportation networks to maintain a robust economy and how efficient energy use, low or no emissions, alternative materials, novel manufacturing processes, effectiveness and efficiency, and appropriate levels of automation and connectivity will drive the next generation of transportation. The program addressed the need for the next generation of transportation to have positive impacts on social and economic sustainability and the need to provide better accessibility to services and reconnecting communities. The event was led by ION member, past ION president, and ION Fellow, Dr. Dorota Grejner-Brzezinska, The Ohio State University and ERVA PI with several ION contributors. A follow-up report on the virtual event will be covered in future issues of the ION Newsletter.

ION is also partnering with the Air Force Institute of Technology's (AFIT) Autonomy and Navigation Technology Center (ANT) to co-host the full-day Magnetic Navigation Workshop taking place on Monday, April 24, 2023, at the Hyatt Regency Monterey in Monterey, California. Magnetic navigation (MagNav), which uses Earth anomalies and other environmental magnetic sources, is quickly becoming a reliable alternative navigation signal that can provide a backup in situations in which other navigation techniques are unavailable or unreliable. This workshop covers the important implementation aspects of MagNav including the availability of magnetic maps, vehicle magnetic calibration, and navigation filter techniques.

The Magnetic Navigation Workshop is being held in conjunction with the upcoming IEEE/ION Position, Location, and Navigation Symposium (PLANS) on April 24–27, 2023, also at the Hyatt Regency Monterey.

Registration for the Magnetic Navigation Workshop opened on November 15. To learn more about the April 24, 2023 event, please visit: ion.org/magnav

"Partnering with organizations like the National Science Foundation and the Air Force Institute of Technology supports ION's mission to advance positioning, navigation, and timing (PNT)," said Lisa Beaty, Executive Director of the Institute of Navigation. "Positioning, navigation, and timing technologies intersect directly with sustainability, energy, productivity, and how communities can thrive in new economies. The ION is always pleased to partner with other organizations who are also working on providing solutions that support the advancement of PNT."

A Navigation System with 10-centimeter Accuracy

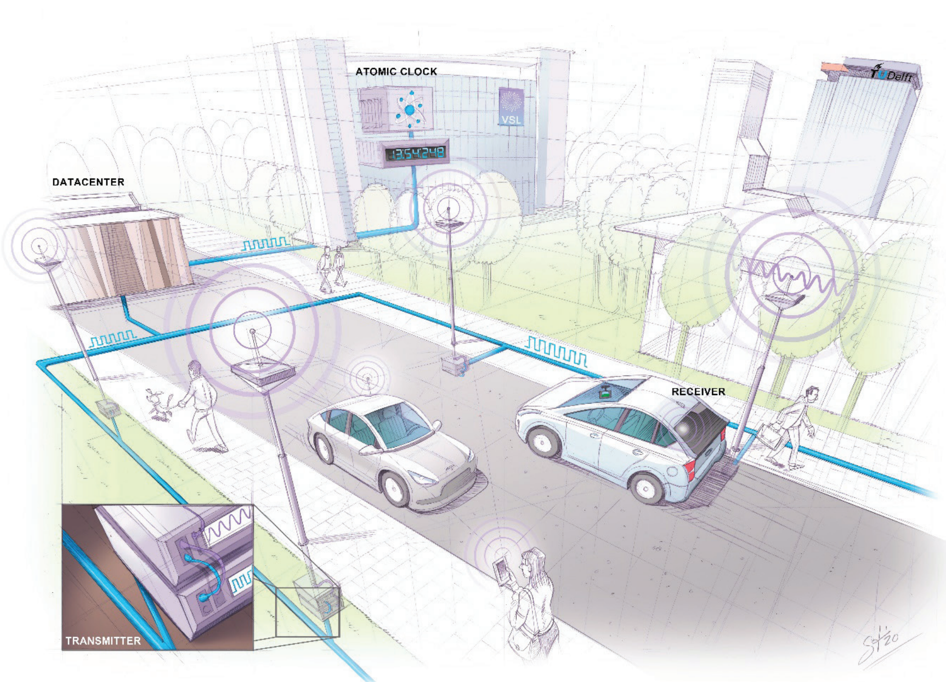
TU Delft / Frank Auperlé

Researchers of Delft University of Technology, Vrije Universiteit Amsterdam, and the National Metrology Institute of the Netherlands have developed an alternative positioning system that is more robust and accurate than GPS, especially in urban settings. The working prototype that demonstrated this new mobile network infrastructure achieved an accuracy of 10 centimeters (RMS). This new technology is important for the implementation of a range of location-based applications, including automated vehicles, quantum communication, and next-generation mobile communication systems.

A lot of our vital infrastructure relies on global navigation satellite systems such as the US GPS and EU Galileo. Yet these systems have their limitations and vulnerabilities. Their radio signals are weak when received on Earth, and accurate positioning is no longer possible if the radio signals are reflected or blocked by buildings. “This can make GPS unreliable in urban settings, for instance” says Christian Tiberius of Delft University of Technology and coordinator of the project, “which is a problem if we want to use automated vehicles. Also, citizens and our authorities actually depend on GPS for many location-based applications and navigation devices. Furthermore, so far we have no general back-up system.”

The aim of the project entitled *SuperGPS* was to develop an alternative positioning system that makes use of the mobile telecommunication network instead of satellites and that could be more robust and accurate than GPS. “We realized that with a few cutting-edge innovations, the telecommunication network could be transformed into a very accurate alternative positioning system that is independent of GPS,” says Jeroen Koelemeij of Vrije Universiteit Amsterdam. “We have succeeded and developed a system that can provide connectivity just like existing mobile and Wi-Fi networks do, as well as accurate positioning and time distribution like GPS.”

One of these innovations is to connect the mobile network to a very accurate atomic clock, so that it can broadcast very accurately timed messages for positioning, just like GPS satellites do



An atomic clock
TU Delft / Stephan Timmers

with the help of the atomic clocks they carry on board. These connections are made through the existing fiber-optic network. Time and frequency distribution can be retrofitted onto existing data carrying fiber connections, and relies on symbol changes in the 1.25 Gb/s bitstream. "We had already been investigating techniques to distribute the national time scale produced by our atomic clocks to users elsewhere through the telecommunication network," says Erik Dierikx of VSL. "With these techniques, we can turn the network into a nationwide distributed atomic clock—with many new applications such as very accurate positioning through mobile networks. With the hybrid optical-wireless system that we have demonstrated now, in principle, anyone can have wireless access to the national time scale produced at VSL. It basically forms an extremely accurate radio clock that is good to the sub-nanosecond level."

Impression of experiments carried out with a road-vehicle (with the white receiver antenna on top), using the prototype system deployed at The Green Village on TU Delft campus; the self-tracking total station in the front is used to deliver the ground-truth trajectory of the car in this experiment.
Christian Tiberius

Furthermore, the system employs radio signals with a bandwidth much larger than commonly used. "Buildings reflect radio signals, which can confuse navigation devices. The large bandwidth of our system increases time resolution and helps sort out these confusing signal reflections, and enables higher positioning accuracy," Gerard Janssen of Delft University of Technology explains. The prototype system uses 160 MHz of bandwidth, where a GNSS typically uses bands of ten or a few tens of MHz at most. For the implementation, we chose to use OFDM as a digital transmission scheme, as to anticipate embedding in Wi-Fi and 5G telecommunication. By default, 16 adjacent bands of each 10 MHz with 64 subcarriers are used at a center frequency of 3.96 GHz. "At the same time, bandwidth within the radio spectrum is very scarce and, therefore, expensive. We circumvent this by using only a number of related small bandwidth radio signals spread over a large virtual bandwidth. This has the advantage that only a small fraction of the virtual bandwidth is actually used and the OFDM signals can be very similar to those of mobile phones." With the prototype, the position update rate is 1,000 Hz, and the maximum range of a transmitter is several hundreds of meters.

More information

See the full publication in *Nature* online at: https://www.nature.com/articles/s41586-022-05315-7. Full citation: Koelemeij, J.C.J., Dun, H., Diouf, C.E.V. et al. A hybrid optical–wireless network for decimetre-level terrestrial positioning. Nature 611, 473–478 (2022). https://doi.org/10.1038/s41586-022-05315-7.

The results reported in *Nature* were made possible with the aid of grants from the Applied and Engineering Sciences domain of the Dutch Research Council (NWO).

More information is available on the project website, SuperGPS.

Engineers Study Bird Flight to Understand Response to Air Disturbances

Lessons that could one day apply to uncrewed aerial vehicles or other flying machines

Wind tunnel models of gull wings combined with aerodynamic studies provide insights into how birds control flight.

Christina Harvey/UC Davis

The fascination with bird flight is centuries old, but exactly how birds can be so agile in the air has remained mysterious. A new study, partly supported by the U.S. National Science Foundation and published in Proceedings of the National Academy of Sciences, uses modeling and aerodynamics to describe how gulls can change the shape of their wings to control their response to gusts or other disturbances. The lessons could one day apply to uncrewed aerial vehicles or other flying machines.

"Birds easily perform challenging maneuvers and they're adaptable, so what exactly about their flight is most useful to implement in future aircraft?" asks Christina Harvey, an aerospace engineer at the University of California, Davis, and lead author on the paper. Co-author on the paper is Daniel Inman, University of Michigan.

In previous work, Harvey and colleagues analyzed the flight dynamics of 22 bird species and looked at aircraft design. Aircraft are typically designed to be stable or unstable. A stable aircraft will tend to return to steady flight when perturbed, for example, by being pushed up by a wind gust. This is desirable in an airliner, but not in a jet fighter. Highly maneuverable aircraft are designed to be unstable. Harvey and colleagues showed that almost all the bird species studied are capable of both stable and unstable flight and use wing movements to shift between these modes.

Gulls can adjust how they respond to perturbations by adjusting their wrist and elbow joints and morphing the shape of the wings. The team was able to predict the gulls' flying qualities and speed of recovery from a perturbation such as a gust. That reaction time also gives insights into the controllable range for the bird and into applying bird flight dynamics to aircraft.

As uncrewed aerial vehicles, or drones, become more widely used, they need to be able to navigate complex urban environments, something birds do very well. A deeper understanding of bird flight could help improve drone designs for various uses.

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Space Weather Indices and Trends

(1 December 2021- 8 February 2022)

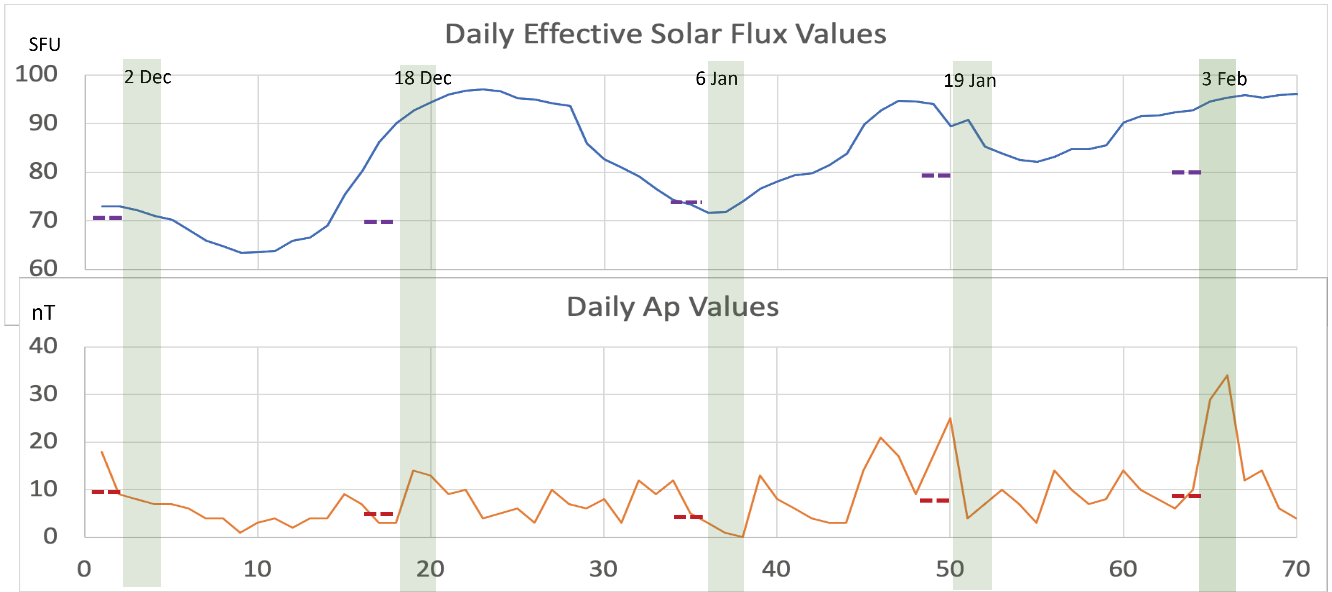

Fig.1. Daily space weather indices leading to the 3 Feb 2022 Starlink launch: Green bars highlight 2-day post-launch intervals; the blue curve is a solar EUV index in solar flux units (from Space Environment Technologies LLC). Purple dashes show the average value of the S10 index in the 30 days prior to each launch. Orange curve (Ap index) measures global geomagnetic activity in nanotesla (produced by GFZ German Research Centre for Geosciences); it shows the enhanced activity which added to the heating trend from solar EUV wavelengths. Red dashes show average values of the Ap index 30 days prior to each launch.

continued from page 1

thermosphere (100–1000 km) was higher and more variable than anticipated at the orbit-insertion altitude. To the surprise of many in the space world, only 11 of the 49 satellites from the launch reached operational altitude.

Deployment Profile

SpaceX demonstrated that its Falcon 9 rocket could boost about 50 Starlink V1.5 spacecraft into an elliptical orbit with perigee at ~210 km and apogee at ~350 km. At perigee, the satellites deploy from the mothership, then individual spacecraft viability is assessed before further orbit-raising to operational altitude. At 210 km, considered to be in the very low Earth orbit (VLEO) regime, the thermosphere is sufficiently dense to allow any Starlink spacecraft identified as not mission capable to be quickly and intentionally deorbited. Disposal is hastened by commanding a VLEO spacecraft to put its maximum area perpendicular to the flow, allowing for the most interaction with atmospheric atoms and molecules (high ballistic coefficient) rather than flying in a streamlined configuration with a low ballistic coefficient. After a short check-out period, usually less than 48 hours, spacecraft deemed "healthy" are commanded to begin orbit-raising by on-board electric propulsion thrusting. For nominal conditions, propulsive thrusting begins as soon as possible at apogee (orbit high-point) to raise the satellite perigee (orbit low-point) above the denser part of the lower thermosphere.

Very Low Earth Orbit

SpaceX attributed the ultimate loss of the 38 satellites to a minor geomagnetic storm[1]. Their early analysis suggested the problem was rooted in an ~50% increase in satellite drag near 210 km altitude, compared to previous Starlink launches. This VLEO altitude, where Starlink traditionally had initiated its crucial orbit-raising procedures, was in a "sweet spot" of mission trade space—an altitude allowing maximum mass (number of spacecraft) to be delivered by the launcher, but also allowing for quick disposal via satellite drag if a spacecraft was not performing properly. Conveniently, nature supports the disposal via a tenuous atmospheric density of ~ 1 x10-10 kg/m3 during solar minimum (roughly one ten-billionth of sea level density: ~1 kg/m3) that causes orbit decay. Inconveniently, nature can provide excess density when the thermosphere is heated by solar and geomagnetic storms.

1 https://www.spacex.com/updates/

Why Such a Problem?

The intensity of the minor geomagnetic storm, mentioned as the culprit in the demise of nearly 40 satellites, is one reached hundreds of times per solar cycle. So, why was this February 2022 launch so problematic and different from previous launches? An accumulation of seemingly small factors combined to produce an unanticipated result. Analyses by the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) in concert with Starlink[2] (and by several independent researchers) have highlighted additional factors behind the thermospheric neutral density increases in the early February

2 Fang et al. (2022). Space weather environment during the SpaceX Starlink satellite loss in February 2022. *Space Weather*, 20, e2022SW003193. https://doi.org/10.1029/2022SW003193

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2022 launch.

Thermospheric density has multiple interacting contributors: solar short-wave energy at extreme ultraviolet (EUV) wavelengths heats the thermosphere, as do currents and particles flowing into the atmosphere from Earth's magnetic domain during geomagnetic storms. The effects of multiple storms and multiple energy sources are nonlinear and time-variable. In early February 2022, the estimated solar EUV irradiance was about 40% above the 2017–2021 average, indicating that solar cycle 25 was gearing up. Further, the minor storm on February 3, 2022, was followed by a second minor storm within a mere 24 hours [3,4]. Models suggest that the thermosphere was unable to relax before the second storm hit.

Rough Atmosphere

A combined SWPC-Starlink analysis using a newly operational physics-based, full atmosphere model (Whole Atmosphere Model or WAM[5]) showed these factors had combined to produce thermospheric density upheavals substantially larger than those estimated by the empirical model run by Starlink. The effects of the second minor storm superposed on the already disturbed thermospheric state excited by prior solar and geomagnetic energy deposition. Further complications were identified in that the thermosphere's density during storm time has always been notoriously uneven. The dayside atmosphere is more expanded than the nightside; similarly, locations close to a localized energy input such as the aurora would also experience dynamic and localized increases and decreases in density. To summarize: the Starlink spacecraft were flying through regions of heated, expanded, and corrugated atmosphere not seen during previous launches. The lower portions of the orbit envelope, where satellite drag is most effective, were most impacted.

The basic empirical model used by Starlink, a climatology-based model based on proxies for solar activity and geomagnetic storming, could not capture the superposition of factors nor the dynamic changes in thermospheric density, especially effects at perigee altitudes. Starlink kept many of the small satellites in safe mode, hoping they could ride out the storm. However, while in safe mode, the newly launched spacecraft were subject to rotational motion imposed by uneven drag forces[6]. This dynamic torquing further decreased orbital stability, making attitude control and station keeping even more difficult during perigee. For 38 of the satellites, this combination of factors meant that orbit-raising maneuvers would not work and, in some cases, could not even be initiated.

Addressing the Problem

At the next opportunity (about three weeks later), with quick and deliberate modification to launch and flight operations, Starlink successfully delivered a new tranche of satellites to an orbit with perigee closer to 300 km. In terms of forecasting, the SWPC's Whole Atmosphere Model output is becoming more accessible to a broader customer base. Further, other independent modelers are assessing and preparing new nowcasting and forecasting products that may provide additional support for LEO and VLEO operations.

Broader Impacts

One may ask if such an event has the potential for broader impacts, such as in the global navigation satellite system (GNSS) community. GNSS signals are used by some operators for satellite precision orbit determination. This number is steadily increasing with larger commercial constellations such as Starlink and Spire, among others, relying on GNSS signals for navigational purposes. Since the thermosphere provides the massive underpinning of the ionosphere, when the thermosphere is disturbed, ionospheric irregularities that lead to signal scintillation and loss-of-lock are likely to be enhanced. The loss of navigation information coupled with force modeling errors due to perturbed atmospheric density can lead to a domino effect for trajectory predictions, conjunction assessment, and collision avoidance. This may be especially concerning for satellites such as Starlink that rely on the GNSS signals for their automatic collision avoidance maneuvers.

Needs

Given the growth in space and launch activity, the lessons learned from the Starlink incident should be part of mission planning/operations for all users of LEOs. Strong to extreme space weather storms will happen in solar cycle 25 and will affect the full depth of the LEO environment, not just the VLEO altitudes. Recent publications (see footnotes) focusing on this event reported that the variability in modeled regional density was very high: 10–150%. Lacking density measurements at VLEOs, model uncertainty is also high. Future entities operating in space could help ensure their own safety and success by contributing observations as the airlines do for terrestrial weather. Where reliability is needed most, as in the case of collision avoidance, lack of observations, large errors, and large uncertainties, pose significant challenges. The 2022 com-

3 Dang et al. (2022). Unveiling the space weather during the Starlink satellites destruction event on 4 February 2022. *Space Weather*, 20, e2022SW003152. https://doi.org/10.1029/2022SW003152

4 Lin et al. (2022). Thermospheric neutral density variation during the "SpaceX" storm: Implications from physics-based whole geospace modeling. *Space Weather*, 20, e2022SW003254. https://doi.org/10.1029/2022SW003254

5 https://www.swpc.noaa.gov/products/wam-ipe

6 Ray et al. (2022). The impact of space weather on very low Earth orbit (VLEO) satellites. *Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS) 2022*. https://amostech.com/TechnicalPapers/2022/Atmospherics_Space-Weather/Ray.pdf

munity consensus report on space weather[7] published by the National Academy of Science Engineering and Medicine notes that investment and commitment to space weather observations and modeling are crucial for beating down the uncertainty in space weather forecasting.

Mission planning, as well as operations, are further complicated by the fact that there is no consensus in the community on what atmospheric model should be used in what scenario. Where semi-empirical models cannot capture the thermospheric density perturbations during storm periods, as has been made evident by the Starlink loss event, they can usually model the average behavior of the density quite well, since they are calibrated to historical data.

On the other hand, physics-based models can be biased due to a lack of data calibration, though their response to changes in space weather is rooted in the physics of the system. Any specific model cannot provide the solution to this complex problem as the answer lies in the world of terrestrial weather modeling—ensemble modeling with data assimilation. LEO space operations would benefit from an ensemble modeling approach for upper atmosphere forecasting to bring it to the same footing as terrestrial weather forecasting. Efficient ways of assimilating more consistent and better-placed measurements of upper atmospheric behavior into ensemble models are a must. That will require a workforce versed in physics, modeling, and data science.

Dr. Delores J. Knipp is a research professor in the Smead Aerospace Engineering Science Department and a senior research associate with the Space Weather Technology Research and Education Center at the University of Colorado Boulder. She is an American Meteorological Society Fellow.

Dr. Vishal Ray is a senior astrodynamics engineer at Kayhan Space in Lafayette, Colorado.

7 National Academies of Sciences, Engineering, and Medicine. 2022. *Planning the Future Space Weather Operations and Research Infrastructure: Proceedings of the Phase II Workshop*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26712

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Iridium satellites offer PNT capability
Iridium

continued from page 1

Morales, StarNav CEO, whose company has built a multi-constellation PNT receiver that uses both GNSS and LEO satellite signals.

While LEO PNT is seen as an augmentation, Xona Space Systems believes the system would not be a replacement for GPS. “There is no need to replace GPS or GNSS as the value they bring to our society is monumental. There is, however, a clear need for more PNT capability in certain industries which is where complementary commercial LEO PNT comes into the picture,” said Tyler Reid, Xona Space Systems’ Chief Technology Officer and co-founder.

Not everyone is jumping on the commercial LEO PNT bandwagon. GNSS expert Logan Scott says that, unless the industry provides a solution more qualitatively different from GPS, they will not be successful in a commercial market—particularly if they are charging for the service.

“It needs to be different—like a voice-only flip phone vs. an iPhone. Free is really hard to compete with,” Scott said. “LEO is neat stuff, technologically, but when it comes to civil augmentation, I’m much more a fan of 5G positioning, 802.11az, etc. Yes, the coverage is limited, but then again, where do you want to provide coverage? I’d argue—where people are.”

Reid believes the biggest drawback of LEO positioning is that it takes more satellites, compared to MEO, to achieve the same coverage and geometry in terms of dilution of precision (DOP). “The satellite footprint of a LEO satellite is nearly a tenth of a satellite in MEO, hence, it takes nearly tenfold more satellites in LEO to achieve the same coverage. DOP isn’t the only factor; the other is user mask angle sensitivity,” he said. “With a LEO constellation vs. MEO, satellites tend to be lower above the horizon, so care must be taken in the constellation design to ensure there are enough satellites that are useful to the user in the intended use case environment.”

Morales said that several issues arise when LEO satellites are used for PNT. “Namely, since they were not designed specifically for PNT, accurate satellite ephemeris or timing information is not transmitted down to the user equipment like in a GNSS signal—or one of the upcoming cooperative LEO PNT services,” he said. “The user equipment must employ algorithms to deal with determining the satellite orbits and correct for clock errors while estimating the user’s position and timing errors. Besides that, many LEO constellations only have a couple satellites overhead that are transmitting usable signals at any given time. There is no silver bullet for addressing the challenges of accurate and reliable PNT for all settings and applications.”

Besides the technical challenges that come with designing an extremely complicated system, are the business challenges, Morales said. “People have been using GPS for practically free for many years. People that will be looking to pay for a PNT service are those that care about extra security and safety guarantees for safety-critical systems," he said.

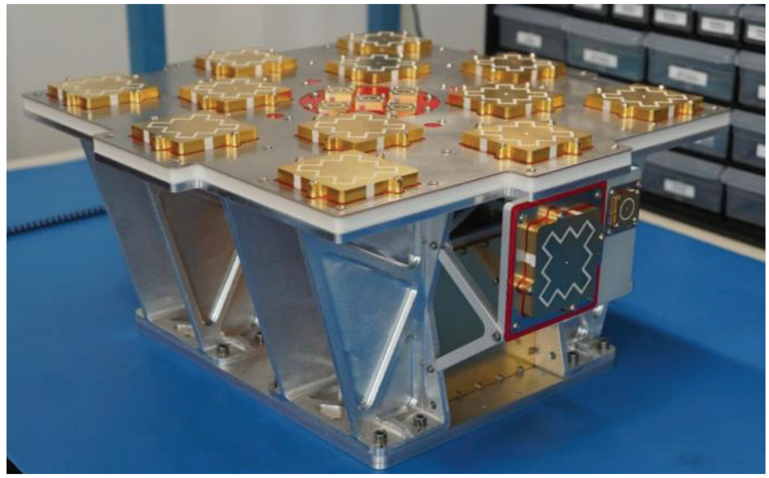
Reid said Xona's approach to a dedicated LEO PNT system is to, not only enhance existing GNSSs, but act as an independent constellation when needed. "Enhancements include a data pipe of GNSS corrections and other data which can be used in conjunction with fast-moving LEO satellites for accelerated convergence of precise point positioning. Additional, more powerful, and resilient LEO signals lead to improved availability and robustness of positioning solutions, meaning PNT in more places more of the time."

For its part, Xona, which has raised more than $25 million in funding, launched the Huginn prototype satellite in May 2022 aboard a SpaceX Falcon 9. The company hopes to have 300 navigation cubesats in orbit.

Beaming from the satellites will be Xona's Pulsar PNT service, which will be rolled out in a phased approach starting in 2025. "The first phase is a one-in-view LEO constellation inclined to give coverage over mid-latitudes for population centers, representing approximately 40 satellites [in] orbit," Reid said. "In addition to a data pipe for GNSS enhancement, this service brings independent time transfer for stationary users, including critical infrastructure."

Reid says that phase two expands the one-in-view coverage globally with the deployment of additional polar orbiting satellites, bringing the total in orbit to 70. "These are both stepping stones to the phase three deployment which targets approximately 300 satellites and GPS-level satellite visibility and geometry."

Reid said that, in addition to working with StarNav for user equipment, the company has partnered with Hexagon, where NovAtel receivers are demonstrating early support of its Pulsar signals. "We have also announced a collaboration with Spirent Federal Systems to develop



Xona PNT payload, which includes antenna elements that provide the PNT signal
Xona Space

simulation and test capabilities for Xona signals to aid future receiver development and testing."

StarNav is also working with LEO pioneer Globalstar, which is the service provider for Apple's new SoS service. "Globalstar uses a [code-division multiple access] strategy to efficiently use its spectrum allocation for its communication service. In fact, it is like GPS L5 in that it has both an inner and outer chipping sequence," Morales said. "This enables us to build a special receiver to produce pseudoranges between the user equipment and the passing satellites using the transmitted signal, much like we do from GPS signals."

Other companies involved in LEO PNT include ION member Satelles, who has partnered with Orolia to offer timing and location signals through a channel on the Iridium Next satellites. Another company, Trustpoint, like Xona, plans to build and launch a small satellite constellation in LEO to offer positioning, navigation, and timing services.

Other Countries Planning LEO PNT…

The European Space Agency's (ESA) Navigation Directorate recently said it is planning an in-orbit demonstration with new navigation satellites in low Earth orbit to supplement its existing 23 Galileo satellites. The ESA program, called LEO-PNT, tests the constellation through a 6-12 satellite demonstration.

The ESA said the plan is to build "at least a half-a-dozen satellites to test capabilities and key technologies, as well as demonstrating signals and frequency bands for use by a follow-on operational constellation."

In Australia, FrontierSI has signed an agreement with Geoscience Australia, Curtin University, and the University of Newcastle to enhance Ginan (Geoscience Australia's GNSS analysis center software). The company said new features will support LEO satellites as an important component of Geoscience Australia's Positioning Australia program.

International activity, including projects planned in China and the United Arab Emirates, does not bother Reid, who says that strong interest showcases the value of additional LEO signals for PNT. "We see these efforts more as tailwinds and market validation than direct competition, as there are a variety of shapes this could take in each of their implementations to support applications that may be most critical to the given government actor," he said. "Furthermore, the utility of multiple MEO constellations is clear and I think the same can be true of LEO, particularly with some having a focus on commercial users."

Kevin Dennehy has been writing about GNSS for 30 years. He is editor of Location Business News: https://locationbusinessnews.substack.com

University, Partners Deploy Carbon Dioxide-Sensing Underwater Glider

Heather McFarland

Alaska has a new tool for tracking ocean acidification—a 7-foot-long, bright pink Seaglider. The University of Alaska Fairbanks and its commercial partners are the first U.S. team to measure carbon dioxide, the driving factor in ocean acidification, with an unoccupied underwater vehicle.

From left, Kemme, Abdi and Hauri compare measurements taken by the Seaglider with lab instruments at the Alutiiq Pride Marine Institute to ensure the accuracy of the data being gathered.
Heather McFarland

Globally, the pH of the ocean is decreasing as humans burn coal, oil and gas. When carbon dioxide from these activities is absorbed by the ocean, it affects the ability of marine organisms to build and maintain their shells and may also change the behavior of some fish.

The Gulf of Alaska's cold waters naturally hold more carbon dioxide, so it only takes a little added human-made CO2 to reach a threshold that puts marine organisms at risk. Melting glaciers that dump freshwater into the ocean can further reduce the number of building blocks available for shells.

Despite the urgent risk to commercial, subsistence and sport fishing in Alaska, data are lacking to determine the status of ocean acidification around the state.

"In order to understand how the human-made carbon dioxide in the atmosphere changes the oceans, we also need to know how ocean chemistry varies naturally throughout the year," explained Claudine Hauri, an oceanographer at the UAF International Arctic Research Center.

Technological limitations restricted research in the past. Ocean moorings gathered data at a single location year-round, or ships sampled along transects for several weeks from spring to fall. Although these tools are still needed and provide critical information, large areas of the ocean are not sampled, especially in winter.

Hauri and her team devised a plan to fill those data gaps. Working with international commercial partners, they developed a way to integrate a carbon dioxide sensor with a Seaglider that can dive up to 1,000 meters and carry out weeks-long missions to remote parts of the ocean in every season.

Andrew McDonnell, a scientist from the UAF College of Fisheries and Ocean Sciences, prepares to take measurements of carbon dioxide and other ocean chemistry parameters from aboard the research vessel Nanuq during a recent project experiment.
Heather McFarland

"My job is to find the compromise between what the scientists want and what the glider can do," said Ehsan Abdi, an electronics engineer with Advanced Offshore Operations Inc. and Cyprus Subsea.

The integration was no simple task and required specialized skill in mechanical and electronics engineering, as well as in materials science. For example, Abdi had to consider how the heavier sensor changed the buoyancy of the Seaglider while moving through the water. He made adjustments as needed using weights and fabricated material created on a 3D printer.

Meanwhile, Jöran Kemme and his colleagues at 4H JENA Engineering redesigned one of the market's most precise carbon dioxide sensors for underwater measurements. The new design, called Contros HydroC CO2, is lighter and more compact, yet its precision still requires a larger size and higher power consumption than the sensors a Seaglider usually carries.

Scientists and their industry partners aboard the research vessel Nanuq recover the carbon dioxide-measuring Seaglider after a test dive in the Gulf of Alaska.
Heather McFarland

"The most exciting thing is seeing such a big and power-hungry sensor go on such a humble and small glider that was not meant to do stuff like this," said Abdi. "That's why it's challenging, and that's why we've had so many problems. But that's the fun part of it as well."

This spring the science and industry team were in Seward testing the new carbon dioxide Seaglider. They relied on many local partners to test and adjust the glider before sending it to sea. Hauri made sure the glider was balanced correctly while swimming in a tank normally meant for sea lions at the Alaska SeaLife Center. At Alutiiq Pride Marine Institute the team compared measurements taken by the Seaglider to those from instruments used in labs.

The Seaglider took its first ride into Resurrection Bay via the UAF Seward Marine Center's research vessel Nanuq. In a series of consecutively deeper dives, the team tested the Seaglider's maneuverability and response to different temperatures and depths, and compared its ability to measure carbon dioxide to ship-based sensors.

Though many hours were spent bobbing in Resurrection Bay adjusting sensors, reprogramming the Seaglider and examining real-time data, the team was driven by the promise of better carbon dioxide measurements in Alaska's oceans and globally. They plan to make the details of the sensor integration available to others so teams around the world can study ocean acidification more efficiently and develop more strategic and innovative responses.

"I'm excited by the possibility of having a whole fleet of these seagliders continuously measuring CO2. It's important to have people from all around the world working on this, especially because it is a worldwide issue," Kemme said.

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Heather McFarland

Marvin B. May

Twenty Twentieth Century Navigation Hall of Famers

The twentieth century was replete with magnificent contributors to the art, science, and business of navigation. Down selecting amongst the contributors to a field of twenty has been one of the most difficult tasks that I have undertaken in my twenty-five years as the Institute of Navigation's Historian. As a feeble effort to apologize for the omissions of worthy navigation contributors, I recognize in this selection process that my field of view is narrow and obscured by my own limited experiences. Clearly the selections are biased towards white American males. Although only the individual names are mentioned, in almost all cases the advancements were made by a group of people working collaboratively. Another inevitable bias is that: "Success breeds many fathers, while failure is an orphan", resulting in the omission of major contributors who, for whatever reason, were unfortunate to labor on less successful programs. The only strict criteria utilized was that the major contributions were made in the twentieth century; five of the contributors are alive and continuing to work on navigation. Overall factors in the selection process besides scientific navigation contributions were leadership qualities and business successes.

The names are listed below in alphabetical order followed by a short clause stating their respective principal contribution(s). In lieu of listing the dates of birth (and death, where applicable), I listed the years that the individuals' major achievements were made. These selections are not ranked in order; rather, it is alphabetical.

• **Richard Anderle,** with major contributions from 1959 through 1981, focused on satellite geodesy and navigation.

Weems receiving the ION's Thurlow Award, 1955

• **Herman Anschutz-Kaempfe,** with major contributions from 1910 through 1925, focused on gyrocompasses and inertial instrument development.

• **Robert Dippy,** with major contributions from 1938 through 1944, focused on Gee and LORAN radio navigation.

• **Charles Draper,** with major contributions from 1940 through 1955, focused on inertial navigation leadership.

• **Roger Easton**, with major contributions from 1955 through 1975, focused on GPS concept formulation.

• **Albert Einstein,** with major contributions from 1905 through 1918, focused on lasers as well as special and general relativistic corrections to satellite navigation.

• **James Farrell,** with major contributions from 1968 through 1999, focused on inertial navigation as well as navigation simulation.

• **Herve LeFevre**, with major contributions from 1970 through 1999, focused on optical gyroscope accuracy.

• **Alfred Loomis,** with major contributions from 1935 through 1945, focused on LORAN initiation and the creation of Tuxedo Park.

• **Frank McClure,** with major contributions from 1960 through 1964, focused on ideas for the initiation of the first major satellite navigation system.

• **Arnold Nordisieck,** with major contributions from 1950 through 1955, focused on electrostatic gyroscope development.

• **Bradford Parkinson,** with major contributions from 1972 through 1999, focused on GPS leadership.

• **Benjamin Remondi,** with major contributions from 1985 through 1995, focused on GPS carrier-phase techniques and algorithms.

• **Otto Schiller,** with major contributions from 1907 through 1930, focused on the principles and development of radio navigation.

• **Richard Shorthill,** with major contributions from 1975 through 1985, focused on the development of a fiber optic gyroscope.

• **Elmer Sperry,** with major contributions from 1910 through 1935, focused on gyrocompass and aviation navigation.

• **James Spilker,** with major contributions from 1959 through 1999, focused on GPS code and delay lock loop development.

• **Thomas Stansell,** with major contributions from 1961 through 1999, focused on satellite navigation development.

• **Phil Ward**, with major contributions from 1979 through 1994, focused on efforts towards the commercialization and accuracy improvement of GPS.

• **Phillip Van Horn Weems**, with major contributions from 1943 through 1962, focused on ship and aircraft navigation instrumentation and algorithms.

Marvin B. May is Professor Emeritus of navigation and Chief Scientist of Mayven Engineering. His emails are mayven4@comcast.net and mbm16@psu.edu

Defense Matters

A Time to Reflect and Look Forward

Doug Taggart
President
Overlook Systems Technologies, Inc.

As we transition from one calendar year to the next, we often find ourselves reflecting on prior year events to gain insights into what the future may hold.

Noting that the year 2023 will mark the 50th anniversary of the Air Force gaining approval to proceed with Global Positioning System (GPS), what follows are a number of events that have impacted how the GPS has evolved over the last 50 years.

50 years ago – April 17, 1973: The Deputy Secretary of Defense, William P. Clements, Jr., signed a memorandum initiating the Defense Navigation Satellite Development Program (DNSDP) as a joint service enterprise. Later that year, on December 17, 1973, the Defense System Acquisition and Review Council (DSARC) formally approved the DNSDP, which restructured the Air Force's 621B program and, by then, had become known as NAVSTAR GPS. The first phase of the program included four satellites, the launch vehicles, three varieties of user equipment, a satellite control facility, and an extensive test program.

45 years ago – February 22,1978: The first GPS Block I satellite was launched from Vandenburg Air Force Base in California. The final Block I satellite (there were a total of 11 built, 10 of which were successfully placed in orbit) was launched on October 9, 1985.

43 years ago – July 1, 1980: The first edition of the Federal Radionavigation Plan (FRP) was released as part of a Presidential Report to Congress, prepared in response to the International Maritime Satellite (INMARSAT) Act of 1978. It marked the first time that a joint Department of Transportation (DOT) and Department of Defense (DoD) plan for common-use (both civil and military) systems had been developed. The plan noted that the DOT was responsible "for public safety and transportation economy," while the DoD was responsible "for national security in normal and stressed situations."[1]

40 years ago – September 1, 1983: The intentional shootdown of Korean Air Flight KAL007 by a Soviet interceptor aircraft following a navigation error resulted in the airliner straying into Soviet airspace. Following the incident, the White House released a statement that included an announcement by President Reagan that the DoD's future GPS system would be made available for civilian and commercial use around the globe.

28 years ago – April 27, 1995: GPS reached full operational capability after completing its original design goals.

[1] *DOT-DoD. (1980). Federal Radionavigation Plan: Volume II Requirements [Technical Report]. https://rosap.ntl.bts.gov/view/dot/12021*

27 years ago – March 28, 1996: Presidential Decision Directive NSTC-6 established the national policy for the management and use of the US Global Positioning System and related US government augmentations. The policy addressed the dual-use functionality of GPS and provided a strategic vision for the future management and use of GPS for military, civil, commercial, and scientific interests—both national and international.

26 years ago – March 28, 1997: The first interagency GPS Executive Board meeting was held at the Pentagon. The meeting was co-chaired by Dr. Paul Kaminski (Under Secretary of Defense, Acquisition and Technology) and Mr. Frank Kruesi (Assistant Secretary for Transportation Policy). Notable topics on the agenda included: the Gore Commission Recommendations regarding a second and third civil GPS frequency; status on international consultations with Japan, Europe, and Russia on space-based PNT; the DoD's GPS CAPSTONE Requirements Document (CRD) review to include the size of the baseline GPS constellation; and the expansion of the Coast Guard's DGPS system beyond the maritime community.

23 years ago – May 2, 2000: The White House announced that GPS Selective Availability (S/A), the intentional degradation of the accuracy available from civil GPS signals, would be discontinued immediately. The decision to end the practice was based on a recommendation by the Secretary of Defense in coordination with the Departments of State, Transportation, Commerce, the Director of Central Intelligence, and other executive branch departments and agencies.

22 years ago – September 11, 2001: The Department of Transportation released the study, *Vulnerability Assessment* *of the Transportation Infrastructure Relying on the Global Positioning System.* The report recommended creating awareness among the aviation, maritime, and surface user communities of the vulnerability of GPS and the need to reduce degradation or loss of the GPS signal by implementing systems to monitor, report, and locate unintentional interference to GPS and assessing the applicability of military GPS anti-jamming technology. The report also recommended working with the DoD and industry to make appropriate technologies available for civilian uses, identifying appropriate backup systems, integrity warnings, and operational procedures for each safety-critical application, encouraging the development of low-cost systems as backups to GPS, and continuing the ongoing GPS modernization program involving higher GPS broadcast power and the eventual availability of three civil frequencies.

18 years ago – September 26, 2005: The first GPS Block IIR-M satellite with the second civilian signal (L2C) was launched.

15 years ago – September 1, 2008: The *National PNT Architecture Study Final Report* was issued by the Director of the National Security Space Office on behalf of the Departments of Defense and Transportation, who co-chaired the study effort. The report summarized the results of a national study conducted between May 2006 and August 2007. The PNT architecture was national in scope and included the DoD, intelligence community, and civil, commercial, and international users and systems supporting global US interests. It addressed all sources of PNT information and served as the basis for the current national PNT Enterprise as it exists today.

14 years ago – April 10, 2009: The first GPS IIR-M satellite with the L5 signal began to transmit.

5 years ago – December 23, 2018: The first GPS III satellite was launched. The design life of the Block III series is 15 years. A total block of 10 GPS III satellites and 22 GPS IIIF satellites was planned.

4 years ago – April 15, 2019: The DoD released its *Strategy for the Department of Defense Positioning, Navigation, and Timing (PNT) Enterprise (Unclassified Version).* The strategy was founded on the premise that having assured PNT access for the warfighter would be paramount. To maximize the probability of maintaining a military PNT advantage, a layered PNT enterprise architecture was envisioned, with military user equipment built to integrate multiple diverse sources of PNT leveraging a modular, open system architecture design.

3 years ago – December 8, 2020: The US Space Force issued an operational acceptance certification for GPS Military-Code Early Use following tests at the master control stations located at the Vandenberg and Schriever Air Force bases.

2 years ago – April 8, 2021: The DoD established the PNT Oversight Council to provide oversight of the DoD portion of the PNT Enterprise in coordination with various DoD components and organizations that provide or support the functions of the PNT Enterprise.

Looking ahead to 2023 in a soundbite, the Space Force plans to launch the 6th GPS-III satellite. The DoD PNT Oversight Council will continue to wrestle with the timing of when M-Code user equipment will be available, and, in a sad and somber reflection, the GNSS community will no longer have the thoughtful insights and thoroughly researched journalistic articles prepared and made available to us by Dee Ann Divis.

In Memory of Dee Ann Divis December 19, 1960 – November 22, 2022

In our lives, the one commodity that we can never get back is time. From the moment we take our first breath to the moment we take our last, time ticks on.

When you are born, that is the date they put on the left side of your headstone; when you die, they put another on the right; but the dash in the middle is the time you were able to make your mark, leave your legacy, and make a contribution. I have known Dee Ann Divis for over 25 years. In her gathering of information about the world of PNT, she would sometimes call to confirm a lead, verify a fact, or gain some insights. I trusted her in my disclosures and was proud to call her my friend. Hearing of her passing stunned me, saddened me, and reminded me that our time here is short—we should all strive to make our dash meaningful. Rest in peace, Dee Ann.

The Business of GNSS

By Kevin Dennehy

Trimble's RTX technology used in GM's Super Cruise
GM

Since our last column, the biggest business transaction came from ION member Trimble when it agreed to acquire Germany-based Transporeon for $1.98 billion. The deal, an all-cash transaction with Transporeon's largest shareholder, Hg, allows Trimble to have access to 145,000 carriers and logistics service providers and 1,400 shippers through its Europe-based transportation management platform.

Trimble also reported, along with General Motors (GM), that more than 34 million miles have been driven with GM's Super Cruise engaged on vehicles. Super Cruise has used Trimble's real-time extended (RTX) technology to deliver GNSS corrections since 2017 on the 2018 Cadillac CT6.

In Other Business News

ION member HERE Technologies announced it will power hands-free driving for BMW. The company said that the BMW 7 Series will be the first vehicle to roll out SAE International's Level 2+ at speeds of 130 miles per hour in the United States and Canada.

Hexagon AB announced a partnership with Germany-based ZF Group that integrates its software positioning engine and GNSS correction services into mass-production advanced driver assistance systems (ADAS) and autonomous driving solutions. Hexagon's software positioning engine and correction services will be integrated into ZF's ProConnect platform.

NextNav has acquired the privately held geolocation company, and ION member, Nestwave SAS for $18 million. The deal's consideration value is $19.3 million, which consists of $4.3 million in cash and $15 million in NextNav common stock, the company said.

New Product Announcements

ION member VectorNav Technologies has been chosen to be the exclusive supplier of GNSS/INS systems for the Indy Autonomous Challenge (IAC). VectorNav will supply IAC with its VN-310 Dual Antenna GNSS/INS with Real-Time Kinematic (RTK) positioning.

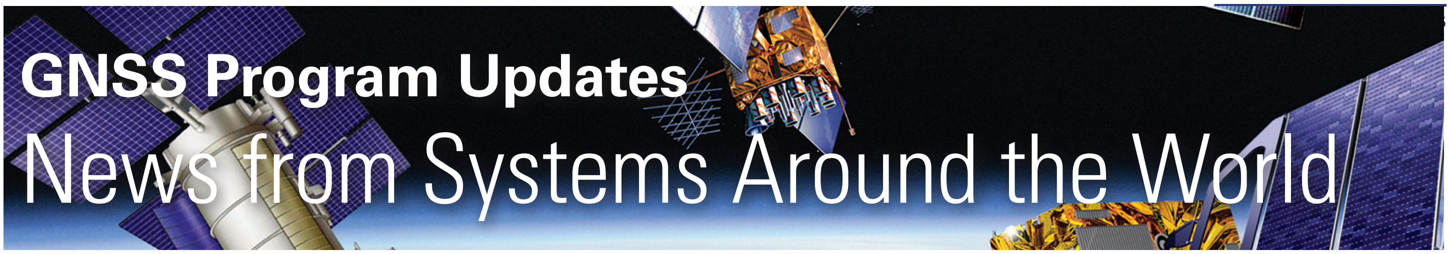
Septentrio has launched its AsteRx SB3 ProBase IP68-housed GNSS base station. These receivers include the AsteRx SB3 Pro rover receiver, AsteRx SB3 Pro+ rover and base receiver, and the AsteRx SB3 CLAS for the Japanese market, the company said.

Thalwil, Switzerland-based u-blox has announced that its dead-reckoning module will provide lane-level accurate positioning data for Li Auto's Li L9 SUV's assisted smart driving system. The Li L9 comes equipped with a Li AD MAX smart driving system with navigation on ADAS functionality, the company said.

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

Above: Septentrio's new AsteRx SB3 ProBase GNSS base station
Septentrio

Right: BMW Group is using HERE HD Live Map in its 7 Series cars
HERE



Russia Launches Last GLONASS-M Satellite

Kevin Dennehy

GLONASS

Despite a war raging in Ukraine, a Soyuz rocket carrying a GLONASS-M satellite was launched from the Plesetsk Cosmodrome on November 28, according to Roscosmos, the Russian space agency. The spacecraft, designated Cosmos 2564, is the 61st and final spacecraft in the GLONASS-M line, which was first launched in 2003, according to published reports.

Last GLONASS-M satellite launched
Roscosmos

The new satellite will operate 12,000 miles above the Earth. Russia will be launching the newer GLONASS-K, first launched in 2011, in the future. However, reports indicate that production of these newer satellites have been delayed due to sanctions stemming from the Ukraine invasion.

GPS

ION member Lockheed Martin was recently awarded a $744 million US Space Force contract for three GPS 3F satellites. The contract option is part of a $7.2-billion 2018 procurement that calls for as many as 22 satellites.

The new GPS 3F satellites—space vehicles 18, 19, and 20—include advanced anti-jamming capabilities, search-and-rescue payload, an enhanced nuclear detection detonation system, and better geolocation accuracy, the company said.

Galileo

In early November, the last first-generation Galileo satellite was shipped from the European Space Agency's (ESA) ESTEC Test Center to Orbitale Hochtechnologie Bremen (OHB) for storage until launch. Work on Galileo began two decades ago with two test GIOVE satellites, followed by several operation launches, the ESA said.

The current constellation consists of 34 full operational satellites (FOCs): the initial GIOVE satellites and an in-orbit Galileo validation satellite. Second-generation Galileo satellites are in development.

Kevin Dennehy has been writing about GNSS for 30 years. He is editor of Location Business News: https://locationbusinessnews.substack.com

First Nano-Satellite Launched in Zimbabwe

A summary as originally reported by the Centre for African Journalists (CAJ) News Africa

Zimbabwe launched their country's first nano-satellite in November in an effort to help collect data to monitor disasters, boost agriculture, enhance mineral mapping, and for other security purposes.

Scholar Miyetani Chauke lamented that, in the entire African continent, only Algeria, Kenya, Nigeria, and South Africa had committed to contributing at least one satellite to the constellation focusing on Earth observation and natural resource management.

"This is a shame for the continent hence we applaud Zimbabwe's new satellite into orbit," Scholar Miyetani Chauke told CAJ News Africa.

He said the nano-satellites were cheaper, smaller, and faster-produced than conventional satellites.

Chauke argued for African countries to take advantage of such low-cost networks for monitoring their own countries' disasters, security, and agriculture for increased food production.

"Zimbabwe desperately wants more eyes in the sky," Chauke said.

"Otherwise depending on foreign satellites such as the United States, Europe, or any other foreign power will not help much, especially when it comes to self-determination, sovereignty, and autonomy," he said.

Chauke said that Zimbabwe, and possibly all African countries, were reliant on international satellites for information about monitoring.

"For example, the country does not have any control over images being sent to her on weather, security, or general information," Chauke argued.

"Sometimes, we as a country do not know when such images from foreign owned satellites would be made available to our authorities – this is the danger of depending on other nations' satellites," he said.

New Review Paper

Integrity of Visual Navigation—Developments, Challenges, and Prospects Multi-Epoch 3D-Mapping-Aided Positioning Using Bayesian Filtering Techniques

Chen Zhu

The integrity concept plays an important role in GNSS-based navigation for safety critical applications. However, it is still a challenging problem to quantify the integrity of visual navigation methods, which have great potentials as a complementary or alternative navigation technology of GNSS in urban environments (e.g., in applications of urban air mobility and autonomous driving).

In this review paper, the authors review the specific challenges to quantify visual navigation integrity to answer the question of why the existing integrity-monitoring technology developed for GNSS cannot be directly applied to cameras. In addition, the current research developments in the field are surveyed, and views on crucial problems to be solved in the future are explored. Moreover, an integrity description framework to monitor errors in multiple processing phases have been proposed in this work so that existing works can be better categorized and future developments can benefit from a systematic approach.

The paper includes a description of multiple tests performed on UAVs and ground vehicles, along with the available public data sets that summarize the challenges in visual navigation integrity observed in real camera measurement data. The challenges are observed from real-life data instead of simulations. References to significant publications are provided.

With the provided review and proposed framework, more advanced developments in the visual navigation integrity field are anticipated so that mature solutions can be obtained with the efforts from the joint community. With the capability of quantifying the error in vision systems and ensuring the integrity of visual navigation outputs, it can be anticipated that standards and certification processes can be established to guarantee the reliability of utilizing vision-based technologies in safety critical applications. As this day arrives in the near future, the visual navigation technology can be utilized with trust to play a more significant role instead of in a "do-my-best" manner.

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

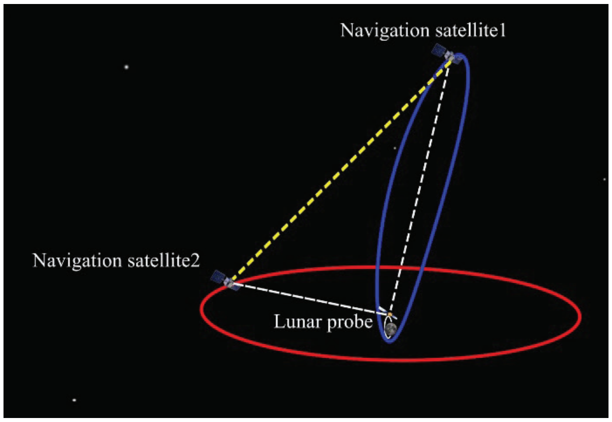
Zhu, C., Meurer, M., & Günther, C. (2022). Integrity of visual navigation—Developments, challenges, and prospects. NAVIGATION, 69(2). https://doi.org/10.33012/navi.518

Comparison of Autonomous Orbit Determination for Satellite Pairs in Lunar Halo and Distant Retrograde Orbits

Xi-Yun Hou and Zhao-Yang Gao

Traditional PNT vs. LiAISON

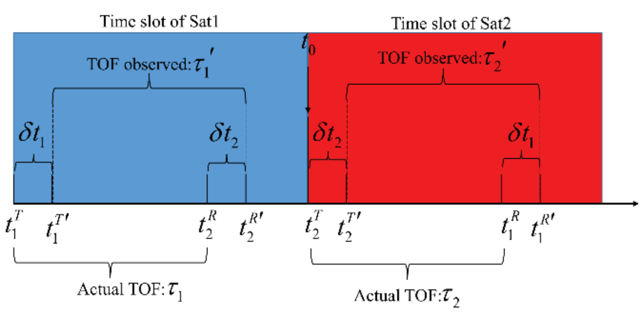
With the continued development of lunar exploration, many countries have proposed plans to return to the Moon. It is anticipated that there will be more and more frequent travel between the Earth and the Moon. Traditional PNT techniques that are strictly dependent on ground stations may not provide sufficient support to the rapidly growing number of lunar probes. Autonomous navigation that can be achieved on board is essential for this case. The LiAISON (Linked Autonomous Interplanetary Satellite Orbit Navigation) technique based on SST (Satellite-to-Satellite Tracking) data can achieve AOD (Autonomous Orbit Determination) without the sup-



port of the ground stations, which is an innovative and promising autonomous navigation method for lunar missions in the future.

AOD Performance Analysis

Previous studies focus on scenarios in which the AOD process is based on the SST data between a navigation satellite and a user satellite. This means that the AOD results have to be transmitted back to the navigation satellite, which is usually not practical. A more practical scenario is one in which a navigation constellation moves into the proximity of the Moon and the states of the constellation have been determined in advance. The whole AOD process is self-contained. Then, the navigation message would be broadcast from the navigation satellites to user satellites. Considering the cost of building such an autonomous lunar navigation constellation, a minimum configuration of two satellites would be a good starting point. Also, considering the service volume of such a constellation, the two satellites should move on orbits with high enough altitudes. Based on these two considerations, we chose the well-studied DROs (Distant Retrograde Orbits) and halo orbits as candidate orbits for the navigation satellite pairs. A comprehensive study on the AOD performance of satellite pairs in halo orbits and DROs is carried out.



DAGDOP

A novel factor is proposed, which is coined with the term dynamic and geometric dilution of precision (DAGDOP). It captures both the dynamic characteristics and the observation geometry of the constellation, and can be reduced to the well-known factor of geometric dilution of precision (GDOP) if no dynamics are involved. This study showed that this factor agrees quite well with AOD accuracy. As a result, it can be used as an indicator of AOD accuracy without actually performing the AOD process. It is more time-efficient using this factor. This factor is especially useful for satellite constellation design when there are massive candidate orbits. It can also be applied to other types of observational data.

Simulation

A hybrid configuration composed of a halo orbit and a DRO is proposed for the first time, and is verified in a simulated real model that includes a high-fidelity force model and measurement model. A dual one-way ranging (DOWR) method is applied in this work. Two satellites move on their respective orbits, transmitting ranging signals to each other. A time slot of 1 second is allotted to each satellite for transmitting signals. Through Monte-Carlo simulations, the AOD accuracy of the satellite pair is verified. 100 runs of the AOD process were conducted. The average AOD accuracy of the halo orbit was about 170 meters, and that of the DRO was about 190 meters. The relative time synchronization error of two satellites was less than 30 nanoseconds.

Commercial or Military Applications

Commercial travels between the Earth and the Moon in the future will benefit from the autonomous navigation constellation discussed in this work. Furthermore, the service volume of the autonomous navigation constellation will not be limited in the vicinity of the Moon. It can also work as an anchor station of the GPS constellation in case of the destruction of ground stations in war.

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

Gao, Z.-Y., & Hou, X.-Y. (2022) Comparison of autonomous orbit determination for satellite pairs in lunar halo and distant retrograde orbits. NAVIGATION, 69(2). https://doi.org/10.33012/navi.522

Multi-Epoch 3D-Mapping-Aided Positioning Using Bayesian Filtering Techniques

Qiming Zhong

The performance of conventional GNSS in urban areas is limited by the blocking, reflecting, and diffracting effects of buildings on satellite signals. As 3D mapping data of buildings have been demonstrated in numerous studies to significantly improve GNSS performance in these environments, some companies have subsequently introduced 3D city models into GNSS positioning technology to help improve the quality of location services in cities. For example, Google has announced that, as of Spring 2021, they have made 3D-mapping-aided (3DMA) GNSS positioning services available to Android users in around 4,000 cities worldwide.

3DMA Developed at University College London

The 3DMA GNSS developed by Zhong and Groves at the University College London runs on a hypothesis testing approach and consists of a set of algorithms: Visibility prediction, shadow matching (SM), likelihood-based ranging (LBR), and solution integration. Visibility predictions are made at each candidate position using a 3D building model to predict which satellites are line-of-sight (LOS) and which are non-line-of-sight (NLOS). SM uses signal strength (specifically, carrier power-to-noise density ratio) to measure satellite visibility and matches it with visibility predictions from 3D mapping to achieve positioning. This takes advantage of the fact that LOS and NLOS signals have different signal strength distributions. LBR is a pseudorange-matching method that maps error distributions of pseudorange innovations from LOS and NLOS signals into symmetric and asymmetric distributions, respectively. Compared to ray-tracing-based pseudorange matching, the method has the advantage of lower computational load as well as the potential to compute position solutions on mobile devices in real time without excessive loss of accuracy. Finally, the SM and LBR solutions are combined to give the final 3DMA GNSS solution.

Location-based services typically use single-epoch positioning, while pedestrian and vehicle navigation applications use filtered solutions. Filtering algorithms use the new measurements at each epoch to correct the navigation solution predicted from previous information. The extended Kalman filter is a common solution in multi-epoch GNSS positioning, which linearizes state transition and observation models using Taylor's theorem. The particle filter is an effective way of tackling nonlinear observation and process models. It uses a set of particles with equal likelihood to represent the probability distribution of a state estimation, regardless of the form of the distribution. Thus, it is suited to model the non-Gaussian and often multi-modal position solution distributions that can occur in 3DMA GNSS. The proposed grid filter can also represent the likelihood distribution of nonlinear state estimation. Unlike the particle filter, the hypotheses of the grid filter are comprised of a uniformly distributed grid with different likelihoods that better fit the physics of the problem. At the same time, this allows our 3DMA GNSS positioning algorithm to be easily extended to multi-epoch situations, as the grid filter shares the same hypothesis grid.

Testing the Proposed Methods in the City of London

The proposed methods were tested using both pedestrian and vehicle GNSS data sets, covering two main navigation scenarios applicable to cities. The static pedestrian navigation data was collected at various locations in the City of London using a ublox EVK M8T GNSS receiver. London is an example of a typical European city in which the roads are generally narrow and the walls of the buildings are mainly made of masonry (as shown in Figure 1). The vehicle navigation data was collected with a trial van equipped with a Racelogic Labsat 3 GNSS front-end (as shown in Figure 2) in Canary Wharf, London. The measurement data were comprised of intermediate frequency samples and were subsequently processed by Focal Point Positioning. The travel trajectory of the vehicle test contained both central

Figure 1. City of London
Google Maps


Figure 2. Test equipment in the back of the trial van
Imperial College of London


Figure 3. The central area of Canary Wharf
Google Maps

and non-central areas of Canary Wharf with different environmental characteristics. In the central area, there were many high-rise buildings with glass and steel surfaces (as shown in Figure 3) that are highly prone to obscure and reflect satellite signals. In the non-central area, on the other hand, there were mostly low-rise buildings of masonry material (as shown in Figure 4), which are more open overhead and are less likely to interfere with satellite signals than in the central area.

Figure 4. The non-central area of Canary Wharf
Google Maps

The results show that filtering has a greater impact on mobile positioning than static positioning, while 3DMA GNSS brings more significant improvements to positioning accuracy in denser environments than in more open areas. 3DMA GNSS techniques and filtering algorithms could benefit from each other. The former provides the latter with a better positioning solution in the measurement update step, while the latter, in turn, rewards the former with a better initial position and a smaller search area. Thus, multi-epoch 3DMA GNSS filtering should bring maximum benefits to mobile positioning in dense environments. In vehicle tests at Canary Wharf, the 3DMA GNSS filtering gave a root-mean-square horizontal position error of about 11 m, which was a reduction of approximately 68% and 57%, compared to single-epoch 3DMA GNSS and filtered conventional GNSS, respectively.

Comparing Grid and Particle Filtering Results

3DMA GNSS grid filtering and particle filtering showed similar performance in position accuracy. In terms of efficiency, 3DMA GNSS grid filtering can achieve solutions with errors comparable to those of 3DMA GNSS particle filtering using fewer particles. Theoretically, grid filtering consumes less resources and runs faster than particle filtering. In practice, however, the efficiency of grid filtering is reduced due to the convolution operation in the system propagation step.

The experimental results show the potential of our 3DMA GNSS algorithms to achieve a lower computational load than those using ray tracing, while retaining good positioning accuracy. The proposed grid filtering may be able to provide alternative filtering methods for positioning and navigation algorithms using hypothesis testing approaches, as well as providing a potential new idea for those using particle filtering.

Future Applications

Currently, the proposed method is still in the experimental phase. Potential applications include optimizing satellite visibility predictions, improving the scoring model for 3DMA GNSS, adding outlier detection, etc. The outlier detection work was presented at the ION GNSS+ 2022 conference in September. Work is still being done to improve aspects of the algorithms with the future goal of having the methodology applied to locally computed, real-time urban positioning and navigation with lane-level accuracy on consumer-grade devices.

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

Zhong, Q., & Groves, P. D. (2022) Multi-epoch 3D-mapping-aided positioning using Bayesian filtering techniques. NAVIGATION, 69(2). https://doi.org/10.33012/navi.515

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ION News and Notes

ELECTION RESULTS

On January 26, 2023, at the conclusion of the ION's International Technical and ION Precise Time Transfer and Time Interval meetings, the following newly elected officers were set to begin their two-year terms:

President: Dr. Sherman Lo
Executive Vice President: Dr. Gary McGraw
Treasurer: Dr. Frank van Graas
Eastern Vice President: Dr. Jacob Campbell
Western Vice President: Dr. Alex Stratton
Eastern Council Member-at-Large:
Barbara Clark — Dr. Sabrina Ugazio
Western Council Member-at-Large:
Dr. Juan Blanch — Laura Norman
Technical Representatives:
Dr. Fabio Davis — Dr. Christoph Günther
Dr. Joanna Hinks — Dr. Nobuaki Kubo
Dr. Heidi Kuusniemi — Dr. David De Lorenzo
Dr. Okuary Osechas — Dr. Kirsten Strandjord

In addition to those elected above, Dr. Frank van Diggelen, Dr. Thomas Powell and Sandy Kennedy will continue to serve on the ION Executive Committee as Immediate Past President, Military Division Chair, and Satellite Division Chair, respectfully.

The following standing committee chairs were also appointed to two-year terms:

Awards Committee Chair: Dr. Michael Meurer
Bylaws Committee Chair: Tim Murphy
Ethics Chair: Dr. Terry Moore
Fellow Selection Chair: Charles Schue
Finance Chair: Dr. Jason Rife
Membership Chair: Dr. Mohammed Khider
Meetings Chair: Jeff Martin
Nominating Chair: Dr. Frank van Diggelen
Publications Chair: Dr. Richard Langley
Technical Committees Chair: Dr. Gary McGraw

Prof. Terry Moore Named Officer of the Most Excellent Order of the British Empire

Prof. Terry Moore, Emeritus Professor and former Director of the Nottingham Geospatial Institute, UK, will be recognized in 2023 by the British crown as an "Officer of the Most Excellent Order of the British Empire" for services to satellite navigation.

He said: "It's a great honor to be recognized and nominated for this award. Indeed, I am particularly proud of the significant impact that satellite navigation systems have on everyone's daily lives, even without them knowing, and I hope that this award helps us to continue to stress the vital importance of the technology we now take for granted…"

Over the course of his career, Prof. Moore has taken a leading role in national and European initiatives aimed at integrating academic research and teaching in Global Navigation Satellite Systems (GNSS). He is a member of the US National Space-Based Positioning, Navigation and Timing (PNT) Advisory Board and of the European Space Agency (ESA) GNSS Science Advisory Committee. He has been actively involved with both the Royal Institute of Navigation (RIN) and the ION, serving in numerous capacities. Prof. Moore is an ION Kepler Award winner (2017), and an RIN and ION Fellow.

In Memoriam

Dee Ann Divis died November 22, 2022, in Arlington, Virginia. Dee spent nearly 40 years in the Washington, D.C., area working for a number of publications as an investigative reporter specializing in Global Positioning Systems (GPS) and other position, navigation, and timing systems (PNT).

During her prolific career, Dee Ann provided original reporting on GPS and PNT technologies; was briefly editor of the *ION Newsletter*, covering all aspects of PNT (2021); freelance reporter for Al Jazeera covering commercial space, space exploration, artificial intelligence, autonomous vehicles, robotics, drones and other related areas of technology, policy and markets; Washington editor/founding editor of *Inside Unmanned Systems,* reporting on unmanned technology sectors, government programs, policy issues and technology advances; contributing editor for *Inside GNSS* magazine in which she wrote regularly about navigation-related policy issues impacting satellite systems; assistant managing editor for the *Washington Examiner* covering news operations for the metropolitan daily newspaper; Fellow for the Institute for Justice and Journalism; senior science and technology editor for United Press International; space section editor for AviationNow.com, and editor for Aerospace Daily's Space Business Today (McGraw Hill).

Dee won numerous awards for her writing, including the Robert D.G. Lewis Watchdog Award in 2012, from the Washington, D.C., chapter of the Society of Professional Journalists; and the Dateline Award for Washington Correspondent twice (2012-2013). Dee Ann earned a bachelor's from the University of Nebraska-Lincoln, and was a Massachusetts Institute of Technology Knight Science Journalism Fellow.

New England Section News

After a three-year hiatus due to Covid, the New England ION section restarted with a meeting on the evening of October 6th at Draper Laboratory in Cambridge, Massachusetts. Draper was a gracious host of the meeting, and we thank them for their

Corporate Profile

Cynexus Technologies

www.cynexustech.com

Cynexus Technologies is a systems and software engineering company providing guidance, navigation, and control solutions. The Cynexus team are experts in hydrodynamic and aerodynamic modeling, simulation and flight control systems, and deliver proprietary hardware and software solutions with diverse applications in sea, air, and land vehicles, both autonomous and manned.

The company's flagship technology is an inertial navigation system (INS) not reliant on GPS or GNSS signals for positioning and capable of 0.02 (or better) nmi/hr unaided performance. This solution eliminates cybersecurity threats to defense, commercial, and critical infrastructure applications. The INS is not susceptible to jamming or spoofing and provides accurate navigation outputs during long reset periods encountered in cyber-hacked, GPS-denied, or GPS-compromised environments.

Cynexus products apply to all air, land, and sea platforms, piloted and unmanned, in the defense and commercial sectors in which the operational threat of compromised GPS navigation has become a major industry concern.

For more information on corporate membership in the Institute of Navigation, please contact Kenneth P. Esthus at 703-366-2723 extension 1004

Calendar of Upcoming Events

MARCH 2023

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

Contact: Bundeswehr University Munich

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

APRIL 2023

24: 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

Web: ion.org

MAY 2023

31-2 June: European Navigation Conference (ENC) 2023, Noordwijk, The Netherlands

Contact: European Group of Institutes of Navigation (EUGIN)

Web: https://www.enc2023.eu/

JUNE 2023

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

Contact: ION

Web: 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

Web: 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

Web: ion.org

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hospitality. We anticipate our next meeting to be in early spring.

Prior to the start of presentations, the attendees socialized and networked while enjoying pizza and other light refreshments. It was wonderful to see folks reconnecting and excited for the meeting. Dr. Keith McDonald, the chair of the section, provided introductory comments, introduced the other New England officers, and set the stage for the remainder of the exchange (see notes below).

The speakers were Dr. Hadi Wassaf, an electrical engineer in the Aviation Weather and Positioning, Navigation, and Timing (PNT) Applications Division of the U.S. DOT Volpe National Transportation Systems Center. Dr. Jason Rife is professor and Chair of the Department of Mechanical Engineering at Tufts University in Medford, Massachusetts, where he directs the ASAR Laboratory. They briefed on the topic of safe navigation for automated driving systems (ADSs).

The first portion of the briefing focused on defining rigorous mathematical definitions for availability, continuity, accuracy, and resiliency based on the probability of threats. A framework for quantifying the performance of the system was also discussed. Since ADSs are intended to provide critical decision and control functions traditionally provided by drivers, these contributions allow for system evaluation, particularly to ensure that they perform as expected in challenging environments (when sensor signals are jammed, spoofed, degraded, etc.).

The second portion of the briefing focused on one such ADS sensor—lidar. Lidar algorithms are grouped into scan matching (i.e., dead reckoning) or registration using a previously stored map for absolute positioning. Several sources of error exist for lidar that reduce integrity, including lidar alignment errors, pose, changes in sample location, and even the roughness of the surface. A new algorithm, known as ICE-T and developed by Tufts, provides covariance estimates to quantify lidar error—a novel contribution that traditional lidar algorithms do not provide. The ICE-T algorithm is a natural candidate to provide rigorous measures for integration into the ADS framework presented in the first half of the briefing.

The briefers fielded questions from the audience prior to meeting closure.

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