

GPS WORLD

GNSS
POSITIONING
NAVIGATION
TIMING

EVOLUTION

Machine Learning
for Ionosphere
Prediction

THE INDUSTRY'S MOST TRUSTED TECHNICAL RESOURCE SINCE 1990

MODERN NORTHSTAR

Starlink LEO PNT Across
Land, Air, Stratosphere
and Arctic Seas



No GNSS

GNSS

Starlink



**ROBOTIC ROVERS
REVOLUTIONIZE MILITARY
RUNWAY ASSESSMENT**

JANUARY/FEBRUARY 2026 | Vol 37 | No 1
GPSWORLD.COM

A NORTH COAST MEDIA PUBLICATION

UNLOCK EXPERT INSIGHTS

Free Webinars



UPCOMING:

- GNSS Anti-Jamming and Anti-Spoofing Technology Explained, sponsored by Calian (*Live event February 26*)

ON-DEMAND:

- Building a Layered Future: Resilient GNSS Alternatives That Complement, Not Compete, with GPS, sponsored by NextNav
- Unlocking the Power of LEO Constellations: Testing and Performance with Xona, Trimble, and Safran, sponsored by Safran Electronics & Defense
- Resiliency in Space: Developing Space Technologies That Endure, sponsored by Novatel
- Power-Efficient GNSS: Optimizing Location Platforms for Longevity and Accuracy, sponsored by Quectel
- Augmented Reality NAVWAR Testing: Fast-Track PNT System Deployment, sponsored by Safran Federal Systems
- Multi-Orbit GEO/LEO PNT Resiliency with VIAVI SecureTime Services, sponsored by VIAVI Solutions



Register for free at gpsworld.com/webinars

PARTNER WITH GPS WORLD TO HOST YOUR NEXT WEBINAR EVENT.

Contact Tod McCloskey at tmccloskey@northcoastmedia.net or call 216-363-7921 for more details.

CONTENTS

VOL. 37 NO. 1 GPSWORLD.COM

JAN/FEB 2026

COVER STORY

18 MODERN NORTHSTAR

Starlink LEO PNT Across Land, Air, Stratosphere and Arctic Seas

BY ZAHER (ZAK) M. KASSAS, SAMER HAYEK, WILL BARRETT, SHARBEL KOZHAYA,
PAUL EL-KOUBA, FAEZEH MOOSELI, JENNIFER SANDERSON AND JOE SAROUFIM

Researchers from The Ohio State University present the most advanced low-Earth orbit positioning, navigation and timing (LEO PNT) results to date with Starlink on four mobile platforms at geographically dispersed locations:

1. Ground vehicle in Pennsylvania
2. UAV in Ohio
3. Extremely high-altitude balloon in New Mexico
4. Maritime vessel in the Arctic near Greenland

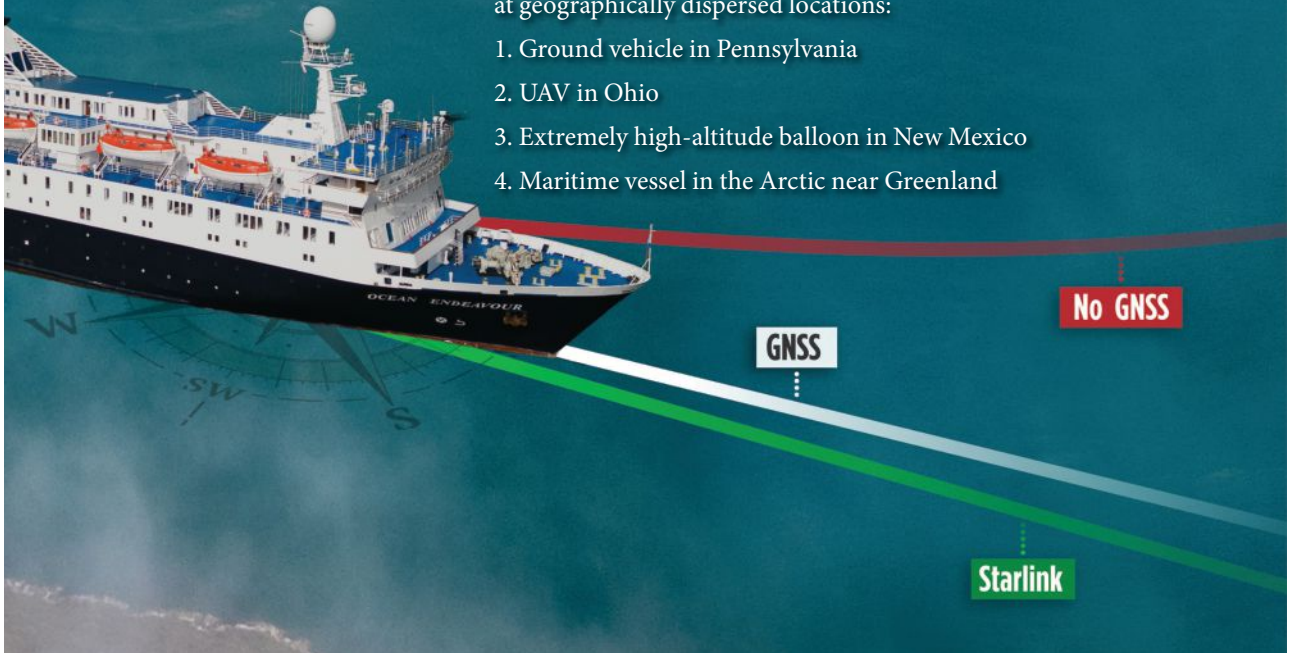


Image courtesy of authors

SECONDARY FEATURE

27 Cleared for the Dirt

How robotic rovers are revolutionizing military runway assessment

BY PIETERJAN DE MEULEMEESTER AND ALAIN MULS



BENS Development Team of the Royal Military Academy of Belgium

ON THE COVER

Experimental hardware aboard a research vessel during August 2024 Arctic navigation trials off Baffin Island, Nunavut, Canada. The system captured Starlink signals using an upward-facing LNBF connected to a B205-mini USRP and Raspberry Pi 4, processing data at 2.5 MSps over Ku-band. (Credit: Courtesy of authors)

EVOLUTION

36 The Use of Machine Learning for Station-Specific Ionosphere Prediction in GNSS Positioning

BY TAIWO OSANYIN AND SUNIL BISNATH

OPINIONS AND DEPARTMENTS

5 FIRST FIX

Explore Your New Online Experience

6 EAB PNT Q&A

With the increase in reported GNSS jamming incidents affecting commercial aviation, what technical approaches show the most promise for ensuring reliable PNT?

WITH MIGUEL AMOR, MITCH NARINS AND PAUL MCBURNEY

7 UPCOMING EVENTS

2026 Conferences and Trade Shows

8 SYSTEM OF SYSTEMS

Galileo Adds Two New Satellites • China Increases Investments in BeiDou Constellation • Moldova's Positioning System Now Uses Galileo • Positioning Australia Expands Capabilities with Ginan v4 Release

41 AD INDEX

42 SEEN & HEARD

It's All Happening Downtown • What on Earth is Happening? • Making Better Robots with GNSS • 2,000 and Counting

LAUNCHPAD

12 AUTONOMOUS

13 SURVEYING & MAPPING

16 TRANSPORTATION

MARKETWATCH

32 TRANSPORTATION

33 SURVEYING

34 DEFENSE

34 SPACE & EARTH

ONLINENOW

EVOLUTION

The Rise of LEO PNT

BY MATTEO GALA, TYLER REID, THYAGARAJA MARATHE, AURORE SIBOIS, SRINIVAS TANTRY, KAZUMA GUNNING AND SUNIL BISNATH

Everyday life is saturated with location-dependent devices. They are multiplying faster than ever and their requirements have surpassed what GPS can support. Innovation in low-Earth orbit (LEO) satellites have seen exponential growth in the past 10 years, unlocking new possibilities in further connecting our world.

In 2016, the total number of satellites operational in space from commercial and government operators was approximately 1,500. This number had been stable for decades, with linear growth since the launch of Sputnik in 1957. Today, there are now more than 8,000 satellites operational in space — with nearly all growth happening in LEO.

There are multiple reasons why. The cost of space access has decreased with reusable rockets and greater competition. The demand for connectivity has driven deployment of multiple constellations to deliver internet from space. Latency is extremely important in communications and resolution in Earth observation.

While innovation in LEO satellites has primarily focused on connectivity and Earth observation, there is a generational opportunity to innovate in the positioning, navigation and timing (PNT) infrastructure that silently powers modern life. 🌐

Read more at gpsworld.com/the-rise-of-leo-pnt/.

EDITORIAL

Editor Diane Sofranec
dsfranec@northcoastmedia.net | 216-706-3793

Editor-at-Large Tracy Cozzens
tcozzens@northcoastmedia.net

Associate Editor Jesse Khalil
jkhall@northcoastmedia.net | 216-363-7930

Digital Media Specialist RJ Simon
rsimon@northcoastmedia.net | 216-675-6001

Creative Director Courtney Townsend
ctownsend@northcoastmedia.net | 216-363-7931

Junior Graphic Designer Amelia Joliat
ajoliat@northcoastmedia.net | 216-706-3780

CONTRIBUTING EDITORS

Professional OEM & UAV Tony Murfin | tamurfin@verizon.net

Survey Dave Zilkoski | dzilkoski@gpsworld.com

Evolution Dr. Sunil Bisnath | sunil.bisnath@lassonde.yorku.ca

BUSINESS

Sales Director Tod McCloskey
tmccloskey@northcoastmedia.net | 216-706-7921

Director of Research and Data Tabatha Jeter
tjeter@northcoastmedia.net | 216-973-4395

Event Manager Rachel Rosen
rrosen@northcoastmedia.net | 216-363-7936

Marketing & Sales Manager, Buyers Guide
buyersguide@northcoastmedia.net

PUBLISHING SERVICES

Manager, Production Services Chris Anderson
canderson@northcoastmedia.net | 216-978-5341

Senior Audience Development Manager Antoinette Sanchez-Perkins
asanchez-perkins@northcoastmedia.net | 216-706-3750

Audience Marketing Manager Hillary Blaser
hblaser@northcoastmedia.net | 216-440-0411

Reprints & Permissions Wright's Reprints
northcoastmedia@wrightsmedia.com

Circulation/Subscriber Services
gpsworld@omedia.com | USA: 847-513-6030

NORTH COAST MEDIA LLC

1360 East 9th St, Tenth Floor
Cleveland, OH 44114, USA

President & CEO Kevin Stoltman
kstoltman@northcoastmedia.net | 216-706-3740

Vice President of Finance & Operations Steve Galperin
sgalperin@northcoastmedia.net | 216-706-3705

Vice President of Content Marty Whitford
mwhitford@northcoastmedia.net | 216-706-3766

Vice President of Marketing Michelle Mitchell
mmitchell@northcoastmedia.net | 216-363-7922

MANUSCRIPTS: *GPS World* welcomes unsolicited articles but cannot be held responsible for their safekeeping or return. Send to: 1360 East 9th St., Tenth Floor, IMG Center, Cleveland, OH 44114, USA. Every precaution is taken to ensure accuracy, but publishers cannot accept responsibility for the accuracy of information supplied herein or for any opinion expressed. **REPRINTS:** Reprints of all articles are available (500 minimum). Contact: northcoastmedia@wrightsmedia.com, Wright's Media, 2407 Timberloch Place, The Woodlands, TX 77380. **SUBSCRIBER SERVICES:** To subscribe, change your address, and all other services, e-mail: gpsworld@omedia.com or call 847-513-6030. **LIST RENTAL:** Contact: 800-529-9020, Brian Scheikman, bscheikman@infocrell.com, The Information Refinery, Inc. 2407 Timberloch Place, The Woodlands, TX 77380. **INTERNATIONAL LICENSING:** Wright's Media, 2407 Timberloch Place, The Woodlands, TX 77380. **ACCOUNTING OFFICE AND OFFICE OF PUBLICATION:** 1360 East 9th St., Tenth Floor, IMG Center, Cleveland, OH 44114, USA. *GPS WORLD* does not verify any claims or other information appearing in any of the advertisements contained in the publication and cannot take any responsibility for any losses or other damages incurred by readers in reliance on such content. The opinions expressed by *GPS World's* contributors are theirs and do not necessarily reflect the policy or position of this magazine or of its publisher, North Coast Media.

GPS World is published 6 times in February, April, May, July, August and November



Explore Your New Online Experience

Technology is a powerful tool that has changed the way you work, communicate with colleagues, and solve problems. It is constantly evolving, and no one knows that better than the readers of *GPS World*. No doubt technological advances have made you more efficient and productive in the workplace, whether your duties involve surveying and mapping, transportation, or defense.

Since 1990, *GPS World* has focused on technical, practical ever-changing applications. The print edition has helped advance the development and deployment of GPS/GNSS and other positioning, navigation and timing (PNT) solutions while the website delivers the latest news and top headlines.

GPS World now offers an improved online experience for longtime readers like you, as well as casual users. The redesigned website introduces new features aimed at improving the way you access and read the content you have come to rely on.

Registration on **gpsworld.com** is completely free and takes less than a minute. There are many benefits to registering. You will be able to:

Create reading lists. You can save articles and organize your favorite content into custom lists that are easily accessible later.

Select topics of interest. You can generate a personalized content feed within your online dashboard to ensure you see the content you care about most. These topic selections also help drive additional content recommendations on article pages, which will further enhance your engagement on the website.

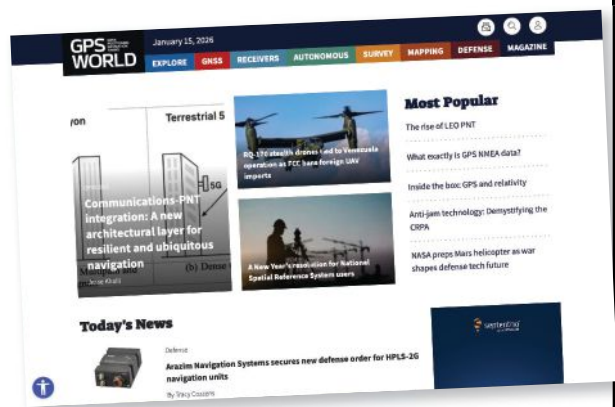
Manage your newsletter and magazine subscriptions. Your subscription information is readily available on your user dashboard. If you are a current *GPS World* subscriber, your customer information will be automatically connected to your *GPS World* website account.

Listenable content is one of the most exciting new features, and it's available to all users, regardless of their registration status. New technology allows *GPS World* editors to generate audio using an AI-based text-to-speech platform, which places an audio widget directly on the article pages so you can listen to content in full. The homepage also includes a section that highlights the most recent articles that have audio.

The market segments *GPS World* covers are easier to access, thanks to colored tabs at the top of the website. There, you will find a collection of content covering GNSS, Receivers, Autonomous, Surveying, Mapping and Defense.

You also will get easy access to our annual Buyers Guides, Product Showcase, expert commentaries, and back issues.

The new features and improvements introduced with the redesign of the website will enhance your reading — and listening — experience. 🌐



With the increase in reported GNSS jamming incidents affecting commercial aviation, what technical approaches show the most promise for ensuring reliable PNT?

“Aviation encompasses a diverse range of applications and missions, requiring support from various positioning, navigation and timing (PNT) solutions. As with most challenges, employing multiple strategies often yields optimal outcomes, particularly in scenarios where a one-size-fits-all approach is impractical. I firmly believe in the enduring importance of the guidance historically imparted to navigators: to ‘utilize all available means.’



However, it is crucial to recognize that GNSS jamming is not the primary concern. Fortunately, aviation has historically and continues to rely on resilient ground-based alternatives, although many of these systems have been in service for several decades and require upgrades and replacements. The more pressing issue for aviation and other PNT applications lies in spoofing. I strongly advocate for the abandonment of the concept of employing a single, non-resilient solution for critical functions, a practice once referred to as ‘GPS sole-means.’”

Read the full responses at gpsworld.com/opinions

Miguel Amor
Septentrio

Thibault Bonnevie
SBG Systems

Alison Brown
NAVSYS Corporation

Ismael Colomina
GeoNumerics

Bernard Gruber
Northrop Grumman

Richard B. Langley
University of New Brunswick

Paul McBurney
oneNav

Jules McNeff
Overlook Systems Technologies

Mitch Narins
Strategic Synergies

Washington Yotto Ochieng
Imperial College London

Bradford W. Parkinson
Stanford Center for Position, Navigation and Time

Stuart Riley
Trimble

Michael Swiek
GPS Alliance

Julian Thomas
Racelogic Ltd.

Rob Van Brunt
Spirit Federal Systems



“Ensuring reliable navigation and timing in the presence of increasing GNSS jamming requires

both stronger technology and faster modernization in aviation. Today, the most effective protection is a layered approach, starting with advanced interference mitigation at the receiver level. Modern anti-jamming algorithms and robust signal processing, combined with multi-frequency and multi-constellation capabilities, provide important diversity and allow systems to continue operating even in difficult RF environments. CRPA antennas also further improve resilience by enabling spatial filtering and adaptive nulling, suppressing jammers before they impact the receiver.”



“Controlled Reception Pattern Antennas (CRPAs) and adoption of L5. As discussed by Brad Parkinson, Ph.D., at

the most recent National Space-based PNT Advisory Board (PNTAB) meeting, the CRPA is the big-hammer anti-jam solution. It’s great to hear that the ITAR restrictions have been removed. For commercial aviation, the long pole to deployment is likely dependent on an FAA certification procedure. The other advice from PNTAB is that L5 has a much smaller denial radius. So, once again, the U.S. Government and FAA are on the critical path: We need L5 to be declared healthy and usable, which likely requires an upgrade of RTCA MOPS.”

2026 Conferences and Trade Shows

GEO WEEK
Feb. 16-18, Denver



ION Pacific PNT
April 13-16,
Honolulu, Hawaii



AUVSI XPONENTIAL
May 11-14, Houston



**ION Joint Navigation
Conference (JNC)**
June 1-4,
Greater Cincinnati Area



Esri User Conference
July 13-17, San Diego



Commercial UAV Expo
Sept. 1-3, Las Vegas



ION GNSS+
Sept. 14-18, Orlando



INTERGEO
Sept. 15-17-9
Munich, Germany



**Trimble Dimensions
User Conference**
Nov. 9-11, Las Vegas



Dates and locations are subject to change.

GNSS | CRPA | INERTIAL | JAMMING

CAST

NAVIGATION

**Delivering Peak
Precision in GNSS
Inertial Simulation**



**Coherence
Accuracy
Repeatability
Productivity**



castnav.com

Dynamic GNSS/INS simulation
systems that will make your job easier

SYSTEM OF SYSTEMS

POLICY AND SYSTEM DEVELOPMENTS IN GNSS AND OTHER PNT TECHNOLOGIES



IN DECEMBER, two new satellites refreshed the Galileo constellation.

European Space Agency

Galileo Adds Two New Satellites

Europe has given fresh momentum to its Galileo navigation system with the successful Dec. 17 launch of two new satellites aboard an Ariane 6 rocket. The launch, the 14th of the program (L14), is one of the final three planned launches of first-generation (G1G) satellites. The two

new satellites will strengthen the global PNT services provided by the system.

The launch comes at a critical moment for the constellation, which needs to replace its oldest satellites, according to GMV, the lead developer and operator of the Galileo ground control segment.

More than 4 billion users worldwide routinely rely on Galileo. This launch

milestone ensures Europe's ability to operate its own radionavigation system, which is essential for intelligent transportation, logistics, precision agriculture, defense, public safety, communications network operations, and energy generation and transmission.

From centers in Oberpfaffenhofen, Germany, and Fucino, Italy, GMV manages post-separation operations from the launch vehicle and ensures the correct insertion of the new satellites into the constellation. GMV also operates 24/7 to monitor the health and position of each satellite, plan and execute orbital maneuvers, ensure signal integrity, and manage critical system operations.

Coming Soon: Second-Gen Galileo

The L15 and L16 missions will complete the first generation of the system before transitioning to the second-generation Galileo satellites (G2G) under development. These will introduce advanced capabilities, greater accuracy, and enhanced resilience against interference and cyber threats, GMV said. 🌐

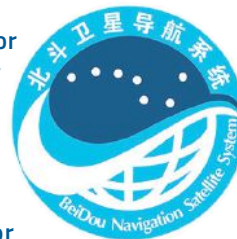
China Increases Investments in BeiDou Constellation

China's BeiDou satellite navigation system (BDS) has secured approximately \$1.78 billion in funding for new projects, positioning itself to compete more effectively with its primary rival, GPS. This significant financial boost was announced at the Third International Summit on BDS, coinciding with the system's 30th anniversary.

The investment package includes \$1.1 billion, which is designated for adopting BeiDou in both industrial and consumer applications, according to *Hunan Daily*. Part of the funding has been allocated to an Indonesian di-

aster prevention agency for the development of an early warning system.

China's Ministry of Industry and Information Technology has also selected 39 pilot cities for large-scale BDS applications. These cities are expected to increase BDS usage rates as the system transitions into its third-generation phase. This aims to expand BeiDou's domestic footprint and showcase its capabilities on a broader scale, according to China's Ministry of Industry and



Information Technology.

China launched two new satellites in September 2024, bringing the total number of active satellites in the BeiDou constellation to 50. The newly launched satellites, part of the third-generation model, represent the second batch placed into medium-Earth orbit (MEO) since the system was declared operational in July 2020. With 64 satellites launched, China continues to expand and enhance the BeiDou system. 🌐

Moldova's Positioning System Now Uses Galileo

The National Positioning System in Moldova, MOLDPOS, has been integrated into the European Position Determination System (EUPOS), a pan-European GNSS augmentation service.

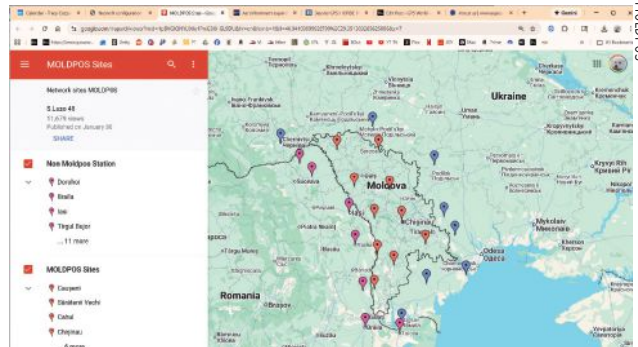
The MOLDPOS navigational system uses both GPS and GLONASS, and Galileo has now been added.

Creation of MOLDPOS was gradual. First, sites for placement of MOLDPOS stations were selected, then the stations were installed. Once installations were in place, the system was tested and launched. Now it is integrated into EUPOS.

Moldova had been a member of the European Position Determination System since 2008.

According to Norwegian Ambassador to Moldova Øystein Hovdkinn, Moldova and Norway are situated in opposite parts of Europe, but it did not impede establishing friendly relations. Norway provided financial aid to build MOLDPOS.

Hovdkinn said the Government of Norway supports the program of reforms in Moldova. The project's goal is to promote Moldova's development as a modern country and to



MOLDOVA MOLDPOS STATIONS are depicted in red.

promote its integration in Europe.

According to Gheorghe Duca, president of the Moldovan Academy of Sciences, implementation of MOLDPOS will have a positive influence upon the country's social, economic and scientific sectors.

"A digital map is necessary for preventing floods, for rehabilitating roads, in agriculture and in science," Duca said, adding that Moldova is the first country on the border with the European Union that will have digital maps, expected to be available in 10 months. 🌐

Positioning Australia Expands Capabilities with Ginan v4 Release

Geoscience Australia has released Ginan V4, the latest version of its home-grown, open-source toolkit for precise point positioning. Developed under the Positioning Australia program, Ginan V4 delivers world-class GNSS capabilities to innovators, researchers and industry professionals.

Version 4 features a new intuitive graphical user interface (GUI) that makes data processing faster, easier and more accessible. The new GUI was designed to lower the barrier to entry for users across sectors. With simple data loading and streamlined output downloads, the new interface enables anyone — from navigation specialists to disaster response teams — to harness centimeter-level accuracy without needing advanced technical expertise.

Ginan V4 also introduces enhanced robustness and improved software

formatting, reducing errors and accelerating processing speeds. Users can expect smoother workflows and reliable results, whether calculating orbital mechanics or pinpointing precise locations on Earth's surface.

Ginan V4 remains fully modular, empowering users to build their own capabilities depending on their needs. From surveying and geospatial analysis to emergency response and scientific research, the toolkit supports innovation across diverse applications.

Key benefits of Ginan V4

- **User-friendly interface.** Simplifies data loading and output generation.
- **Enhanced robustness and speed.** Fewer errors, faster processing.
- **Modular design.** Customize capabilities for orbital mechanics, surveying or disaster response.



- **GNSS accuracy.** Centimeter-level precision based on satellite observations.
- **Free and open source.** Available to download via Geoscience Australia's GitHub.

As part of Positioning Australia's suite of capabilities, Ginan V4 reflects Geoscience Australia's commitment to delivering GNSS capabilities that support innovation, safety and productivity. By making the software free and open source, the program ensures that Australian expertise continues to drive global advances in positioning technology. 🌐



Q+A with Safran Electronics & Defense Julien Auger

Why Inertial Navigation Is Essential for Modern Surveying and Mapping

To start, could you explain the core principle behind an inertial navigation system, or INS?

Certainly. At its core, an INS determines position, velocity and orientation by integrating acceleration and angular rate data collected by an inertial measurement unit (IMU). The IMU houses accelerometers and gyroscopes along three axes. By processing this data in real time, the system continuously computes movement relative to a known starting point. What makes INS particularly valuable is that it operates independently of external signals — unlike GNSS — making it highly reliable in environments where satellite visibility is poor or intermittent.

What are the main technical challenges in developing a high-performance INS?

The biggest challenge is drift. Even tiny sensor errors accumulate over time, gradually degrading accuracy. High-end INS mitigate this with ultra-stable sensors, such as hemispherical resonator gyroscopes, and by applying sophisticated filtering and bias compensation algorithms in real time. Environmental influences such as temperature fluctuations, vibration and shock also play a major role, so the system must be designed to remain stable and precise under demanding real-world conditions.

How does INS complement GNSS in applications like surveying and mapping?

GNSS provides absolute position but

is vulnerable to spoofing, jamming, blockage, or multipath errors in urban canyons, forests, or tunnels. INS steps in to fill those gaps, providing continuous, high-frequency position and orientation data. When the two systems are integrated, INS effectively bridges GNSS outages and stabilizes trajectory data. This fusion is crucial for mobile lidar, photogrammetry and airborne mapping, where maintaining alignment and precision is essential.

Can you share a real-world example where INS performance proved decisive?

Absolutely. In one lidar survey conducted in a dense downtown area, GNSS-only positioning led to errors of several meters because of signal blockage and reflections. By integrating a high-grade INS, the team was able to maintain uninterrupted position and attitude data. The result was precisely aligned point clouds and far less time spent on post-processing. Without the INS, the dataset likely would have required expensive re-surveying and manual corrections.

What trends are shaping next-generation INS technology?

We're seeing rapid progress on both hardware and software fronts. On the hardware side, hemispherical resonator gyroscope provides high stability, while MEMS-based sensors are becoming more accurate and compact. On the software side, smarter algorithms — including adaptive filtering and machine learning-based error modeling — are enhancing

long-term performance. Altogether, these advances are enabling smaller, lighter and more deployable systems that still deliver survey-grade accuracy.

How are these advances applied in practical INS systems today?

Modern INS units now combine high-stability gyroscopes with advanced digital signal processing to deliver exceptionally low drift and robust performance in the field. Their compact and ruggedized designs make them versatile across land, sea and air platforms — even in GNSS-denied areas. For surveyors and mapping professionals, that means they can maintain data integrity, continuity and accuracy no matter the terrain or operational challenge.

And how does Geonyx specifically address these operational needs?

Geonyx is a fully digital inertial navigation system using advanced HRG technology to deliver ultra-low drift and exceptional stability. It provides precise, reliable navigation even without GNSS, making it ideal for mapping and surveying in any environment. In short, it's precision without dependence.

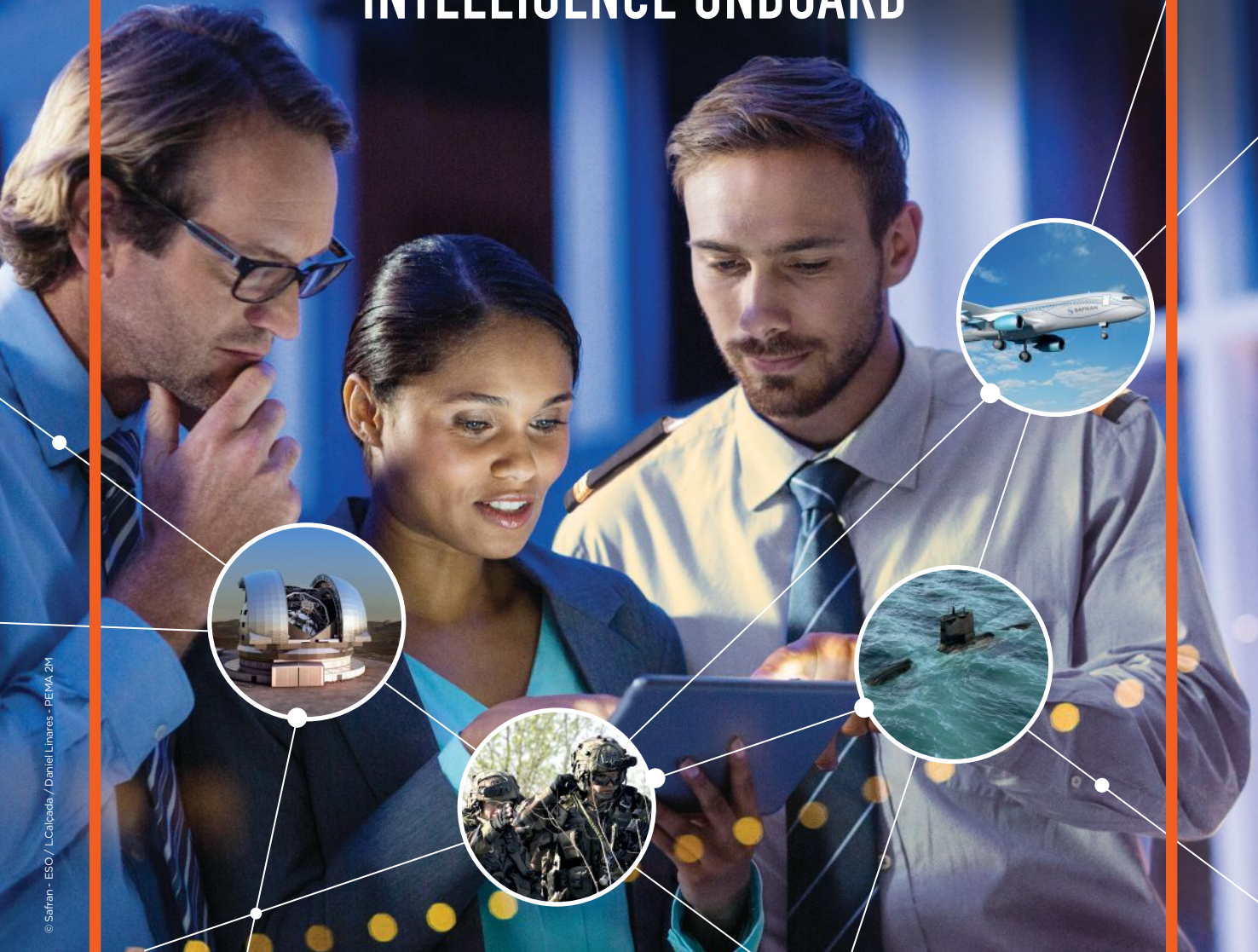
Julien Auger, INS Product Manager



ELECTRONICS & DEFENSE

OBSERVE, DECIDE, GUIDE

INTELLIGENCE ONBOARD



© Safran - ESO / L. Calçada / Daniel Linares - PEIMA 214

SAFRAN ELECTRONICS & DEFENSE, INTELLIGENCE ONBOARD

Day after day, you face critical challenges. The products and services developed by Safran Electronics & Defense, whether civil or military, deliver the technological superiority, effectiveness, reliability and competitiveness you expect. We're with you every step of the way, building in the intelligence that gives you a critical advantage in observation, decision-making and guidance. You can count on Safran Electronics & Defense, your strategic partner on land, at sea, in the air and in space.

safran-electronics-defense.com

🐦: @SafranElecDef

 **SAFRAN**

1



2



3



4



1. DELIVERY DRONES

VOLATUS DEPLOYS MEDICAL SUPPLIES IN CANADA

Volatus Aerospace has integrated the Trimble PX-1 RTX solution into its commercial delivery drone service to achieve accurate and robust positioning and heading. The Trimble module provides Volatus' clients with a turnkey solution for highly accurate aerial data acquisition and fully remote drone operations in real-world missions, including beyond visual line of sight (BVLOS). The PX-1 RTX uses Trimble's CenterPoint RTX corrections along with compact, high-performance GNSS-inertial hardware to deliver real-time, centimeter-level positioning and highly precise inertial-derived true heading measurements. This technology reduces operational risks associated with poor sensor performance or magnetic interference by providing enhanced positioning redundancy.

Volatus Aerospace, volatusaerospace.com, Trimble, trimble.com

2. DEFENSE DRONE

FOR BORDER PROTECTION AND LONG-RANGE SURVEILLANCE MISSIONS

The ERE95 Mini by CopterPIX operational platform is fully capable of GNSS-denied missions and integrates a long-range, anti-jamming communication system supporting distances of more than 20 km. It has an endurance of 2 hours and can carry up to 5 kg of payload for up to 1 hour. It also has integrated daylight and thermal imaging for advanced surveillance. With a fully foldable frame, the platform collapses into a backpack-sized kit, making it suitable for rapid mobility and field operations. Its modular "puzzle" architecture allows quick adaptation of SDR modules, optical payloads, and navigation solutions, enabling mission-specific configurations. To support rapid field deployment, the ERE95 Mini features a mechanical and electrical quick-connect interface, allowing operators to switch payloads in seconds and maintain continuous operational readiness across all missions.

CopterPIX, copterpix.pro

3. VISUAL NAVIGATION

INTEGRATED INTO LONG-ENDURANCE UNMANNED AIRCRAFT SYSTEM

AeroVironment has integrated its visual navigation system (VNS) kit with the Puma Long Endurance (LE) small unmanned aircraft system, delivering GNSS-denied navigation capability. The VNS kit uses advanced computer vision and onboard processing to deliver precise, GNSS-independent navigation. Using a suite of downward-facing sensors, cameras and onboard computing, the VNS kit performs visual inertial odometry to capture and analyze terrain imagery, estimating true aircraft position in real time. The system fuses continuous visual data from the cameras with motion inputs from onboard inertial sensors to calculate precise position, velocity and orientation — allowing the aircraft to know where it is and where it is going when GNSS is not available. It automatically transitions between GNSS-enabled and GNSS-denied modes with zero pilot input, ensuring uninterrupted mission continuity in contested environments.

AeroVironment, avinc.com

4. COUNTER-DRONE RADAR

LOW POWER, SMALL FOOTPRINT SETUP FOR CLOSE-AIRSPACE AWARENESS

The Portable 360 Radar is a rugged, easily transportable radar kit that delivers reliable close-airspace awareness with panoramic coverage for rapid-response counter-drone operations, from safeguarding stadiums and large public gatherings to border security and battlespaces. The MatrixSpace platform unifies threat awareness across multiple networked Portable 360 Radar systems and other sensors, without compromising local operation. By combining AI edge processing with MatrixSpace AiCloud Enterprise software, central command centers get an enhanced common operating picture and deep airspace activity analytics to assure public safety.

MatrixSpace, matrixspace.com

1. LASER RTK RECEIVER

RELIABLE IN COMPLEX AND GNSS-LIMITED ENVIRONMENTS

The SatLab SL8 Laser RTK GNSS receiver combines dual cameras, GNSS, an IMU and visible laser technology to make surveying faster and easier. With non-contact measurement, image-assisted targeting, CAD live-view stakeout, and a built-in LoRa radio. It ensures smooth, reliable work even in complex or GNSS-limited environments. The SL8 achieves 2 cm accuracy within 10 meters and enables efficient data collection across bridges, tunnels, riverbanks, and other sites where traditional GNSS methods are restricted. It features image-assisted targeting through SatSurv software, displaying laser points directly on real-time images for quick and precise aiming. Its automotive-grade IMU requires no manual calibration or initialization and enhances measurement accuracy by up to 40% in GNSS-challenged areas. A built-in multi-protocol LoRa transceiver provides stable transmission beyond 15 km and compatibility with multiple RTK brands. The integrated CAD and visual stakeout functions combine live imagery with CAD data, allowing users to visualize target points on site and increase layout efficiency by up to 50%.



SatLab Geosolutions, satlabgeo.com

2. UTILITY MAPPING

PARTNERSHIP AIMS TO PROVIDE PRECISE MAPS

A complete precision mapping solution for the utility and critical infrastructure industries worldwide is the goal of a partnership between ProStar Holdings and Tersus GNSS. The partnership will integrate



Tersus's survey-grade GNSS receivers with ProStar's PointMan Underground Utility Mapping Software, providing an affordable, field-ready solution.

The partnership will use ProStar's LinQD

open API integration platform, which is designed to enable seamless interoperability between emerging technologies and legacy systems, creating a robust global ecosystem for geospatial intelligence, uniting equipment manufacturers and service providers under the initiative.

ProStar Holdings, prostarcorp.com, Tersus GNSS, tersus-gnss.com

3. HANDHELD SCANNER

DESIGNED FOR MOBILE MAPPING AND REALITY CAPTURE

The MVP S1 RTK-SLAM handheld 3D laser scanner uses GNSS through an AI-driven RTK-SLAM workflow, as well as lidar data with imagery from dual 48-megapixel panoramic cameras. The combination provides survey-grade results in both GNSS-denied and open environments. The system achieves centimeter-level accuracy outdoors and maintains performance indoors or underground through SLAM processing. TimeSync 3.0 synchronizes the hardware, aligning sensor data at the microsecond level and supporting consistent datasets and reliable post-processing. A mobile application



provides users with real-time feedback, including previews of colorized point clouds while scanning, as well as basic scan reports on site. This feature helps operators verify

data completeness and quality before leaving the field, reducing the need for repeat visits. The MVP S1 supports 3D gaussian splatting (3DGS), enabling creation of textured, photorealistic 3D models. This capability is useful for building information modeling, construction progress monitoring, underground surveys, forestry analysis and industrial site documentation.

Tersus GNSS, tersus-gnss.com

4. GPR SYSTEMS FOR UAVS

ENABLE EXTENDED SUBSURFACE MAPPING

The MALÅ GeoDrone 600 and Zond Aero 600 NG are two new high-resolution

ground-penetrating radar (GPR) systems for UAVs. They significantly enhance high-resolution subsurface investigations with drones, supporting applications in engineering

surveys, utility mapping, archaeology, environmental studies and geophysical research. They enable surveyors to capture consistent, high-quality subsurface data in areas difficult, slow or unsafe to access with traditional ground instruments. Operating at 600 MHz, the antennas offer a balance between penetration depth and fine near-surface resolution. Typical penetration from the drone is up to 2 meters, depending on surface conditions, while SPH Engineering's True Terrain Following ensures stable antenna height to maintain data quality and repeatability.

SPH Engineering, sphengineering.com



5. VISUAL RTK SYSTEM

FOR HIGH-PRECISION SURVEYING, PHOTO SURVEYS AND 3D MODELING



The Astra1 Mobile Visual RTK is a professional-grade GNSS receiver engineered to redefine high-precision mobile data acquisition. It is built to meet the demand for highly portable, reliable, high-precision tools that simplify complex field operations. At 60 grams, the Astra1 is an ultra-compact solution designed to deliver reliable, centimeter-level positioning and advanced 3D mapping capabilities through seamless integration with a smartphone and the proprietary Anypos App. Accuracy is RTK 8mm+1PPM horizontally,

15mm+1PPM vertically, photo survey <4 cm (2-15 m distance). The Astra1 allows users to capture photos with precise RTK coordinates, enabling the creation of accurate 3D models for detailed construction verification and digital twinning applications.

Aurora Navigation, auroranav.com

Q+A with Francois Freulon, Director of Product Management

Septentrio's Resilience Validated at Jammertest

Septentrio's GNSS experts traveled to Norway to validate and improve resilience of its GNSS technology



Francois Freulon

Septentrio designs GNSS receivers with a high level of reliability and resilience against intentional and unintentional GNSS jamming as well as spoofing*. Testing the receiver technology under live interference conditions is crucial to validate and continuously improve anti-jam and anti-spoof algorithms. That is why every year, Septentrio participates in Jammertest, an event organized by the Norwegian government on the remote island of Andøya, where live interference testing takes place in a controlled environment over a five-day

period. Septentrio's Director of Product Management, Francois Freulon, answers several questions on the topic.

Why does Septentrio participate in the Jammertest event?

Jammertest is the only public event in the world focusing on jamming and spoofing in a real environment. As a result, we can test our receivers against very powerful and even military-grade jammers both in static and kinematic conditions. Our GNSS experts took our test van over 3500 km northwards by road, train and ferry from Belgium to Norway. There they tested more than 30 receivers, both from Septentrio and other brands, pushing them to their limits for a full week, covering over 250 distinct jamming and spoofing scenarios. These test scenarios have significantly evolved over the years and are now representative of what we see in GNSS contested areas.

What's in it for the end customer?

The insights gained from these tests contribute directly to enhancing the robustness and reliability of the positioning, navigation and timing (PNT) systems that Septentrio develops for mission-critical applications or critical infrastructure. By continuously

improving our **AIM+ Anti-Jamming and Anti-Spoofing technology**, we are always advancing our mitigation capabilities against evolving threats, while rigorously testing and validating our latest technology before deploying it in our commercial products.

What are some takeaways from the Jammertest 2025 results?

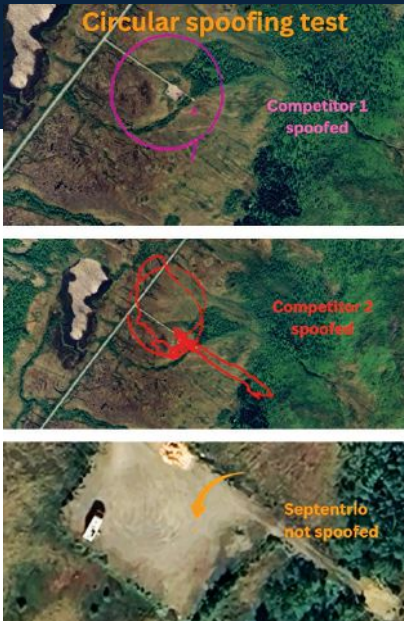
We tested our latest **mosaic-G5 module family**, released earlier this year, and confirmed that it performs exceptionally well under all scenarios. In particular, its jamming and spoofing detection flags consistently demonstrated accurate threat awareness, combined with effective mitigation capabilities of AIM+.

What are your plans for the near future?

Looking ahead, Septentrio will **expand its mosaic-G5 family in 2026 with new variants** focused on ultimate resilience designed to protect mission-critical applications or critical infrastructure against growing security threats. Septentrio will disclose its results from the Jammertest, including



Septentrio took its receivers to the Jammertest in Norway where they underwent rigorous testing under live jamming and spoofing conditions.



At Jammertest, this static spoofing test was able to spoof two non-Septentrio GNSS receivers into showing circular movement, while the Septentrio receiver reported the spoofing, and its positioning was not spoofed.

benchmarking against other GNSS brands during a **webinar on February 5**. A comprehensive report of the results will then be published on our website.

Septentrio resilience validated at Jammertest

After five days of intensive testing, Septentrio’s proprietary AIM+ anti-jamming and anti-spoofing technology proved to be effective under various jamming and spoofing scenarios. Especially remarkable were the spoofing detection and mitigation results, which prove that the key to effective situational awareness and resilience lies in having multiple anti-spoofing mechanisms working together. These

mechanisms consist of multi-frequency GNSS technology, anomaly detection and cryptographic authentication such as Galileo’s OSNMA. For more information join Septentrio’s webinar on February 5: Results Jammertest 2025 — Resilient GNSS in an Era of Rising Jamming & Spoofing.

** Jamming is a form of radio interference which occurs when GPS frequency is overpowered by other radio waves, resulting in accuracy degradation or even total loss of position. Spoofing is a malicious form of radio interference, where misleading signals are sent into the receiver, resulting in faulty coordinates, which lead the target away from its predefined track.*

septentrio
part of HEXAGON

Live webinar:

**RESULTS JAMMERTEST 25
RESILIENT GNSS IN AN ERA OF
RISING JAMMING AND
SPOOFING**

Feb 5th 2026
05:00 pm CET | 11:00 am EST

www.septentrio.com/webinar

1. 5G CELLULAR MODULE

AUTOMOTIVE-GRADE MODULE INTEGRATES DUAL-BAND GNSS

The AR588MA is a 5G-advanced (5G-A) automotive-grade cellular module that integrates dual-band GNSS supporting both L1 and L5 bands with up to 30 Hz output. Based on MediaTek's latest-generation MT2739 platform, the AR588MA supports 5G-A communication technology and complies with the 3GPP R18 standard protocol. It features both NB-NTN and NR-NTN satellite communication capabilities and supports dual-SIM dual-active (DSDA) technology, offering improved stability and reliability on cellular connections. It also includes intelligent driving scenario recognition. Designed in compliance with the AEC-Q104 Grade 2 automotive standard, it delivers fast, stable connectivity and reliable security for in-vehicle communication and benefits on-roof applications, such as smart antennas for automotive, with higher-temperature support.

Quectel Wireless Solutions, quectel.com

①



2. HEAVE ACCURACY

IMU UPGRADE ACCOUNTS FOR MARITIME WAVE MOTION

A firmware upgrade to the Xsens Sirius and Xsens Avior IMUs delivers centimeter-level vertical displacement measurements for marine stabilization and control systems. The new Heave feature enables real-time stabilization and wave compensation in a wide range of marine applications. Marine engineers can access comprehensive motion data — roll, pitch, yaw and heave — from a single compact sensor, eliminating the need for external processing or oversized tactical-grade systems while maintaining the precision required for offshore platforms, vessels, docking systems, marine robots, buoys and surveying equipment.

Xsens, xsens.com

②



3. LIDAR WITH CAMERA

COMPACT MODULE REDUCES OEM INTEGRATION COMPLEXITY

The InnovizThree is fully colored long-range lidar with camera that creates a compact sensor-fusion module designed to reduce OEM integration complexity. The solution combines lidar and RGB sensing in a single compact perception module, purpose-built for behind-the-windshield installations, drones, micro-robotics and humanoids. The consolidation of an RGB camera inside InnovizThree reinforces Innoviz's commitment to scalable, OEM-friendly sensor-fusion perception solutions designed for series production and long-term deployment, with the potential to enable faster deployment and cost savings. The RGB sensing capabilities are factory-aligned with the lidar, enabling precise and consistent visual-to-lidar geometry across production units. This alignment, combined with hardware-synchronized capture, will enable reliable multi-modal sensor-fusion data correlation while reducing calibration effort during vehicle integration.

Innoviz Technologies, innoviz.tech

③



4. AGX PLATFORM

HIGH-INTEGRITY GNSS INTEGRATION FOR AUTONOMOUS DRIVING

Swift Navigation is collaborating with Nvidia to enable a scalable, cost-effective approach to autonomous driving by integrating the Nvidia Drive AGX platform with Swift's globally referenced, centimeter-accurate GNSS positioning. Swift Navigation offloads absolute localization to the GNSS sensor stack using its Swift Automotive Suite. The suite is a complete, modular software solution for safe, high-integrity precise vehicle localization that combines the centimeter-level Skylark Precise Positioning Service with the Starling positioning engine, software that fuses raw GNSS data and corrections with IMU and wheel odometry to deliver high-integrity, centimeter-accurate positioning (PVT). By using Swift's high-precision stack for lane-level positioning, the vehicle's optical sensors focus on obstacle detection and safety, lowering system cost and complexity.

Swift Navigation, swiftnav.com

④



FlashMovie / iStock / Getty Images Plus / Getty Images



5. 5G GNSS ANTENNAS SUITABLE FOR FLEET AND RAIL APPLICATIONS

Sinclair's new SM 5G Family Tier features the SM714 and SM2601 series antennas. The multi-band, multi-port antennas are engineered to deliver superior connectivity, reliability and versatility for GNSS and other mission-critical wireless transportation applications. The SM714 is a 4-in-1 low-profile customizable transit antenna that combines 5G/LTE, Wi-Fi and tri-band GNSS coverage in a single compact form. Supporting 617–5925 MHz, it enables seamless operation across all major 5G and LTE bands. It is suitable for vehicles, fleet systems and connected mobility applications requiring a discreet, high-performance solution. The SM2601D is a 5-in-1 low-profile customizable antenna that features five independent ports: one for PTC (219–223 MHz), one for Wi-Fi (2400–6000 MHz), one for GNSS, and two full-band cellular ports (694–2700 MHz) that support diversity and MIMO operation for multi-radio systems. This dual-cell configuration offers greater throughput, flexibility, and redundancy in complex communication environments.

Sinclair Technologies, sinctech.com

6. LIDAR PLATFORM HIGH-PRECISION DEPTH SENSING AND REAL-TIME VELOCITY MEASUREMENT

New versions of the Carbon lidar platform add 32-line and 64-line variants for compact, cost-sensitive and compute-limited systems. The new models complement existing 128-line configurations and are optimized for industrial autonomy, robotics, drones and smart infrastructure applications. They offer lower data rates and simplified integration while maintaining core FMCW advantages including velocity measurement, interference immunity and high dynamic range. With line resolutions spanning 32, 64 and 128, original equipment manufacturers and system integrators can tailor

performance, bandwidth and compute load to specific use cases, from robotics and automated guided vehicles to drones and embedded edge platforms. The Carbon family's silicon-photonics architecture integrates beam steering and coherent detection on a single photonic chip. The new variants include high-precision depth sensing and real-time velocity measurement, exceptional ambient light immunity and compact design for industrial and mobile environments.

Voyant Photonics, voyantphotonics.com

7. BASE STATION FOR AUTOMOTIVE TRACK AND VARIED ENVIRONMENT TESTING

The NTRIP Base Station from VBOX Automotive combines a multi-constellation, multi-frequency GNSS engine with a built-in networked transport of RTCM via internet protocol (NTRIP) server. The equipment transmits real-time kinematic corrections over radio and cellular or Wi-Fi networks, supporting accurate real-time positioning across wider areas in varied environments compared to traditional radio-only systems. The base station launches in three models, with specifications designed to fit users' needs. All systems combine quad-constellation, dual-frequency GNSS technology with built-in cellular and Wi-Fi connectivity. Compatible with VBOX 4, VBOX 3iS and external GNSS rovers, the new NTRIP Base Station supports both MSM4 and MSM7 RTCM formats, has up to 24 hours of battery life and is rated to IP67 to handle the demands of long outdoor test sessions. Models include Internal GNSS antenna and 2.4 GHz radio (quick to deploy for short-range applications, for temporary or mobile testing); Internal GNSS antenna, no radio (compact and simple, suitable for NTRIP or semi-permanent installations with external high-power radio masts); and External GNSS antenna, no radio (optimized for permanent installations with tripod-mounted antennas for maximum satellite visibility, supporting NTRIP or external radio).

VBOX Automotive, vboxautomotive.co.uk

MODERN NORTHSTAR

Starlink LEO PNT Across Land, Air, Stratosphere and Arctic Seas

BY ZAHER (ZAK) M. KASSAS, SAMER HAYEK, WILL BARRETT, SHARBEL KOZHAYA,
PAUL EL-KOUBA, FAEZEH MOOSELI, JENNIFER SANDERSON AND JOE SAROUFIM
THE OHIO STATE UNIVERSITY



GNSS

No GNSS

Starlink

All figures and tables provided by authors



In January 2015, SpaceX publicly announced its plan to launch Starlink: a mega-constellation of nearly 12,000 satellites in low-Earth orbit (LEO) to provide global broadband internet service. In May 2019, the first batch of 60 operational satellites were launched. In October 2025, Starlink surpassed 10,000 satellites (see **Figure 1**). This remarkable achievement means that Starlink has more satellites than all other constellations have ever launched into LEO combined.

SpaceX is redefining global connectivity, delivering high-speed, low-latency internet anywhere on the planet¹. Its civilian system, Starlink, is bridging the digital divide by providing reliable broadband in remote and underserved regions, enabling education, telemedicine and economic growth. Its defense and government variant, Starshield, is offering secure, resilient communications and rapid data transfer for military operations.

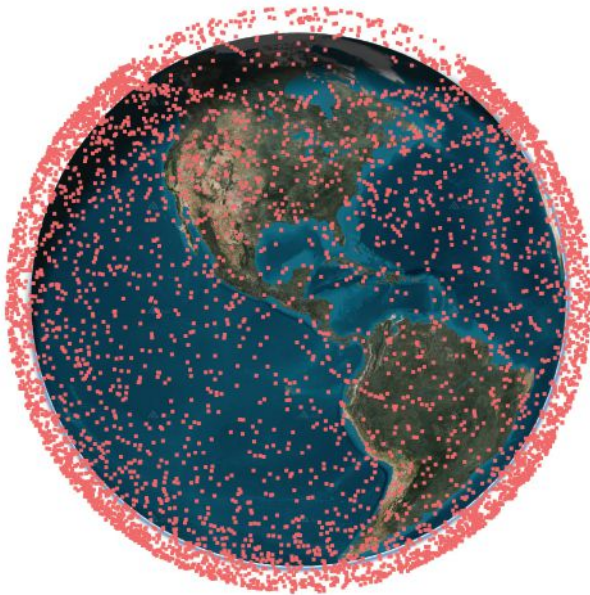


FIGURE 1 The current constellation of Starlink satellites in LEO, as of January 2026.

In the midst of the COVID pandemic, in a quiet campus building, the ASPIN Laboratory was busy researching Starlink's mysterious proprietary signals and the satellites' poorly known orbits. Having demonstrated the first experimental unmanned aerial vehicle (UAV)² and ground vehicle³ navigation using Orbcomm LEO satellites, the team's next grand objective was to exploit Starlink's signals of opportunity for positioning, navigation, and timing (PNT). At the 2021 ION GNSS+ Conference, the team announced a new era of LEO PNT: the first successful

exploitation of Starlink for PNT⁴. The team designed a cognitive software-defined receiver (SDR) capable of tracking the carrier phase⁵ and Doppler⁶ of Starlink's so-called pilot tones along with ephemerides error correction algorithms⁷. The SDR and algorithms were put into test to localize a stationary receiver. Starting from an initial estimate nearly 180 km away, listening to six Starlink satellites resulted in localizing the receiver to within 10 m. This led to worldwide research to study Starlink for PNT, from deciphering Starlink's downlink orthogonal frequency-division multiplexing (OFDM) signals^{8,9}, to analyzing its ephemerides and timing^{10,11}, to studying the achievable PNT performance^{12,13}.

This article presents the most advanced LEO PNT results to date with Starlink on four mobile platforms at geographically dispersed locations:

1. Ground vehicle in Pennsylvania
2. UAV in Ohio
3. Extremely high-altitude balloon in New Mexico
4. Maritime vessel in the Arctic near Greenland

Exploiting Starlink LEO for PNT: The Enablers SDR and Signal Analysis

Unlike GNSS, non-cooperative LEO satellites such as Starlink do not publicly disclose the structure of their downlink signals, so users must build their own "LEO PNT Interface Control Document (ICD)"¹⁴. This can be achieved via "reverse-engineering" the signal. A more powerful approach to "reverse-engineering" is via cognitive SDRs, which employ blind signal processing techniques to learn the signals on-the-fly, regardless of the adopted modulation and multiple-access scheme¹⁵.

The most comprehensive characterization to date of Starlink's downlink signals for PNT was unveiled in¹⁶, utilizing the cognitive SDR approach, in which

1. The *full* OFDM beacon was revealed.
2. Theoretical and experimental description for exploiting Starlink for PNT was provided, showing the maximum achievable carrier-to-noise density ratio (C/N_0) under different scenarios: (i) pilot tones versus OFDM-based beacons and (ii) low-gain versus high-gain reception captures.
3. A Starlink LEO PNT SDR was designed, yielding the first successful extraction of navigation observables (carrier phase, Doppler shift and code phase) from Starlink's OFDM signals.
4. A detailed analysis of the quality of Starlink navigation observables, including (i) signal activity and power levels and (ii) timing corrections that contaminate extracted observables along with mitigation strategies.



Ephemeris and Timing Error Correction

Unlike GNSS, non-cooperative LEO satellites, such as Starlink, do not broadcast ephemeris and clock data, so users rely on public sources, such as two-line element (TLE) files. However, this data degrades over time due to orbital perturbations, limiting their effectiveness for PNT. Recent research addressed this challenge through five main approaches:

1. Differential LEO^{17,18}
2. Machine learning-based orbit prediction^{19,20}
3. Measurement error correction^{21,22}
4. Closed-loop ephemeris tracking^{23,24}
5. Equivalent timing error compensation^{25,26}

The next sections will showcase experimental LEO PNT results with Starlink signals of opportunity. All experiments utilized the SDR developed in¹⁶ and the ephemerides and timing correction methods developed in²⁶⁻²⁸.

Ground Vehicle Navigation in Pennsylvania

The experiment was conducted in June 2025. The ground vehicle navigated for 3 km in 120 seconds on Interstate 79 by Pittsburgh, Pennsylvania. GNSS signals

were available for the first 30 seconds but were virtually cut off for the last 90 seconds, during which the vehicle traversed a 2.25 km trajectory. The vehicle was equipped with a VectorNav VN-310 dual GNSS/INS operating with real-time kinematic (RTK) corrections and a tactical-grade inertial measurement unit (IMU), from which the vehicle's ground truth was generated. Starlink signals were captured over all eight Ku-band downlink channels using an upward low-noise block with feed-horn (LNBF) and processed at 2.5 MSps via two NI X410 USRPs. **Figure 2** shows the ground vehicle's hardware setup.

The vehicle navigated by fusing Doppler shift measurements from 11 Starlink satellites in a tightly-coupled fashion to aid the IMU, while altimeter measurements were fused in a loosely-coupled fashion. IMU updates were performed at a rate of 200 Hz. Starlink Doppler measurement updates were performed at a rate of 1 Hz with measurement noise variance inversely related to the received C/N_0 , ranging between 0.05 (m/s)^2 and 6.5 (m/s)^2 , while altimeter updates were performed at a rate of 10 Hz with a measurement noise variance of 3 m^2 . The vehicle-mounted receiver and LEO satellites' oscillator qualities were assumed to be that of an oven-

controlled crystal oscillator (OCXO). A prior for the vehicle's position and velocity was obtained from the on-board GNSS system. Starlink LEO satellites' ephemeris errors were corrected via the equivalent timing error compensation technique in an online fashion as described in²⁸. Each satellite's equivalent timing error state was initialized with 0, while the relative clock drift state was initialized as the difference between the measured and predicted pseudorange rate.

An extended Kalman filter (EKF) was used to estimate the state vector, consisting of the vehicle's orientation, 3D position, 3D velocity and the IMU's 3D gyroscope and accelerometer biases along with the relative clock drift error between the receiver and each LEO satellite. The Starlink satellites' orbits were generated by propagating TLE files with SGP4 for the duration of the experiment. The navigation solution was generated using three approaches:

1. **Unaided IMU:** The vehicle navigates via open-loop IMU measurements when GNSS measurements are unavailable.
2. **LEO-aided IMU with TLE+SGP4 ephemerides:** The vehicle fuses LEO measurements with IMU and altimeter measurements while incorporating TLE+SGP4 ephemerides in the navigation filter.

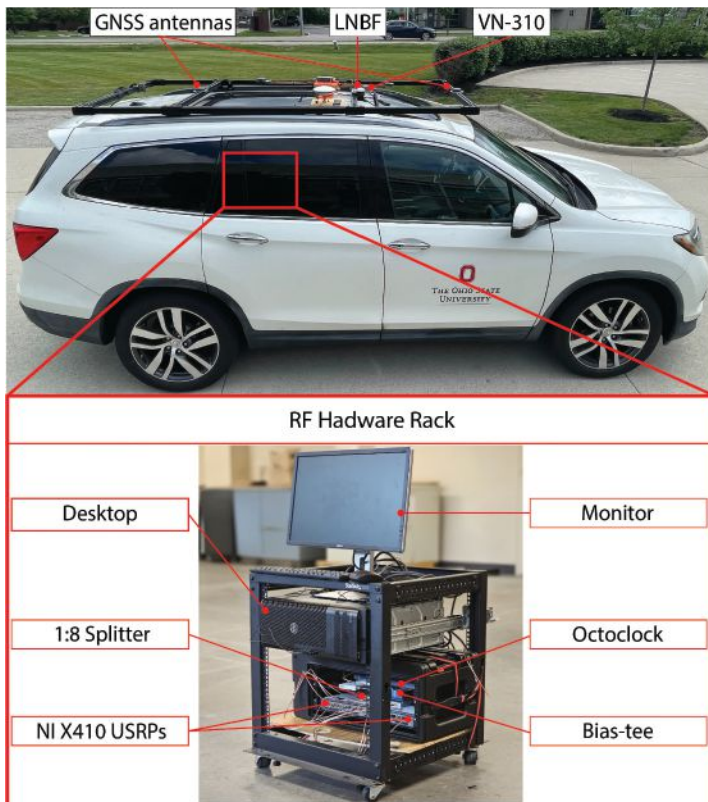


FIGURE 2 Ground vehicle's hardware setup.

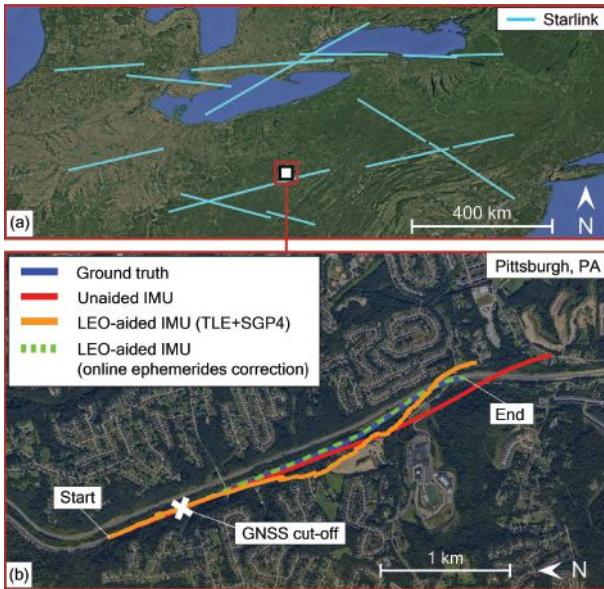


FIGURE 3 Experimental results of Doppler-based ground vehicle navigation with Starlink: (a) trajectories of the 11 Starlink satellites used to navigate the vehicle and (b) vehicle's trajectory (blue) and estimated trajectories via the unaided IMU solution (red) and LEO-aided IMU solutions when incorporating the (i) uncorrected TLE+SGP4 ephemerides (orange) and (ii) online ephemeris correction (green).

3. LEO-aided IMU with online ephemerides corrections:

The vehicle fuses LEO measurements with IMU and altimeter measurements. Starting with TLE+SGP4 ephemerides, the navigation filter estimates an equivalent timing error for each satellite as described in²⁸.

Method	RMSE [m]	Final error [m]
Unaided IMU	258	636
LEO-aided IMU (TLE+SGP4)	150	133
LEO-aided IMU (online corrections)	8.41	11.87

TABLE 1 Experimental results: Ground vehicle 3D position errors.

Figure 3 shows the Starlink satellite trajectories, as well as the vehicle's ground truth and estimated trajectories with the three navigation approaches. The unaided IMU solution drifted to a 3D position root mean squared error (RMSE) of 258 m from the truth trajectory. The LEO-aided IMU solution that incorporated the erroneous TLE+SGP4 ephemerides resulted in a 3D position RMSE of 150 m, while the navigation solution employing the online ephemeris correction method resulted in an RMSE of 8.41 m. Table 1 summarizes the navigation results.

UAV Navigation in Ohio

The experiment was conducted in August 2025. A DJI M600 UAV navigated for 500 m in 75 seconds in Columbus, Ohio. GNSS signals were available for the first 20 seconds of the experiment but were virtually cut off for the last 55 seconds, during which the UAV traversed a 370 m trajectory. The UAV was equipped with a VectorNav VN-310 dual GNSS/INS operating with RTK corrections and a tactical-grade IMU, from which the UAV's ground truth was generated. Starlink signals were captured from the 4 low-side Ku-band channels using an upward LNBF and processed at 2.5 MSps via an NI 2955 USRP. Figure 4

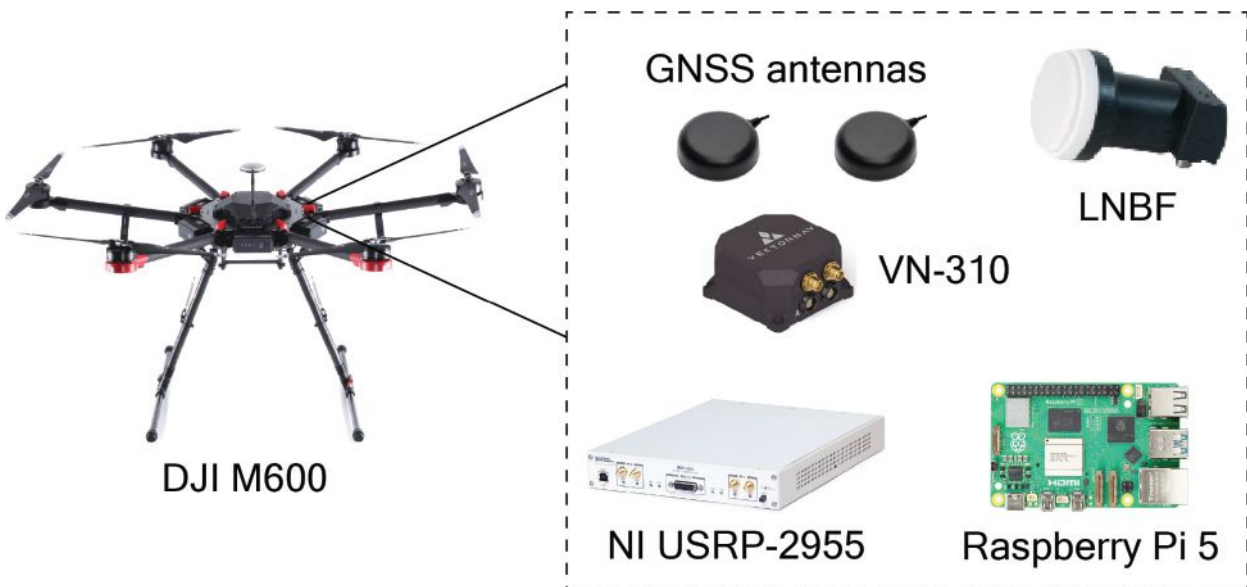


FIGURE 4 UAV's hardware setup.

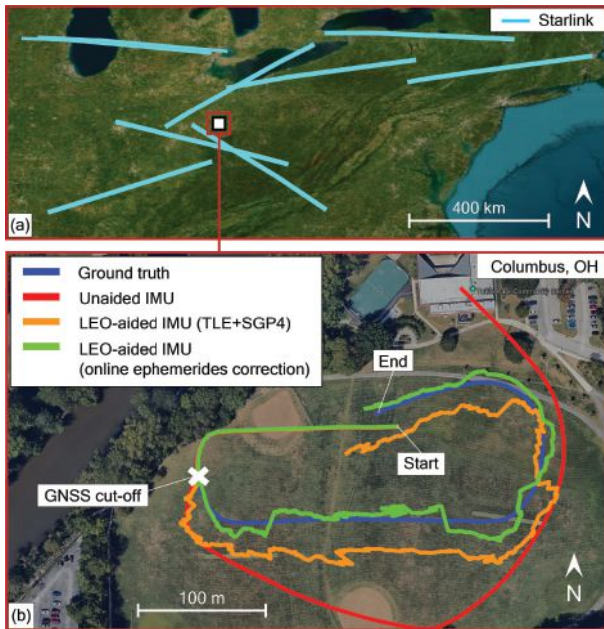


FIGURE 5 Experimental results of Doppler-based UAV navigation with Starlink: (a) trajectories of the nine Starlink satellites used to navigate the UAV and (b) UAV's trajectory (blue) and estimated trajectories via the unaided IMU solution (red) and LEO-aided IMU solutions when incorporating the (i) uncorrected TLE+SGP4 ephemerides (orange) and (ii) online ephemeris correction (green).

shows the UAV's hardware setup.

The UAV navigated by fusing Doppler shift measurements from nine Starlink satellites in a tightly-coupled fashion to aid the IMU, while altimeter measurements were fused in a loosely-coupled fashion. IMU updates were performed at a rate of 200 Hz. Starlink Doppler measurement updates were performed at a rate of 1 Hz with measurement noise variance inversely related to the received C/N_0 , ranging between 0.09 (m/s)^2 and 6.75 (m/s)^2 , while altimeter updates were performed at a rate of 10 Hz with a measurement noise variance of 3 m^2 . The UAV-mounted receiver and LEO satellites' oscillator qualities were assumed to be that of an OCXO. A prior for the UAV position and velocity was obtained from the UAV's on-board GNSS system. Starlink LEO satellites' ephemeris errors were corrected via the equivalent timing error compensation technique in an online fashion as described in ²⁸. Each satellite's equivalent timing error state was initialized with 0, while the relative clock drift state was initialized as the difference between the measured and predicted pseudorange rate.

An EKF was used to estimate the state vector, consisting of the UAV's orientation, 3D position, 3D velocity and the IMU's 3D gyroscope and accelerometer biases, along with the relative clock drift error between the receiver and each

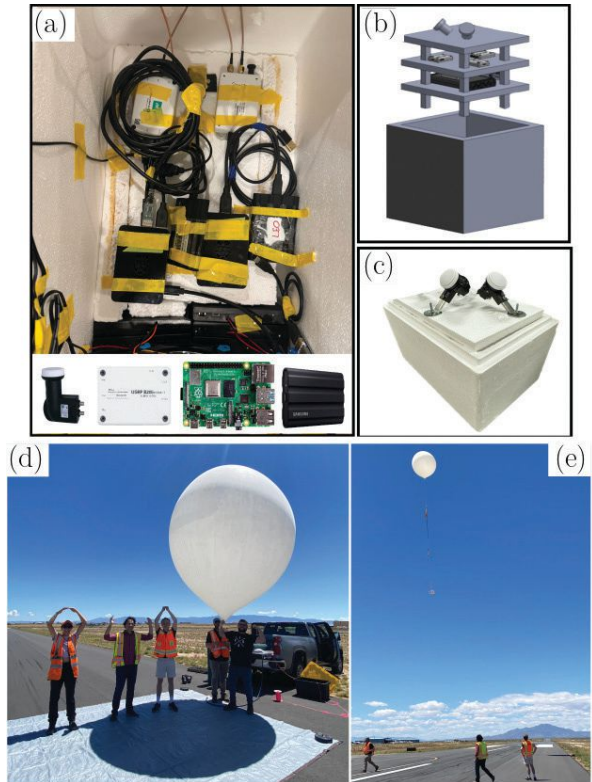


FIGURE 6 (a)-(c) High-altitude balloon's hardware setup. (d) OHIO in New Mexico, left to right: Jennifer Sanderson, Zak Kassas, Will Barrett and the Icarus Balloon. (e) Balloon launch.

LEO satellite. The Starlink satellites' orbits were generated by propagating TLE files with SGP4 for the duration of the experiment. The navigation solution was generated using the three approaches described in Section II.

Figure 5 shows the Starlink satellite trajectories, as well as the UAV's ground truth and estimated trajectories with the three different navigation approaches. The unaided IMU solution drifted to a 3D position RMSE of 46.51 m from the truth trajectory. The LEO-aided IMU solution that incorporated the erroneous TLE+SGP4 ephemerides resulted in a 3D position RMSE of 17.82 m, while the navigation solution employing the online ephemeris correction method resulted in an RMSE of 8.15 m. Table 2 summarizes the navigation results.

High-Altitude Balloon Navigation in New Mexico

The experiment was conducted in July 2024²⁹. The balloon was launched from the Moriarty Municipal Airport in Moriarty, New Mexico, and landed just south of Mountainair, New Mexico, traveling a horizontal distance of about 105 km south with a 3D distance of about 119 km. The balloon reached a peak altitude of about 25.3 km (83,128 ft) above sea level. A specific time period was



Method	RMSE [m]	Final error [m]
Unaided IMU	46.51	83.84
LEO-aided IMU (TLE+SGP4)	17.82	29.18
LEO-aided IMU (online corrections)	8.15	7.74

TABLE 2 Experimental results: UAV 3D position errors.

studied to evaluate utilization of Doppler observables for navigation at an elevation of 82,177 ft. During this period, five different Starlink satellites were tracked over a 50-second period, during which the balloon traveled 948 m. The balloon was equipped with a VectorNav VN-200 GNSS/INS, from which the ground truth trajectory was generated. Starlink signals were captured over two Ku-band downlink channels using an upward LNBF and processed at 2.5 MSps via two Ettus B205-mini USRPs.

Figure 6 shows the balloon’s hardware setup.

The balloon navigated by fusing Doppler shift measurements from five Starlink satellites and altimeter measurements via an EKF. The dynamic model of the high-altitude balloon was chosen as a velocity random walk model, with acceleration process noise spectra

set to $0.5 \text{ m}^2/\text{s}^3$ in the in the East, North and $0.8 \text{ m}^2/\text{s}^3$ in the in Up directions, respectively. Starlink Doppler measurement updates were performed at a rate of 10 Hz with measurement noise variance inversely related to the received C/N_0 , ranging between 1.40 (m/s)^2 and 7.01 (m/s)^2 , while altimeter updates were performed at rate of 10 Hz with a measurement noise variance of 1 m^2 . The process noise covariance for the clock states was constructed according to an OCXO clock quality. A prior for the balloon’s position and velocity was obtained from the on-board GNSS system. Ephemeris data for each satellite was obtained from offline SGP4-propagated TLE, with epoch time corrections made by minimizing the residuals between predicted Doppler and measured Doppler^{26,27}.

The EKF state vector consisted of the balloon’s 3D position and 3D velocity along with the relative clock drift error between the receiver and each LEO satellite. The navigation solution was generated using (i) an open-loop approach, which simply propagated the states via the dynamical model and (ii) the LEO+altimeter approach.

Figure 7 shows the balloon’s ground truth and estimated trajectories with the two different navigation approaches. The open-loop solution drifted to a 3D position RMSE of

SBG SYSTEMS | Motion & Navigation you can trust

APOGEE Series

High performance INS / GNSS:

- Aerial mapping
- Mobile Mapping
- Indoor Mapping
- Maritime Operations
- And more ...

www.sbg-systems.com ITAR Free

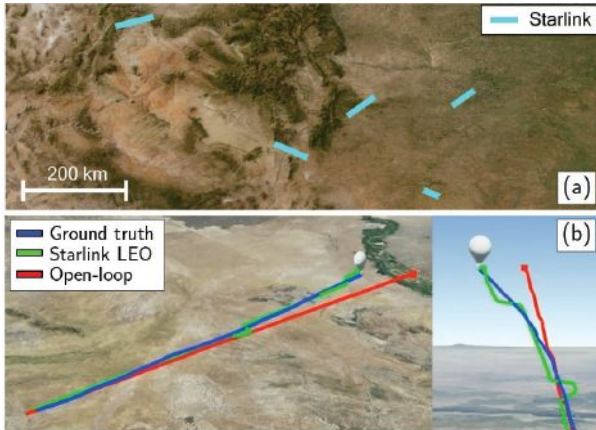


FIGURE 7 Experimental results of Doppler-based high-altitude balloon navigation with Starlink: (a) trajectories of five Starlink satellites used and (b) balloon's trajectory (blue) and estimated trajectories via the open-loop solution (red) and LEO-aided solution (green).

83.34 m from the truth trajectory, while the LEO-aided solution resulted in an RMSE of 12.28 m. **Table 3** summarizes the navigation results.

Maritime Navigation in the Arctic

The experiment was conducted in August 2024³⁰. The vessel navigated for 8.5 km in 20 minutes off the shore of Baffin Island, Nunavut, Canada. Starlink signals were captured over the third Ku-band downlink channel using an upward LNBF and processed at 2.5 MSps via a B205-mini USRP and a Raspberry Pi 4. **Figure 8** shows the vessel's hardware setup.

The vessel navigated by fusing Doppler shift measurements from 12 Starlink satellites and altimeter data via an EKF. The dynamic model of the vessel was chosen as a velocity random walk model. Starlink Doppler measurement and altimeter data updates were both performed at a rate of 10 Hz with measurement noise variances of 4.5 (m/s)² and 3 m², respectively. The vessel-mounted receiver and the LEO satellites' oscillator qualities were assumed to be that of an OCXO. The vessel's position states were initialized from the true position obtained from the on-board GNSS system. The velocity was initialized from the true velocity but with a 10° clockwise error with respect to the vessel's direction-of-motion. The Starlink satellites' orbits were generated by propagating TLE files with SGP4 for the duration of the experiment. Ephemeris

Method	RMSE [m]	Final error [m]
Open-loop	83.34	161.95
LEO+altimeter	12.28	10.23

TABLE 3 Experimental results: High-altitude balloon 3D position errors.

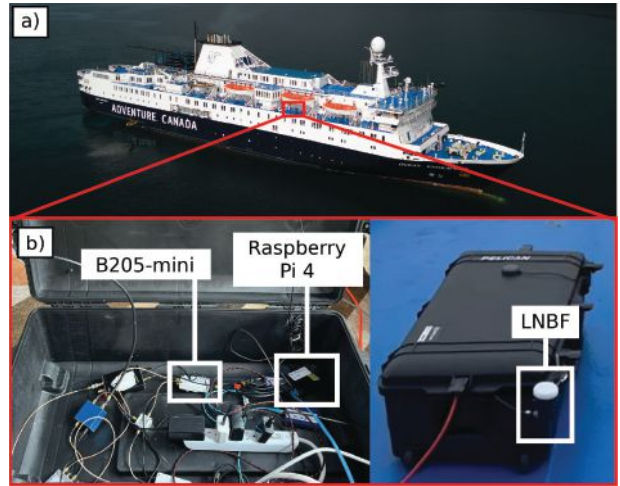


FIGURE 8 Vessel's hardware setup.

Method	RMSE [m]	Final error [m]
Altimeter-only	846.28	1,465.31
LEO+altimeter	122.83	16.26

TABLE 4 Experimental results: Vessel 3D position errors.

errors were corrected by adjusting the TLE epoch time for each satellite^{26,27} to minimize the residuals between predicted Doppler and measured Doppler.

An EKF was used to estimate the state vector, consisting of the vessel's 3D position, 3D velocity and the relative clock drift errors between the receiver and each LEO satellite. The navigation solution was generated via two approaches: (i) using only altimeter data and (ii) using LEO Doppler fused with altimeter data.

Figure 9 shows the Starlink satellite trajectories, as well as the vessel's ground truth and estimated trajectories with the two navigation approaches. The altimeter-only solution drifted to a 3D position RMSE of 846 m from the truth trajectory. The LEO+altimeter solution resulted in a 3D position RMSE of 123 m. **Table 4** summarizes the navigation results.

Acknowledgments

This work was supported in part by the Office of Naval Research (ONR) under Grants N00014-22-1-2242 and N00014-22-1-2115, in part by the Air Force Office of Scientific Research (AFOSR) under Grant FA9550-22-1-0476, in part by the U.S. Department of Transportation under Grant 69A3552348327 for the CARMEN+ University Transportation Center, in part by The Aerospace Corporation under Award 4400000428,



and in part by the Laboratory Directed Research and Development program at Sandia National Laboratories under award 2543953. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DENA0003525. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

The authors would like to thank Vasilios Konstantacos, Jackson Morris, Ethan Shaw, Khaled Hamil, Aiden Short and Andrew Ye for constructing the balloon's payload; Mark Andrews for supervising the payload design; and Prabodh Jhaveri, Danny Bowman, Mike Fleigle and Justin LaPierre for helping with launch and recovery of the balloon. The authors would also like to thank The Explorers Club and Adventure Canada for their help with data collection in the Arctic. The authors would like to thank VectorNav for supplying the VN-200. 🌐

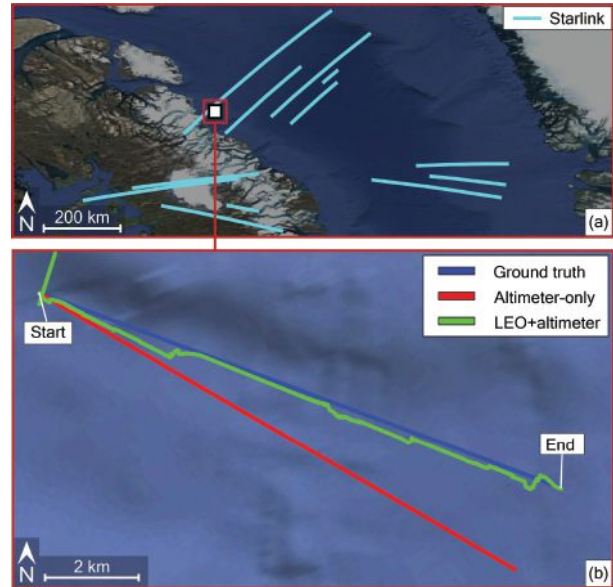


FIGURE 9 Experimental results of Doppler-based vessel navigation with Starlink: (a) trajectories of the 12 Starlink satellites used to navigate the vessel and (b) vessel's true trajectory (blue) and estimated trajectories using (i) only an altimeter (red) and (ii) using LEO + altimeter (green).

Military Qualified GPS Splitters



MIL-Products tested to:

- MIL-STD-461F
- MIL-STD-810F
- MIL-STD-704F



Available in
1x2, 1x4, 1x8

Distribute the GPS/GNSS signals throughout your facility, aircraft, or armored vehicles.

SALESTECH@GPSNETWORKING.COM | 800-463-3063
WWW.GPSNETWORKING.COM | 10% off Military Discount





References

1. A. Yadav, M. Agarwal, S. Agarwal, and S. Verma, "Internet from space anywhere and anytime - Starlink," in *Proceedings of International Conference on Advancement in Electronics & Communication Engineering*, pp. 1-8, 2022.
2. J. Morales, J. Khalife, A. Abdallah, C. Ardito, and Z. Kassas, "Inertial navigation system aiding with Orbcomm LEO satellite Doppler measurements," in *Proceedings of ION GNSS+ Conference*, pp. 2718-2725, 2018.
3. Z. Kassas, J. Morales, and J. Khalife, "New-age satellite-based navigation - STAN: simultaneous tracking and navigation with LEO satellite signals," *Inside GNSS Magazine*, (14)4, pp. 56-65, 2019.
4. M. Neinavaie, J. Khalife, and Z. Kassas, "Exploiting Starlink signals for navigation: first results," in *Proceedings of ION GNSS+ Conference*, pp. 2766-2773, 2021.
5. J. Khalife, M. Neinavaie, and Z. Kassas, "The first carrier phase tracking and positioning results with Starlink LEO satellite signals," *IEEE Transactions on Aerospace and Electronic Systems*, (58)2, pp. 1487-1491, 2022.
6. M. Neinavaie, J. Khalife, and Z. Kassas, "Acquisition, Doppler tracking, and positioning with Starlink LEO satellites: first results," *IEEE Transactions on Aerospace and Electronic Systems*, (58)3, pp. 2606-2610, 2022.
7. Z. Kassas, M. Neinavaie, J. Khalife, N. Khairallah, S. Kozhaya, J. Haidar-Ahmad, and Z. Shadram, "Enter LEO on the GNSS stage: navigation with Starlink satellites," *Inside GNSS Magazine*, (16)6, pp. 42-51, 2021.
8. T. Humphreys, P. Iannucci, Z. Komodromos, and A. Graff, "Signal structure of the Starlink Ku-band downlink," *IEEE Transactions on Aerospace and Electronic Systems*, (59)5, pp. 6016-6030, 2023.
9. M. Neinavaie and Z. Kassas, "Cognitive sensing and navigation with unknown OFDM signals with application to terrestrial 5G and Starlink LEO satellites," *IEEE Journal on Selected Areas in Communications*, (42)1, pp. 146-160, 2024.
10. S. Hayek and Z. Kassas, "Warm start navigation with non-cooperative LEO satellites via online ephemeris error estimation," in *Proceedings of IEEE/ION Position, Location, and Navigation Symposium*, pp. 112-123, 2025.
11. W. Qin, A. Graff, Z. Clements, Z. Komodromos, and T. Humphreys, "Timing properties of the Starlink Ku-band downlink," *IEEE Transactions on Aerospace and Electronic Systems*, (62), pp. 727-744, 2026.
12. H. More, E. Cianca, and M. De Sanctis, "Comparing positioning performance of LEO mega-constellations and GNSS in urban canyons," *IEEE Access*, (12), pp. 24465-24482, 2024.
13. Z. Kassas and J. Saroufim, "LEO PNT frameworks for non-cooperative satellites with poorly known ephemerides: open-loop SGP4, tracking, and differential," *IEEE Aerospace and Electronic Systems Magazine*, (40)9, pp. 46-71, 2025.
14. S. Kozhaya, H. Kanj, and Z. Kassas, "Multi-constellation blind beacon estimation, Doppler tracking, and opportunistic positioning with OneWeb, Starlink, Iridium NEXT, and Orbcomm LEO satellites," in *Proceedings of IEEE/ION Position, Location, and Navigation Symposium*, pp. 1184-1195, 2023.
15. S. Kozhaya, S. Hayek, and Z. Kassas, "Cognitive beacon estimation of unknown LEO satellites signals of opportunity for PNT," *IEEE Journal on Selected Areas in Communications*, pp. 1-16, 2026, in-press.
16. S. Kozhaya, J. Saroufim, and Z. Kassas, "Unveiling Starlink for PNT," *NAVIGATION, Journal of the Institute of Navigation*, (72)1, pp. 1-35, 2026.
17. J. Khalife and Z. Kassas, "Performance-driven design of carrier phase differential navigation frameworks with megaconstellation LEO satellites," *IEEE Transactions on Aerospace and Electronic Systems*, (59)9, pp. 2947-2966, 2023.
18. M. Hasan, M. Kabir, M. Islam, S. Han, and W. Shin, "A double difference Doppler shift-based positioning framework with ephemeris error correction of LEO satellites," *IEEE Systems Journal*, (18)4, pp. 2157-2168, 2024.
19. Z. Kassas, S. Hayek, and J. Haidar-Ahmad, "LEO satellite orbit prediction via closed-loop machine learning with application to opportunistic navigation," *IEEE Aerospace and Electronic Systems Magazine*, (40)1, pp. 34-49, 2024.
20. K. Selvan, A. Siemuri, F. Prol, P. Välisuo, and H. Kuusniemi, "Machine learning for LEO and MEO satellite Orbit prediction," in *Proceedings of ION GNSS+ Conference*, pp. 3556-3571, 2024.
21. J. Saroufim and Z. Kassas, "Ephemeris and timing error disambiguation enabling precise LEO PNT," *IEEE Transactions on Aerospace and Electronic Systems*, (61)3, pp. 6138-6153, 2025.
22. J. Saroufim and Z. Kassas, "LEO ephemeris error modeling enabling long baseline correction for improved PNT," in *Proceedings of IEEE/ION Position, Location, and Navigation Symposium*, pp. 625-630, 2025.
23. N. Khairallah and Z. Kassas, "Ephemeris tracking and error propagation analysis of LEO satellites with application to opportunistic navigation," *IEEE Transactions on Aerospace and Electronic Systems*, (60)2, pp. 1242-1259, 2024.
24. S. Kozhaya, J. Saroufim, S. Hayek, P. El-Kouba, and Z. Kassas, "Light will guide you: passive joint DOA/FOA sensing, tracking, and navigation with unknown LEO satellites," in *Proceedings of IEEE/ION Position, Location, and Navigation Symposium*, pp. 716-727, 2025.
25. Y. Du, H. Qin, and C. Zhao, "LEO satellites/INS integrated positioning framework considering orbit errors based on FKF," *IEEE Transactions on Instrumentation and Measurement*, (73), pp. 1-14, 2024.
26. S. Hayek, J. Saroufim, and Z. Kassas, "Analysis and correction of LEO satellite propagation errors with application to navigation," in *Proceedings of ION GNSS+ Conference*, pp. 1800-1811, 2024.
27. S. Hayek and Z. Kassas, "Modeling and compensation of timing and spatial ephemeris errors of non-cooperative LEO satellites with application to PNT," *IEEE Transactions on Aerospace and Electronic Systems*, (61)3, pp. 5579-5593, 2025.
28. S. Hayek and Z. Kassas, "A reduced-order model for simultaneous tracking and navigation with LEO satellites," *IEEE Aerospace and Electronic Systems Magazine*, in preparation.
29. W. Barrett, J. Sanderson, S. Kozhaya, J. Saroufim and Z. Kassas, "Evaluation of Starlink LEO satellite signals for high-altitude platform station opportunistic navigation," in *IEEE International Conference on Wireless for Space and Extreme Environments*, pp. 100-105, 2024.
30. W. Barrett, S. Kozhaya, Z. Kassas, and D. Marsh, "Navigating the Arctic circle with Starlink and OneWeb LEO satellites," in *Proceedings of IEEE/ION Position, Location, and Navigation Symposium*, pp. 1-6, 2025.

Authors

ZAHER (ZAK) M. KASSAS is the TRC Endowed Chair in Intelligent Transportation Systems and Professor of Electrical and Computer Engineering at The Ohio State University (OSU). He is also Director of the Autonomous Systems Perception, Intelligence, & Navigation (ASPIN) Laboratory and Director of the U.S. Department of Transportation Center for Automated Vehicles Research with Multimodal Assured Navigation (CARMEN).

SAMER HAYEK is a Ph.D. student at OSU and member of the ASPIN Laboratory.

WILL BARRETT was a member of the ASPIN Laboratory.

SHARBEL KOZHAYA is a Senior Research Associate at the ASPIN Laboratory.

PAUL EL-KOUBA is a Ph.D. student at OSU and member of the ASPIN Laboratory.

FAEZEH MOOSELI is a Ph.D. student at OSU and member of the ASPIN Laboratory.

JENNIFER SANDERSON is a Ph.D. student at OSU and member of the ASPIN Laboratory. She is also an R&D Engineer with Sandia National Laboratories.

JOE SAROUFIM is a Ph.D. student at OSU and member of the ASPIN Laboratory.

Cleared for the Dirt

How Robotic Rovers Are Revolutionizing Military Runway Assessment

BY PIETERJAN DE MEULEMEESTER AND ALAIN MULS

Tactical air-lifters such as the Airbus A400M, Lockheed C-130 and Boeing C-17 require precise runway roughness assessments to operate safely on unpaved surfaces. An autonomous rover system developed at the Royal Military Academy of Belgium uses RTK/PPK GNSS positioning and sensor fusion to deliver centimeter-level height measurements, drastically reducing survey time. The system provides a practical solution for rapid runway certification across military operations and humanitarian response missions.

Unpaved Runway Assessment

The Airbus A400M Atlas, the Lockheed C-130 Hercules and the Boeing C-17 Globemaster III routinely operate from unpaved runways in harsh environments far from established infrastructure. Before these aircraft can safely land, flight crews require accurate runway roughness data to assess whether the surface meets operational limits. This assessment relies on precise, quantitative measurements of the runway's surface

characteristics — a task that traditionally requires specialized survey teams and hours of manual work with GNSS equipment, resources that are often unavailable in high-tempo tactical or emergency response scenarios.

The challenge is particularly acute because different aircraft have specific roughness tolerances. The A400M uses an equivalent bump height (EBH) methodology, while Boeing employs its Boeing Bump Criteria. The EBH requires vertical measurement precision of ± 1 cm over wavelengths ranging from 5 to 100 meters. Meeting these stringent requirements with rapid, field-deployable methods has remained an operational gap — until now.

At the Royal Military Academy (RMA) of Belgium, we developed a novel solution to this critical challenge. Our system features a rugged, autonomous unmanned ground vehicle that can rapidly perform a centimeter-accurate runway assessment with minimal

user intervention. It represents a fusion of robotics, geodesy, and advanced GNSS techniques, designed specifically for ease of use by military teams in the field. The system is called Belgian Navigational Surface Inspector (BENSI).

FIGURE 1 shows the BENSI system during a mission at a tactical landing zone with the A400M in the background. **FIGURE 2** shows the BENSI system being configured by the operator during a landing preparation.

This article details the system's architecture, the integration of multiple technologies that enable the stringent precision required achieved by GNSS and sensor fusion, self-driving capabilities and its successful deployment in demanding field tests. We present a military graded solution for ensuring tactical airlift safety, enabled by modern, accessible GNSS technology and robotics.



FIGURE 1 The autonomous UGV (BENSI) during a mission at a tactical landing zone with the A400M Atlas in the background.



FIGURE 2 The BENSI system being configured by the operator during the beach landing preparation at Rømø, Denmark.

BENSI Development Team of the Royal Military Academy of Belgium

BENSI Development Team of the Royal Military Academy of Belgium

Quantifying Runway Roughness

Deployable Air Traffic Management (DATM) and Pathfinders are responsible for ensuring the safety of aircraft operations on unpaved runways. They are tasked with assessing the quality of the runway and the Runway Safety Area (RSA) to ensure that the aircraft can land safely. The pilots analyze their assessment and take the final decision to land.

FIGURE 3 is an example of a landing zone having an unpaved runway that needs to be evaluated for landing. FIGURE 4 overviews the landing zone by mapping and indicating features of the runway that need to be considered by the pilots. An important aspect of the DATM's assessment is the runway's roughness, which is quantified by the EBH.

For modern military transport aircraft operations, runway roughness assessment is a critical safety parameter. Both major manufacturers — Airbus with its EBH methodology and Boeing with its Boeing Bump Criteria — have developed sophisticated approaches to characterize runway longitudinal roughness profiles. These methods analyze height variations over wavelengths ranging from 5 to 100 meters, requiring vertical measurement precision of ± 1 cm. This rigorous assessment is essential to reduce aircraft structural fatigue, minimize maintenance

costs, prevent exceedance of design limit loads, and ultimately ensure safe operations. For the A400M specifically, Airbus requires EBH characterization to determine operational limitations of the aircraft's maximum payload.

Traditionally, achieving this precision would involve a painstaking survey conducted by specialists using a GNSS survey system mounted on a trolley requiring human guidance along the measurement tracks totaling more than 3 km of length. For military units like the DATM and Pathfinder teams, who often are the first on the ground, this is impractical. They need a system that is rapid, reliable, simple to operate without a surveying background, and robust enough for field conditions.

A GNSS-Centric Design

Our solution is a two-part system designed for rapid deployment: a portable GNSS base station and autonomous rover. FIGURE 5 shows a schematic overview of the system architecture.



FIGURE 4 A typical mapping of a landing zone showing a condensed overview of DATM's assessment.

BNSI Development Team of the Royal Military Academy of Belgium

The base station: The system's anchor

Housed in a compact, portable case, weighing just 2 kg including tripod and radios (as seen in FIGURE 2), it serves as the operational hub. Once set up on its lightweight tripod, it performs an automatic survey to establish its precise coordinates. Its primary role for positioning is to generate and transmit Radio Technical Commission for Maritime Services (RTCM) 3.x correction data to the rover via a robust long-range radio link (operating in the 868/900MHz bands).

Beyond its GNSS duties, the base station acts as a self-contained command center. It hosts a Wi-Fi hotspot and a web server, allowing the operator to connect with any standard tablet, smartphone or laptop. This web interface is used for mission planning, command and control of the rover, and real-time monitoring of survey progress. At the end of the mission, the operator can download the EBH data and additional quality metrics of the runway for analysis such as a summary report of the complete measurement, a gradient analysis, and a runway map highlighting zones with bumps or troughs exceeding the specified criteria.

An autonomous, all-terrain surveyor

The UGV is a lightweight but rugged platform chosen for its durability and open-source software architecture,

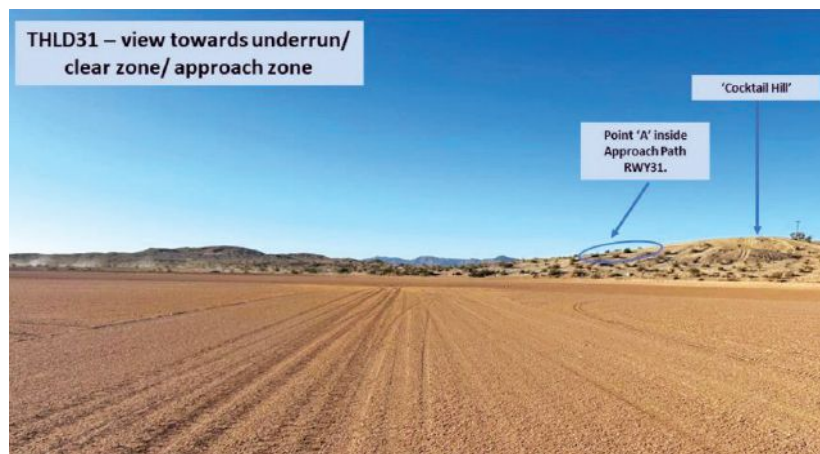


FIGURE 3 An example of a tactical landing zone.

COMOPS AIR

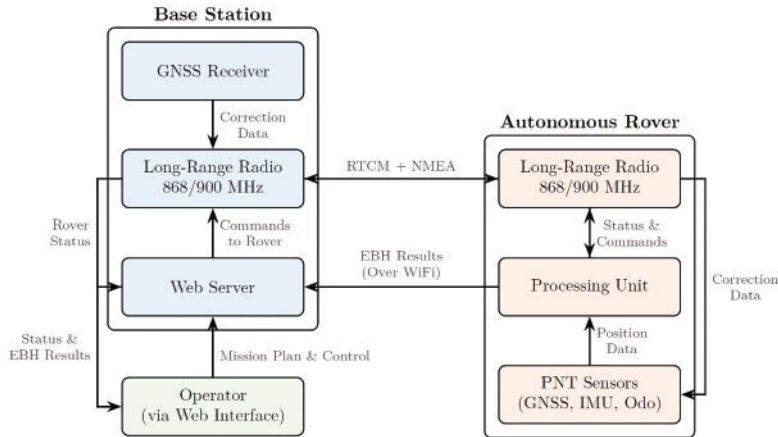


FIGURE 5 A schematic overview of the system architecture, showing the data (NMEA) and correction (RTCM) flow between the base station, rover and operator.

which allows for deep integration of our custom navigation and control algorithms. The rover has been designed to be able to traverse rough terrain and survive in harsh weather conditions. The UGV consists of two parts, the chassis (11 kg) and the processing payload (8 kg). The heart of the rover is the processing payload, which contains a sophisticated sensor suite designed for high-precision localization and navigation.

- **Primary GNSS receiver.** A high-grade, multi-constellation Septentrio receiver with a Calian/Tallysman GNSS antenna provides the main source of positioning information.
- **GNSS heading.** A second Calian/Tallysman GNSS antenna, set up in a moving-base configuration, provides degree-accurate true heading, which is critical for maintaining precise track-following.
- **Inertial measurement unit (IMU).** An industrial-grade Xsens IMU provides high-frequency data on the rover's orientation and acceleration, bridging any brief GNSS outages, providing the sensor fusion algorithm with high-rate data, and helping to smooth the final trajectory.
- **Radio communication.** The radio modules provide robust long-range communication with the base station operating in the 868/900MHz bands.

- **Wheel odometry.** Encoders on the rover's wheels provide continuous velocity information, acting as a crucial input for the sensor fusion algorithm. All sensor data is fed into an onboard mini-PC running the Robot Operating System, a flexible framework for developing robotic applications.

Path to Precision

Achieving centimeter-level accuracy on a moving platform in challenging environments requires more than just a good GNSS receiver. Our approach is built on a robust foundation of sensor fusion and a dual processing strategy using real-time kinematic and post-processing kinematic (RTK/PPK). An extended Kalman filter (EKF) is at the core of the rover's navigation software. The EKF continuously fuses data from the GNSS receivers, IMU and wheel encoders to produce a single, high-integrity "pose" (position and orientation) estimate.

For runway surveying, we employ two modes of GNSS processing:

- **RTK.** During the mission, the rover uses the RTCM corrections from the base station to compute a centimeter-accurate position in real-time. This is used for autonomous navigation, allowing the rover to follow its generated mission plan configured by the operator with high precision.

PPK. While RTK provides excellent real-time results, the most demanding applications benefit from post-processing. Both the rover and the base station log all raw GNSS observables during the mission. After the survey is complete, these raw data files are processed together which allows for more rigorous quality control and can often resolve ambiguities or fix cycle slips that were not solvable in real-time, providing the definitive, highest accuracy trajectory for the EBH analysis.

A final crucial step is extracting the height profile for each EBH track and subsequently transforming and reformatting this data for Airbus' AssurTool. The step also is automated and carried out by the software. It takes care of the following:

- The conversion of the geodetic coordinates (latitude, longitude, and height above the World Geodetic System 1984 [WGS84] ellipsoid) to Universal Transverse Mercator plane coordinates and orthometric heights (heights relative to a geoid).
- The extraction of the height profile of each EBH track.
- Quality control of the precision of the height profile flags tracks that do not meet the required accuracy or show inconsistencies.
- The transformation and reformatting of this data for Airbus' AssurTool.

Self-Driving Capabilities

The rover uses a navigation framework with a custom planner for generating smooth, curved paths that match the rover's turning capabilities and steers the rover using a controller based on the Regulated Pure Pursuit tracking algorithm. A specialized lane-generation algorithm creates optimal survey patterns from runway corner points, with behavior-tree recovery strategies for robust operation. **FIGURE 6** shows a typical EBH survey pattern generated from the mission plan and executed by the rover and a depic-

tion of how the rover plans the smooth curved path between the lanes.

A Streamlined Workflow

The system was designed from the ground up to be operated by non-surveyors. A typical mission workflow is as follows:

Setup. The operator places the base station on a tripod near the runway and unfolds the rover. The entire hardware setup takes less than 10 minutes.

Mission Planning. Using a ruggedized tablet (or any other device with a web browser), the operator connects to the base station's WiFi and opens the web interface. They define the runway by entering the coordinates of the runway's corners. The software automatically calculates the EBH lines based on the required spacing. **FIGURE 7A** shows the user interface displayed on a tablet, showing the EBH mission configuration page.

Execution. The operator initiates the mission, and the UGV autonomously navigates to the start of the first line and begins the survey. The operator can monitor and control the rover's progress, position, and GNSS quality status in real-time on the web interface. **FIGURE 7B** shows the user interface displayed on a tablet, showing the rover control, the real-time status of the UGV and the measurements.

Data Retrieval. Upon completion, the rover returns to the base station. The system automatically processes the data, producing downloadable

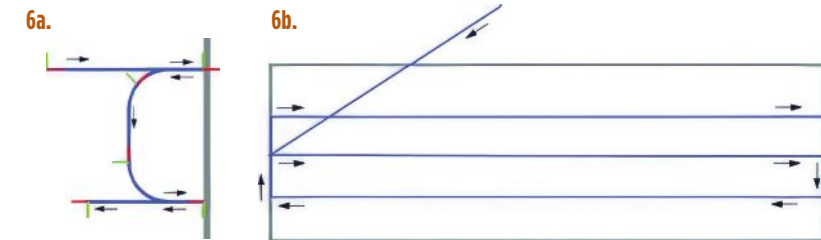


FIGURE 6 Features of the navigation framework used for planning the EBH tracks. (a) A typical EBH survey pattern generated from the mission plan and executed by the rover. (b) A depiction of how the rover plans the smooth curved path between the lanes.

files formatted for direct import into Airbus' AssurTool and additional useful quality metrics for the operator. These consist of a summary report of the complete measurement, a gradient analysis, and a runway map highlighting zones with bumps or troughs exceeding the specified criteria.

Analyzing the Data

Once the rover completes its survey and returns to the base station, the system automatically initiates post-processing of the collected data. This critical step validates the quality of every measurement and generates operator-ready outputs for both Airbus' AssurTool and field assessment.

The post-processing pipeline applies rigorous quality criteria to each survey line. Lines failing these criteria are automatically flagged with detailed diagnostics explaining the cause.

For operational decision-making, the system generates a comprehensive visualization report. The operators receive planimetric maps showing the height profile plots and a detailed gra-

dient analysis identifying critical slope transitions. A key capability is the generation of a 3D interpolated height map of the entire runway surface. This color-coded surface map provides an intuitive view of the runway's topography, clearly highlighting zones with excessive bumps, depressions, or gradient anomalies that facilitates the assessment of the runway.

These analysis reports are accessible through the web interface for immediate download to the operator's tablet. **FIGURES 8** shows examples of the visualization report.

Proven Performance

The UGV system is a mature prototype that has been validated in numerous international military exercises. It has successfully surveyed tactical landing zones in varied environments, from the desert strips of Yuma, Arizona, and 29 Palms, California, to the sandy shores of Denmark and fields in France, Portugal and Italy. In all tests, the system has consistently delivered the sub-centimeter height precision required for A400M EBH certification.

2025 Rømø Head-to-Head Trial. During beach-landing preparations in August 2025, our autonomous rover and a manual system (human-guided trolley) using a professional GNSS survey system ran side-by-side on a 1 000m landing zone on the Rømø beach in Denmark. The BENSI solution matched the manual survey system height profile with a standard deviation of 8mm and demonstrated significantly better lane-

BENSI Development Team of the Royal Military Academy of Belgium

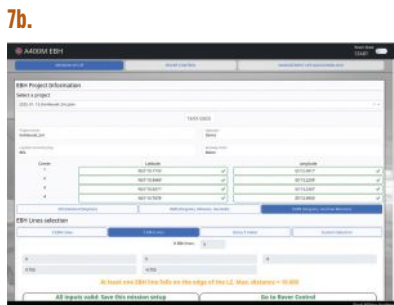
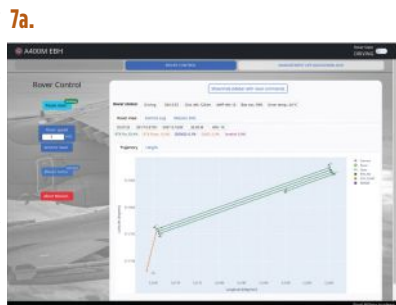


FIGURE 7 The user interface of the web application. (a) The user interface displayed on a tablet, showing the EBH mission configuration. (b) The tablet showing the rover control and the real-time status of the UGV and the EBH results.

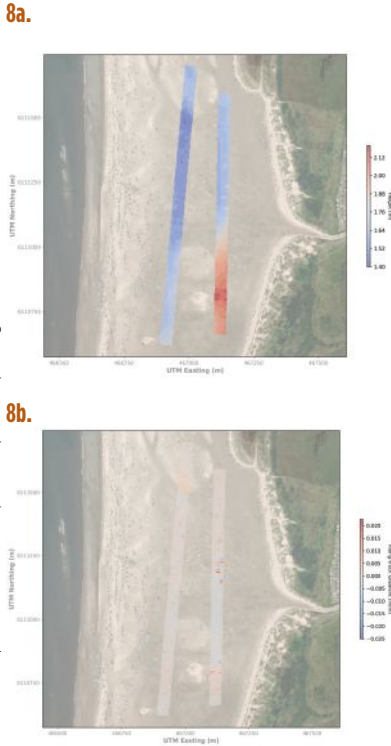


FIGURE 8 2D height and gradient contour maps of two surfaces generated by the BENSI system. (a) A height contour map of two landing zone (LZ) surfaces automatically generated by the BENSI system. (b) A gradient contour map of two LZ surfaces automatically generated by the BENSI system.

tracking consistency (mean deviation: 8,5 cm vs 16 cm and deviation error: 3 cm vs 9 cm). **FIGURE 9** shows the height-error distribution between the BENSI system and the manual survey system at Rømø, Denmark.

Rapid Humanitarian Response

While BENSI was conceived for tactical airlift operations, its capabilities extend naturally to humanitarian assistance and disaster-relief missions. Belgium’s civil rapid-response unit Belgian First Aid & Support Team (B-FAST) routinely deploys doctors, paramedics, firefighters, and other professionals worldwide following earthquakes, floods, or epidemics. Leveraging the A400M’s ability to land on short, unpaved strips away from congested or contested airfields drastically cuts transit times — but

only if the runway’s condition can be certified quickly.

The BENSI system enables a DATM team to quickly relay an EBH report and awareness map of the immediate area to the inbound aircrew. This rapid assessment unlocks critical early access for life-saving medical supplies and personnel when every hour counts.

Conclusion and the Road Ahead

The fusion of autonomous robotics and high-precision GNSS offers a powerful solution to the critical challenge of certifying unpaved runways. Our system saves valuable time, reduces the burden on specialized personnel, and provides objective, high-quality data that directly enhances the safety of tactical airlift operations.

Development is ongoing. Our current efforts focus on several key areas:

- **Improving navigation in degraded environments.** We are exploring tighter coupling between the GNSS and IMU to provide more robust navigation through areas of poor satellite visibility.
- **RSA assessment.** We are experimenting with integrating a lidar sensor to generate a 3D point cloud of the runway and its surroundings. This will automate obstacle detection and the assessment of the RSA, though we are carefully working to

mitigate potential electromagnetic interference from the lidar that can interfere with GNSS reception.

- **Handheld corner point device.** To further improve absolute accuracy, we are developing a small, handheld device that uses RTK corrections from the base station, allowing operators to mark the runway corners with centimeter-level precision.

This project demonstrates a clear application of GNSS technology in a demanding military aviation context, with broader implications for any field requiring rapid and precise surface profiling, from civil engineering to disaster response. 🌐

Authors

PIETERJAN DE MEULEMEESTER (pieterjan.demeulemeester@mil.be) is a Ph.D. research engineer at the RMA of Belgium.

ALAIN MULS (alain.muls@mil.be) is professor at the RMA of Belgium. He teaches the courses *Military Satellite Based Positioning* and *Military Geodesy*.

JARNO VAN AUDENHOVEN (jarno.vanaudenhoven@mil.be) is a Robotics Development and Research Engineer at the RMA of Belgium.

PASCAL DE KIMPE is a technician at the RMA of Belgium.

THE BENSI SYSTEM was developed by the R&D team at the RMA of Belgium in collaboration with Belgian Defense. The system has been successfully field-tested during international military exercises and is being evaluated for operational deployment.

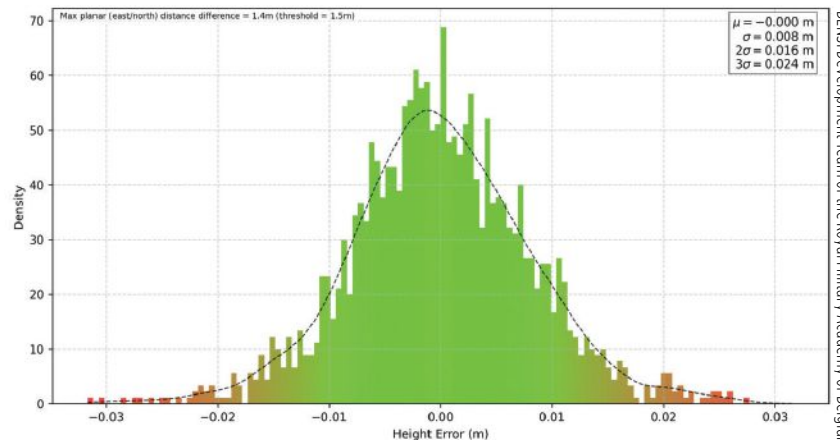


FIGURE 9 Height-error distribution between the BENSI system and the manual survey system at Rømø, Denmark.



THV Galatea

CPI TMD Demonstrates Quantum Navigation at Sea for United Kingdom

CPI Electron Device Business — TMD Technologies Division has successfully completed sea trials of its quantum-hybrid inertial navigation system (INS) aboard the THV Galatea, operated by Trinity House, the General Lighthouse Authority for England, Wales, the Channel Islands and Gibraltar.

This milestone shows that quantum-enabled sensing hardware can operate stably in maritime conditions, with the potential to provide resilient positioning without continuous reliance on GNSS.

Research indicates a 24-hour GNSS outage could cost the UK economy £1.4 billion through cascading effects on logistics, transportation and critical infrastructure, underscoring the need for GNSS-independent solutions. By proving that quantum sensors can operate in operational conditions aboard a working

vessel, CPI TMD is advancing technologies that reduce reliance on satellite navigation and improve resilience across maritime, defense and commercial sectors.

The Harlequin System: Quantum-Enhanced INS

The Harlequin system is a quantum-classical hybrid INS designed to extend GNSS holdover — the ability to maintain accurate position when satellite signals are unavailable or unreliable. Developed under an Innovate UK funded project, with partners from industry and academia, including the University of Strathclyde, and Joseph Cotter's group at Imperial College London, Harlequin integrates classic INS components (a precise clock, a ring laser gyroscope and a MEMS accelerometer) with CPI TMD's gMOT-based

SEE [CPI TMD](#), NEXT PAGE. >>

SURVEYING 

Wingcopter Drones Conduct Aerial Surveys in Japan

Wingcopter’s authorized partner in Japan, ITOCHU Corporation, has signed a memorandum of understanding (MOU) to collaborate on the practical use of Wingcopter’s long-range drones in aerial surveying together with PASCO Corporation and YellowScan Japan.

The companies initially plan to use the Wingcopter 198 in disaster management, where drone-based surveying is playing an increasingly important role, to:

- Create hazard maps and monitor ground deformation as part of effective pre-disaster prevention
- Gather information and assess damage in the event of a disaster
- Measure terrain changes and develop recovery plans during post-disaster restoration

According to Wingcopter, carrying out these tasks is easier and less risky with fixed-wing drones such as the Wingcopter 198 than with traditional human or aircraft-based methods.



Wingcopter

About 70% of Japan’s land consists of mountainous and hilly terrain, with steep slopes and short, fast-flowing rivers. Conventional multi-copter drones would not be suitable for such tasks, as they are limited in range and coverage compared to the Wingcopter 198. 🌐

CPI TMD

◀◀ *CONTINUED FROM PREVIOUS PAGE.*

quantum accelerometer.

The gMOT cold atom source, developed by CPI TMD, the University of Strathclyde and Kelvin Nanotechnology, is a grating-based magneto-optical trap that provides a source of ultra-cold atoms that forms the basis of a portable, rugged quantum sensor.

Conventional INS technology accumulates errors over time, causing position estimates to drift. By integrating its cold-atom accelerometer technology with classical INS technology, Harlequin leverages quantum-enhanced sensing

to perform periodic drift corrections, extending the period over which a vessel can maintain accurate position in the absence of satellite-derived timing and positioning.

Real-World Trials: Operating Around a Working Vessel

The Harlequin trial demonstrates that quantum sensors can operate reliably outside the lab, functioning in the harsh conditions of real-world maritime operations — a crucial validation step toward field-deployable systems.

The sea trial took place aboard the THV Galatea, which is not a scientific test vessel but an operational ship with a demanding day job: keeping shipping routes safe by ensuring buoys and lights are correctly placed and maintained, surveying the seabed for hazards, marking wrecks, and supporting marine-infrastructure projects such as cables and pipelines.

The Harlequin system had to be loaded, tested and unloaded around the Galatea’s regular operational schedule, adding complexity to the trial and underscoring the system’s ability to integrate into real-world maritime workflows.

Next Steps: System Upgrades and Second Trial

Data gathered during the trial will inform a program of system upgrades aimed at improving performance and enhancing suitability for long-term shipboard operation. A second field trial is planned for the end of 2026 to validate improvements and bring it closer to operational readiness. 🌐



The onboard team for the sea trial.

CPI TMD

DEFENSE 

Trust Automation Secures Contract from U.S. Air Force for Counter-Drone Tech

The U.S. Air Force has awarded Trust Automation a \$490-million indefinite delivery, indefinite quantity (IDIQ) contract for the rapid research, development, prototyping, demonstration, evaluation, production and transition of unmanned and counter-unmanned aircraft system (CUAS) capabilities.

As Trust Automation looks ahead to 2026 and beyond, this program represents a pivotal step in addressing the evolving challenges of modern warfare. Work will be performed at Trust's facility in San Luis Obispo, California, and is expected to be completed by Aug. 20, 2030.

Trust is a field-proven leader in defense and counter-small-unmanned aircraft system (C-SUAS) technologies to directly counter UAS activity in C2 and GNSS bands. At the core of its product suite is the Small-Unmanned Air Defense System (SUADS), which delivers fixed-site, such as Air Force base defense operations centers (BDOC), and rapidly deployable protection for key facilities and units in combat zones. These systems provide layered defense with adaptable modular solutions to detect, track



Trust Automation

and defeat Group 1, 2 and 2+ aircraft threats.

Complementing SUADS is the weapons-mountable GAT UAS Jammer, which enables personnel to directly counter UAS activity in GNSS bands. Together with a broader suite of radio frequency products, Trust equips warfighters with scalable options to secure critical operations against evolving UAS threats. 🌐

SPACE & EARTH 

TrustPoint Demonstrates GPS-Independent Navigation Signals to Orbit

TrustPoint has transmitted its first Low-Earth Orbit Navigation System (LEONS) time-transfer and tracking signals from a ground node to spacecraft in orbit. The milestone advances the development of commercial navigation infrastructure in-

dependent of GPS.

GNSS satellites require knowledge of their own time and orbital position to provide accurate data to Earth-based users. Most LEO spacecraft currently rely on GPS or medium-Earth orbit (MEO) signals for that information.

Interference and jamming are increasingly affecting these LEO connections, degrading or blocking signals.

LEONS provides GPS-independent time transfer and orbit tracking. Initially developed for TrustPoint's planned constellation, the system can be adapted for other LEO operators requiring timing and navigation for their spacecraft. The ground-to-space infra-

structure is designed to support a GPS-independent PNT layer in orbit.

"With the pace of modern threats accelerating, the difference between concepts and capabilities matters," said Nicole Hilliard, director of government programs at TrustPoint. "This milestone demonstrates that commercial partners can field resilient, GPS-independent PNT capabilities that strengthen national security architectures and justify continued investment in companies that deliver."

The demonstration supports TrustPoint's participation in the SpaceWERX AltPNT Challenge, which awarded the company two contracts to develop alternative PNT capabilities. The program seeks to deploy new options for precise, dual-use PNT systems. 🌐



TrustPoint

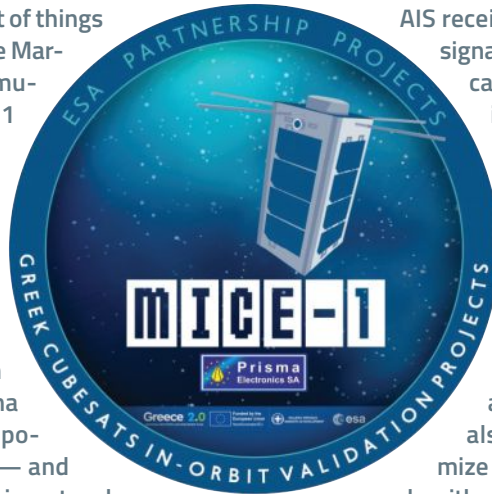
SPACE & EARTH 

Greece's Nanosatellite MICE-1 Supports Maritime Communications

Greece now has its own internet of things (IoT) nanosatellite in space, the Maritime Identification and Communications system (MICE-1). MICE-1 was launched Nov. 28 aboard a Falcon 9 rocket from Vandenberg Space Force Base in California, as part of the Transporter-15 mission by SpaceX.

MICE-1 is the first Greek nanosatellite specifically designed for maritime and IoT communication applications. Developed at the Prisma Electronics facilities in Alexandroupolis, it aims to bring Greek shipping — and critical operational infrastructures in natural disaster scenarios — closer to the capabilities of space. The nanosatellite will collect and process shipping and environmental data in real time using artificial intelligence and advanced encryption techniques to ensure secure data transmission and analysis. It also paves the way for Greece's presence in the field of space applications.

MICE-1 is a 3U CubeSat nanosatellite equipped with an



AIS receiver to record, identify and track ship signals, as well as an S-band IoT communication system. The satellite's objective is to establish direct communication with ships equipped with LAROS technology — Prisma Electronics' innovative platform that facilitates the operational monitoring and optimization of ocean-going vessels.

MICE-1 enables LAROS to leverage the capabilities of space, providing new tools for sustainable and efficient shipping. The company also will use the nanosatellite to optimize and evaluate the artificial intelligence algorithms it has developed, with the aim of assessing functionality impairment, predicting behavior and managing telemetry in line with high cybersecurity standards.

Carried out under the supervision of the European Space Agency (ESA), the mission is part of the Ministry of Digital Governance's national IOD/IOV CubeSat nanosatellite program, which forms part of the Greece 2.0 initiative. 🌐

Prisma Electronics

ArkEdge Space Signs International Agreements to Develop LEO PNT Constellation

Tokyo-based satellite company ArkEdge Space Inc. has signed letters of intent with three international organizations to develop a positioning, navigation and timing satellite network in low-Earth orbit.

The agreements with TrustPoint of the United States, the Royal Institute of Navigation in the United Kingdom and FrontierSI of Australia aim to strengthen satellite-based PNT capabilities for civil, commercial and security applications.

The collaboration represents an early phase in ArkEdge Space's effort to build international partnerships for PNT infrastructure. The company, which designs and operates small satellite constellations, said the project will focus

on improving resilience of positioning and timing systems that support critical infrastructure.

The partners plan to examine policy frameworks and national PNT strategies as the project moves into a demonstration phase. ArkEdge Space said it will expand its network of international partners to support the development of space-based positioning systems.

“By working together, this collaboration represents an important step as we accelerate the development of resilient, trusted PNT capabilities that support critical infrastructure and informed decision-making worldwide,” said ArkEdge Space CEO Takayoshi Fukuyo. 🌐



THE USE OF MACHINE LEARNING FOR STATION-SPECIFIC IONOSPHERE PREDICTION IN GNSS POSITIONING

BY TAIWO OSANYIN AND SUNIL BISNATH

ESSENCE

Ionospheric delay remains a significant error source in GNSS positioning, particularly for single-frequency users and during periods of enhanced space weather activity (Dabbakuti, 2021). While global and regional ionospheric models provide large-scale corrections, they often fail to represent localized ionospheric variability at individual receiver locations (Jee et al., 2010; Osanyin et al., 2025). Consequently, residual ionospheric errors persist in positioning solutions, degrading accuracy for applications including precise point positioning (PPP), real-time navigation, and single-frequency GPS users (Biswas et al., 2022). Hence, accurate modeling of the ionosphere is essential in tackling the principal challenges in high-precision GNSS positioning.

Vertical total electron content (VTEC), a key driver of ionospheric delay, exhibits strong nonlinear temporal variability controlled by solar radiation, geomagnetic activity, seasonal effects, and local electrodynamics (Osanyin et al., 2023; Seemala et al., 2023). Capturing this variability at individual GNSS stations poses a significant challenge. Advances in artificial intelligence (AI), i.e., machine learning (ML) techniques have emerged over the decades as powerful tools for approximating complex non-linear systems and deterministic geophysical processes, while significantly reducing computational cost (Sarker, 2021). As such, they have successfully replaced repeated full-scale numerical simulations by learning input-output relationships directly from data (Zhang et al., 2025). This paradigm shift is particularly relevant for ionospheric modeling, where

long-term GNSS observations provide rich time series well suited for data-driven learning.

Time series forecasting traditionally relies on statistical models such as autoregressive (AR), moving average (MA), autoregressive moving average (ARMA), and autoregressive integrated moving average (ARIMA), which model future values as linear functions of past observations (Kaselimi et al., 2020). They have been widely employed to predict VTEC by extrapolating historical observations. Nonetheless, the classical approaches are inherently limited by assumptions of linearity, stationarity and short-term memory, which restrict their ability to capture complex ionospheric dynamics, particularly during disturbed conditions and over longer prediction horizons. To address these limitations, this study adopts a deep learning-based framework using long short-term memory (LSTM) neural networks for station specific VTEC prediction. Unlike conventional statistical models, LSTM networks are specifically designed to learn non-linear temporal relationships and retain long-term memory in sequential data (Hochreiter and Schmidhuber, 1997).

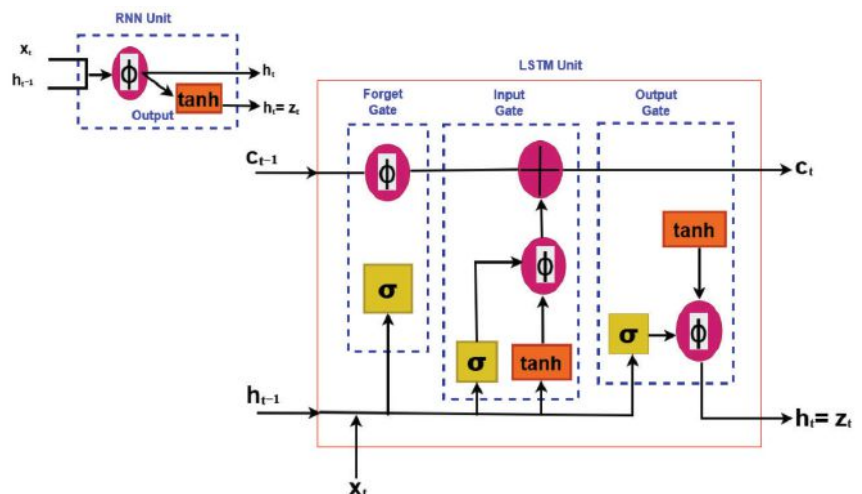


FIGURE 1 Comparison of recurrent neural network (RNN) and long short-term memory (LSTM) structures.



ESSENTIALS

LSTM neural networks for prediction have emerged as a powerful tool for time-series prediction (Hochreiter and Schmidhuber, 1997). LSTM is a type of recurrent neural networks (RNNs) that takes sequences of information and uses recurrent mechanisms and gate techniques (see **FIGURE 1**). RNNs are well known for their ability to process single data points and entire data sequences (Gonzalez and Yu, 2018). The LSTM model has various forms for different types of data inputs. The basic condition of LSTM modeling is that all inputs and outputs are independent of each other. The key to the LSTMs is the cell state, which is protected and controlled by the forget, input and output gates, respectively (Gonzalez and Yu, 2018).

Training deep learning models remains computationally demanding despite their fast prediction capability. LSTM networks consist of interconnected layers with numerous trainable parameters that must be optimized iteratively to accurately capture temporal dependencies in the data. Training typically involves large historical datasets spanning multiple years, which is necessary to expose the model to varying ionospheric conditions, but also increases computational effort (Thompson et al., 2020). The optimization process relies on iterative algorithms such as stochastic gradient descent and variants, requiring repeated forward and backward passes through the network. As the depth of the model and the length of input sequences increase, so does the demand for memory and processing power. These challenges are particularly relevant when training is performed using graphics processing units (GPUs), where memory limitations and data transfer overhead must be carefully managed (Sarker, 2021).

Like all neural networks, LSTM has trainable parameters (weights and biases). These parameters are optimized by minimizing a loss function using gradient-based optimization. Due to its ability to learn time sequences, gradients must be propagated across time steps, not only across layers. This process is accomplished using backpropagation through time, which computes gradients of the loss with respect to all parameters and accumulates gradients across the sequence. The major advantage of LSTM is the use of its gating mechanism in mitigating vanishing gradients, making backpropagation practical for long time series such as VTEC (Adekunle et al., 2025; Hochreiter and Schmidhuber, 1997; Noor and Ige, 2025).

In recent years, LSTM networks have achieved impressive results in modeling complex physical systems characterized by strong non-linearity and long-term temporal dependencies. Notably, LSTM-based approaches

have been successfully applied to atmospheric and geophysical time series, demonstrating superiority in predictive skill compared to traditional empirical and statistical models (see Reddybattula et al. (2022 and references therein). These research results show the capability of LSTM to capture diurnal, seasonal, and storm-time variations. By leveraging historical GNSS-derived VTEC time series, LSTM-based models can adaptively capture both regular ionospheric patterns and transient disturbances, enabling more accurate and robust VTEC forecasts. This data-driven approach directly supports improved ionospheric correction in GNSS positioning, offering a practical and scalable solution to overcome the shortcomings of traditional time series methods.

This study focuses a station-specific vertical total electron content (VTEC) prediction framework based on long short-term time series. The proposed framework treats VTEC prediction as a supervised regression problem. A sequence of past VTEC observations is used to predict future values over one or multiple forecast horizons. Also, emphasis is placed on methodology clarity, practical implementation, and positioning relevance.

ELEMENTS

TEC estimation from GNSS measurements

For the purpose of forecasting local VTEC using time series analysis, this study utilized the GPS dataset provided by the Brazilian Institute for Geography and Statistics (RBGE; www.ibge.gov.br/en/) over Santa Maria (SMAR; -20.720, 306.280), a station located in Brazil over the period of 10 years from January 2010 to December 2019.

VTEC data were derived from dual-frequency GPS observations at the selected station using the standard ionospheric processing techniques, including slant TEC estimation, instrumental bias correction, and mapping to vertical TEC. For more details, readers can consult the GPS-TEC analysis software developed by Seemala and Valladares (2011), which has been employed in this study for TEC processing. The time resolution is selected to be 15 minutes following an average over a sampling interval of 30 seconds. The resulting VTEC time series provides a continuous record of ionospheric variability with a fixed temporal resolution.

Station-Specific LSTM Modeling Framework

A structured deep learning workflow for station-specific VTEC prediction has been adopted using the LSTM framework. The overall methodology follows a sequential pipeline consisting of data collection, preprocessing, feature engineering, model training, evaluation, validation,

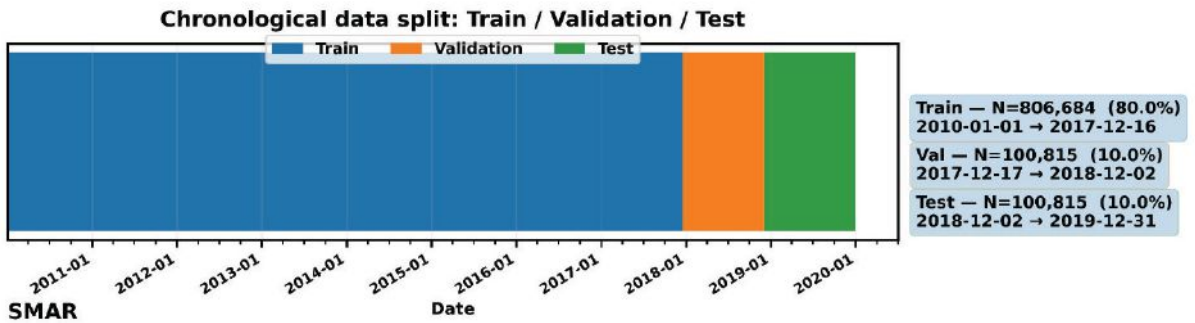


FIGURE 2 Chronological splitting of VTEC dataset for machine learning.

and deployment. This workflow ensures reproducibility, minimizes information leakage, and facilitates integration into GPS positioning engines. The focus is on time series learning at a single station, where temporal dependencies dominate and spatial smoothing from regional or global models is undesirable.

Data Preparation and Model Training

High-quality input data are essential for stable LSTM training. The extracted VTEC time series are preprocessed to remove cycle slips, mitigate differential code biases, and ensure consistent temporal sampling. As shown in FIGURE 2, for this model (as variations can be considered), the dataset has been divided into training (80%), validation (10%), and testing (10%). The validation is mostly required during training the LSTM deep learning model to ensure generalization and prevent overfitting. Furthermore, preprocessing aims at ensuring capability of the model in handling missing data and temporal consistency checks.

Feature engineering mainly converts raw VTEC observations into structured model inputs such as local time (LT) and day-of-year (DOY) features. These features are normalized prior to training, although normalization is applicable to only the training dataset to avoid future leakage. The model consists of an input layer whose dimension equals the number of input features, followed by a single LSTM layer

with 64 memory cells to learn temporal dependencies in the input sequence. A dropout layer with a rate of 0.2 is applied to mitigate overfitting during training. The LSTM representation is then passed to a fully connected (Dense) regression head with n_{out} neurons, where n_{out} equals the number of forecast lead times. Model training minimizes the Huber loss function using gradient-based optimization, while performance is evaluated using RMSE. The optimizer updates the network weights iteratively to reduce the forecast error across the training samples. Early stopping and regularization are applied to further prevent overfitting, particularly during periods of low ionospheric variability. The final outputs are the predicted VTEC at multiple lead times (in this experiment: 30, 60, 120 and 180 minutes). The trained model is suitable for deployment in near real-time ionospheric correction systems: once operational, it ingests the most recent VTEC observations and produces short-term forecasts that can be integrated into GNSS positioning workflows, particularly for single-frequency applications and PPP.

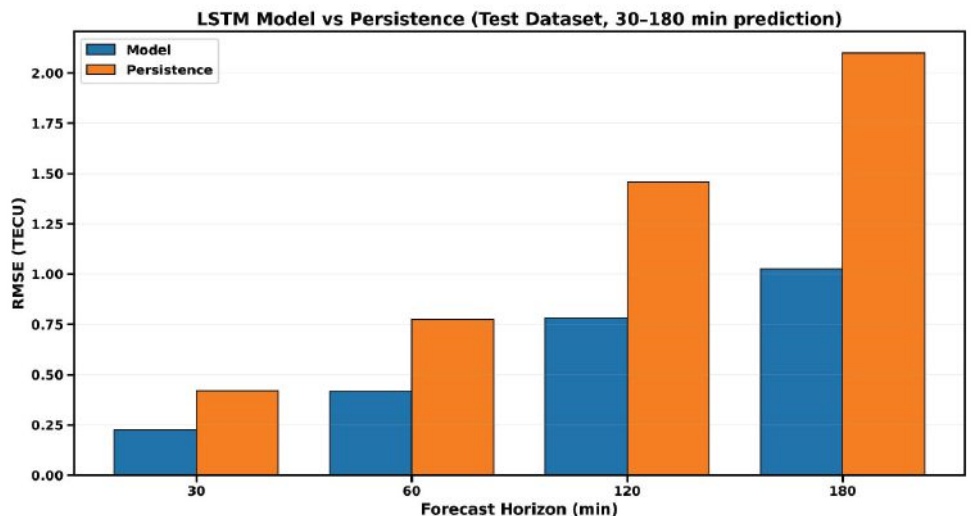


FIGURE 3 Comparison between the RMSE of the LSTM model and persistence for single-station VTEC prediction.

TEC forecast — monthly panels (test) — Horizon +60 min

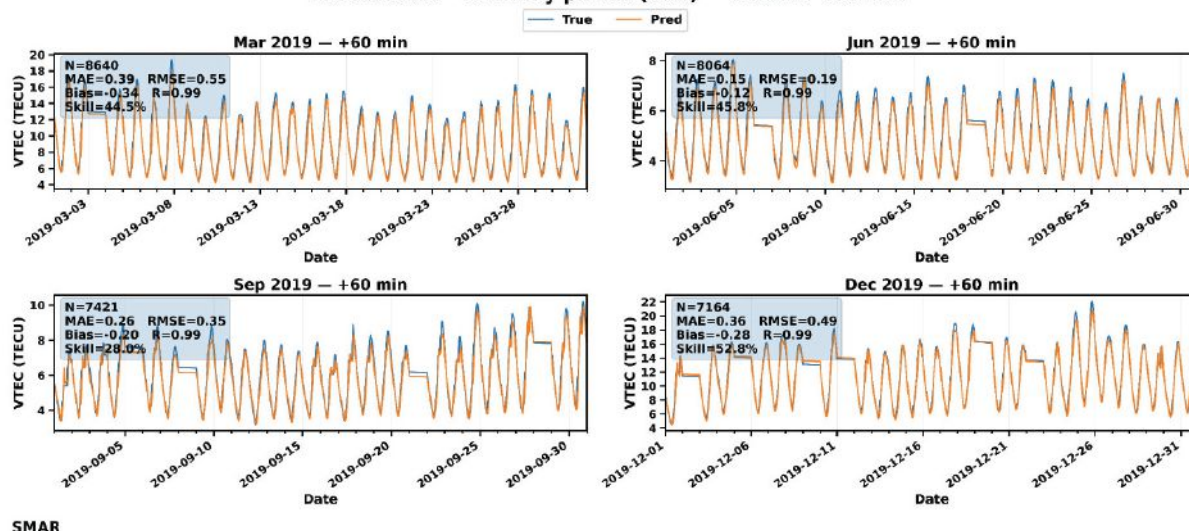


FIGURE 4 Day-to-day variation of VTEC at 60 minutes forecast during July to December 2019. The embedded metrics show the performance of the LSTM model for each month of the testing dataset.

Performance Evaluation and Baseline Comparison

For practical assessment, the LSTM-based predictions are evaluated against commonly used baseline models, including persistence (using the trained model with new data) and skill (the ability of the model to make predictions). These baselines represent the minimum performance expected in operational GNSS ionospheric modeling and serves as internal validation of the overall model’s performance. Evaluation metrics include, but are not limited to, root mean square error (RMSE), mean absolute error (MAE), and relative improvement over persistence (skill). **FIGURE 3** compares the predictive performance of the proposed LSTM model against the persistence baseline on the independent dataset. RMSE increases over time, while persistence largely deviates from the LSTM model, showing the great strength and capability of the LSTM model for time series prediction over the Santa Maria station. For instance, the RMSE of the LSTM model increases from 0.24 TECU to 1.15 TECU from 30 minutes to 3 hours lead time, while that of persistence ranges from 0.41 TECU to 2.25 TECU, respectively.

For further evaluation, day-to-day variation of VTEC at 60 minutes lead time is shown in **FIGURE 4**. GPS TEC (orange curves) shows a strong diurnal cycle with expected daily peaks, while forecast (blue

curves) matches these peaks across months, indicating that the LSTM captures the key deterministic component of TEC variability. **TABLE 1** or the embedded metrics in Figure 4 summarizes an overall accuracy of the LSTM model using the performance metrics: MAE, RMSE, Bias, R, and skill. MAE and RMSE values change with season — with the lowest reported in July. Error increases toward December with the largest RMSE in March (0.549 TECU). September shows moderate error levels. Also, correlation is consistent across all months, which confirms the model’s capability to capture TEC changes and day-to-day variability patterns. The model is nearly unbiased as the bias is consistently close to zero, meaning that the LSTM does not drift systematically and shows that the model underpredicts GPS VTEC. This characteristic is important for operational GNSS corrections, because biased VTEC forecasts would translate to persistence positioning errors. Going by the skill values, even at 60 minutes forecast, the model provides ~27%-52% improvement over persistence. This result implies a major indicator of real predictive ability, especially for GNSS applications.

Month	MAE (TECU)	RMSE (TECU)	Bias (TECU)	R	Skill
Mar	0.39	0.55	-0.34	0.993	44.5
June	0.15	0.18	-0.12	0.994	25.8
Sep	0.26	0.35	-0.20	0.986	28.0
Dec	0.36	0.49	-0.28	0.994	52.8

TABLE 1 Comparison of VTEC performance metrics of the LSTM model at 60 minutes forecast.

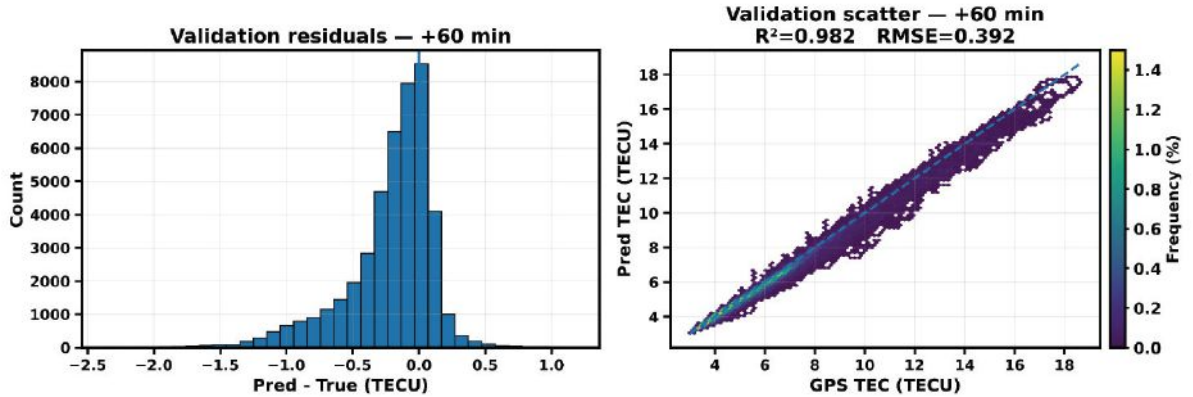


FIGURE 5 Validation diagnostics at 60 minutes forecast horizon. (Left) Histogram of prediction residuals. (Right) Density scatter of predicted versus observed TEC.

Statistical Validation

FIGURE 5 presents the diagnostic of the validation dataset for the SMAR station at a 60-minute forecast horizon. It combines the distribution of prediction residuals (left) and density-based scatter comparison between predicted and observed VTEC values. These analyses help explain the overall agreement of the LSTM model forecast during validation. The residual distribution is mostly concentrated near zero, which implies that most predictions deviate only slightly from observations. The right plot shows the scatter density plot of predicted VTEC against observed GPS VTEC. The points are tightly clustered along the dashed line, indicating that the model corresponds very well (98.2%) to the TEC variance in the validation period. Also, a RMSE of 0.39 TECU reflects a relatively low magnitude error. These findings support the reliability of the proposed LSTM model for VTEC forecasting.

Implications for GNSS Positioning

The cumulative distribution function (CDF) of the absolute equivalent L1 error, denoted by $|\Delta\rho|$, for the Santa Maria station at a forecast horizon of 60 minutes is shown in FIGURE 6. The CDF provides a direct positioning-relevant interpretation of model performance. The steep rise at small error values indicates that most samples exhibit low residual range errors, demonstrating strong correlation performance.

EVOLUTIONARY

This study demonstrates that LSTM-based machine learning

provides a practical and effective approach for station-specific GNSS VTEC prediction during low solar activity. The LSTM model accurately reproduces diurnal and seasonal VTEC variability at the station level. Forecast skill remains stable across increasing horizons, while significant RMSE reductions over persistence confirm the model's predictive value, supporting the feasibility of LSTM-based station-specific VTEC forecasting for operational GNSS applications. By leveraging historical GPS-derived VTEC time series, LSTM neural networks capture complex temporal dependencies that are difficult to model using conventional techniques. This approach offers a valuable complement to existing ionospheric correction models and represents a promising direction for future GNSS positioning systems. The results presented in Table 1 confirm that the proposed LSTM algorithm can derive an accurate predictive model as far as a 3-hour forecast. The proposed approach improves long-term ionospheric prediction and enhances positioning accuracy.

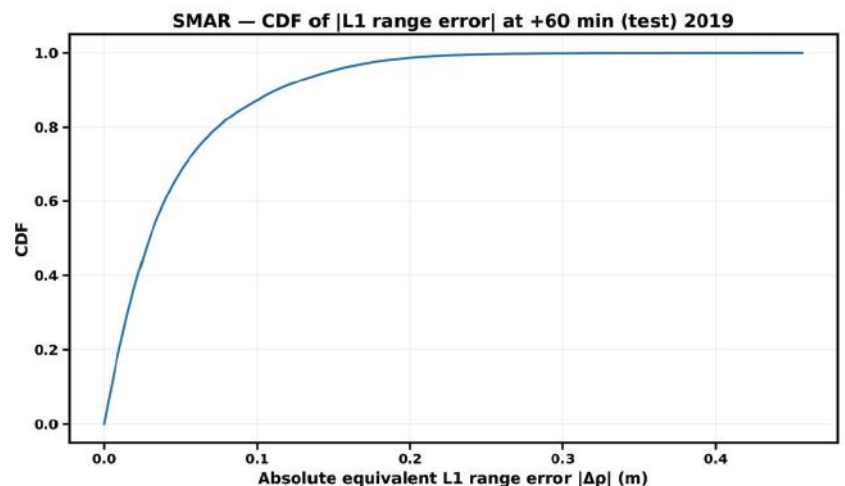


FIGURE 6 CDF of residual VTEC equivalent L1 ranging error at the single station.

While the results demonstrate the potential of AI-based modeling for station-specific VTEC prediction, further investigation is required to assess its limitations. Future research will investigate the sensitivity and robustness of the data-driven approach under extreme geomagnetic storm conditions and maximum solar activity considering multiple stations over the same region. These experiments will help evaluate the LSTM-based modeling reliance for a better positioning GPS accuracy. In addition, combining efficient training strategies with LSTM-based temporal learning offers a practical and scalable solution to station-specific VTEC prediction. The resulting models will bridge the gap between computationally expensive physics-based approaches and overly simplified empirical models, providing accurate, localized ionospheric corrections that directly enhance GPS positioning performance. Therefore, the Bayesian optimization technique would be integrated during model's training to tune LSTM hyperparameters (Adekunle et al., 2025), with the aim of reducing computational cost and improving convergence and generalization in station-specific ionospheric modeling. It is very likely that machine learning will play a significant role in near-term ionospheric modeling/prediction for GNSS. 🌐

DR. TAIWO OSANYIN is a Ph.D. visitor at York University, Toronto, Canada. Her research interests include space physics, atmospheric sciences, statistics, and modeling of the upper atmosphere. Osanyin received a Ph.D. in space geophysics from the National Institute for Space Research, Brazil, an M.Sc. in nuclear science and engineering from Obafemi Awolow University, Nigeria, and a B.Sc. in engineering physics from Obafemi Awolow University, Nigeria.

SUNIL BISNATH is a full professor in the Department of Earth and Space Science and Engineering at York University in Toronto. For more than 25 years, he has been actively researching precise GNSS-focused positioning and navigation solutions and applications. He holds an Honors Bachelor of Science degree and master of science degree in surveying science from the University of Toronto and a Ph.D. in geodesy and geomatics engineering from the University of New Brunswick.

FURTHER READINGS

- Adekunle AA, Fofana I, Picher P, Rodriguez-Celis EM, Arroyo-Fernandez OH, Zemouri R. (2025). Optimizing deep learning predictive models: A comprehensive review of RNN and its variant architectures. *Applied Soft Computing*. Oct 9:114015.
- Biswas T, Banerjee P and Paul A (2022). Impact of low-latitude ionospheric effects on precise position determination. *Radio Science*, 57(4): 1-11.
- Dabbakuti JK (2021). Modeling and optimization of ionospheric model coefficients based on adjusted spherical harmonics function. *Acta Astronautica*, 182: 286-294.
- Gonzalez J and Yu W (2018). Non-linear system modeling using LSTM neural networks. *IFAC-PapersOnLine*, 51(13): 485-489.
- Hochreiter S and Schmidhuber J (1997). Long short-term memory. *Neural Computation*, 9:1735-1780.

- Jee G, Lee HB, Kim YH, Chung JK, Cho J (2010). Assessment of GPS global ionosphere maps (GIM) by comparison between CODE GIM and TOPEX/Jason TEC data: Ionospheric perspective. *Journal of Geophysical Research: Space Physics*. 115: A10.
- Kaselimi M, Voulodimos A, Doulamis N, Doulamis A, Delikaraoglou D. (2020). A causal long short-term memory sequence to sequence model for TEC prediction using GNSS observations. *Remote Sensing*. 12(9): 1354.
- Noor MH and Ige AO (2025). A survey on state-of-the-art deep learning applications and challenges. *Engineering Applications of Artificial Intelligence*. 159: 111225.
- Osanyin TO, Candido CM, Becker-Guedes F, Migoya-Orue Y, Habarulema JB, Obafaye AA, Chingarandi FS, Moraes-Santos SP (2023). Performance of a locally adapted NeQuick-2 model during high solar activity over the Brazilian equatorial and low-latitude region. *Advances in Space Research*. 72(12): 5520-38.
- Osanyin TO, Maria Nicoli Candido C, Becker-Guedes F, Migoya-Orue Y, Habarulema JB (2025). Ingestion of GNSS-Derived-TEC Into NeQuick 2 Model Over South America. *Space Weather*. 23(12): e2024SW004212.
- Reddybattula KD, Nelapudi LS, Moses M, Devanaboyina VR, Ali MA, Jamjareegulgarn P, Panda SK (2022). Ionospheric TEC forecasting over an Indian low latitude location using long short-term memory (LSTM) deep learning network. *Universe*. 8(11): 562.
- Sarker IH (2021). Deep learning: a comprehensive overview on techniques, taxonomy, applications and research directions. *SN Computer Science*. 2(6): 1-20.
- Seemala GK, Katual I, Kapil C, Vichare G (2023). Seasonal and solar activity dependence of TEC over Bharati station, Antarctica. *Polar Science*. 38: 101001.
- Seemala GK, Valladares CE. Statistics of total electron content depletions observed over the South American continent for the year 2008 (2011). *Radio Science*. 46(05): 1-4.
- Thompson Neil C, Kristjan G, Keeheon L, Manso Gabriel F (202). The computational limits of deep learning. Cornell University, arXiv:2007.05558, 10: 2.
- Zhang R, Li H, Shen Y, Yang J, Li W, Zhao D, Hu A (2025). Deep learning applications in ionospheric modeling: progress, challenges, and opportunities. *Remote Sensing*. 17(1): 124.

ADVERTISER INDEX:

COMPANIES FEATURED IN THIS ISSUE

Editor's Note: This ad/edit index is for reader convenience only. The publisher accepts no responsibility for errors or omissions.

ADVERTISER	PAGE(S)
CAST NAVIGATION	7
GPS NETWORKING	25
NOVATEL	BACK COVER
SAFRAN TRUSTED 4D	10-11
SBG SYSTEMS	23
SEPTENTRIO	14-15



WHAT ON EARTH IS HAPPENING?

Several interesting things, according to geologists who study data from the global network of geodetic-quality receivers. A team at the University of the Basque Country found the Iberian Peninsula rotating clockwise as Africa closes on Eurasia by 0.2 inches per year (5 mm), near Gibraltar and the Alboran region. Meanwhile, in a process called lithospheric dripping, Earth's crust is sinking under Central Turkey despite being part of a broader region that has been uplifting for millions of years, according to University of Toronto researchers. Meanwhile, in the U.S. Pacific Northwest, seismic data collected during a National Science Foundation study shows the Cascadia subduction zone actively breaking apart.



MAKING BETTER ROBOTS WITH GNSS

Autonomous robot

navigation in the wild using satellite-based 3D geographical information (Robosat) aims to provide a scalable multi-GIS high-quality data collection platform through using a quadrupedal robot that can autonomously perform long-distance missions in challenging environments, such as the Alps or Finnish forests. Researchers from Finland, Switzerland, Spain and Romania gathered at Tampere University in Finland to share data, identify relevant GIS and GNSS datasets, and leverage AI for autonomous labeling of large-scale data. Key topics included integrating multi-sensor and multi-GIS data to enhance positioning, planning pilot tests with ETH's ANYmal robot (pictured) and TAU's new I/Q GNSS grabber device, and discussing methods for AI-driven data labeling for massive datasets collected in field trials.

IT'S ALL HAPPENING DOWNTOWN

Researchers from Shandong Jianzhu University and the China University of Mining and Technology describe a new smartphone positioning strategy in the Dec. 15, 2025, issue of *Satellite Navigation*. They use a positioning framework that combines 3D map constraints with multiple GNSS observations. By integrating time-differenced carrier-phase information with probabilistic road matching and factor graph optimization, the approach reduces ambiguity in candidate positions and enhances robustness against non-line-of-sight signals. In field tests, the method outperformed existing smartphone GNSS techniques, delivering more reliable location estimates and smoother trajectories even in severe urban canyon conditions.



2,000 AND COUNTING

The International Air Transport Association (IATA) has called for vigilance following the increasing number of GNSS spoofing and jamming incidents worldwide. The growing interference poses a significant risk to flight navigation and pilot safety. Of note is a spike in incidents at major Indian airports. Almost 2,000 GNSS interference incidents have been logged at airports in India since 2023, including the airports in Delhi, Mumbai, Kolkata, Amritsar, Hyderabad, Bengaluru and Chennai. IATA represents more than 360 airlines, accounting for 80% of global air traffic.



PHOTO CREDITS: NYmal ETH robot of the Robosat project, Andrei Cramariuc • Downtown navigation, Ivan Pantic/E+/Getty Images • Earth, Geodetics/NASA Worldview • Passengers embark at New Delhi airport, /rvmages/iStock Unreleased, Getty Images

COPYRIGHT 2026 NORTH COAST MEDIA LLC. All rights reserved. No part of this publication may be reproduced or transmitted in any form by any means, electronic or mechanical including by photocopy, recording, or information storage and retrieval without permission in writing from the publisher. Authorization to photocopy items for internal or personal use, or the internal or personal use of specific clients is granted by North Coast Media LLC for libraries and other users registered with the Copyright Clearance Center, 222 Rosewood Dr, Danvers, MA 01923, phone 978-750-8400, fax 978-750-4470. Call for copying beyond that permitted by Sections 107 or 108 of the U.S. Copyright Law.

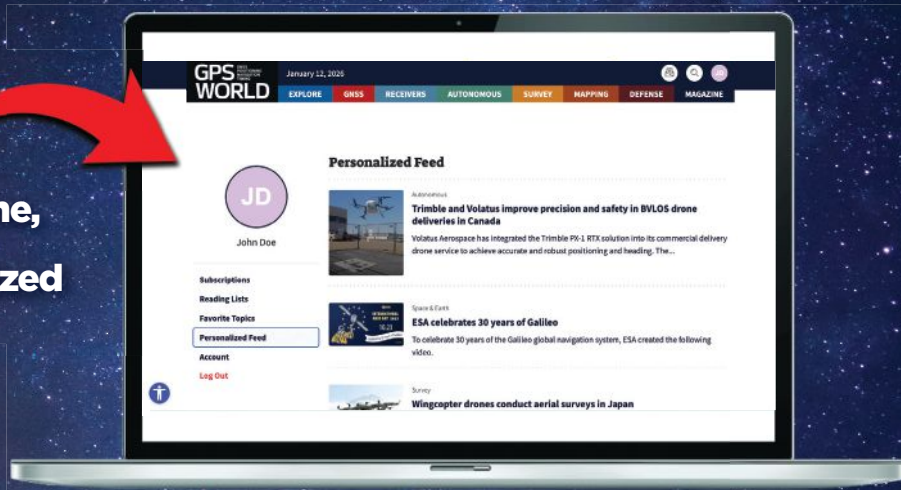
PRIVACY NOTICE: North Coast Media LLC provides certain customer contact data (such as customers' names, addresses, phone numbers and email addresses) to third parties who wish to promote relevant products, services and other opportunities which may be of interest to you. If you do not want North Coast Media LLC to make your contact information available to third parties for marketing purposes, simply call 847-763-4942 between the hours of 8:30 am and 5 pm (CT) and a customer service representative will assist you in removing your name from North Coast Media LLC's lists.

GPS WORLD (ISSN 1048-5104) is published 6 times in February, April, May, July, August and November by North Coast Media LLC, IMG Center, 1360 East 9th Street, Tenth Floor, Cleveland, OH 44114. **SUBSCRIPTION RATES:** For US, Canada and Mexico, 1 year \$49.95 print and digital, 2 years \$79.95. All other countries 1 year print and digital, \$79.95; 2 years, \$129.95. For air-expedited service, include an additional \$75 per order annually. Single copies (prepaid only) \$10 plus postage and handling. For current single copy or back issues, call 847-763-4942. **Periodicals postage paid** at Cleveland OH 44101-9603 and additional mailing offices. **POSTMASTER: Please send address change to GPS World, P.O. Box 20, Lincolnshire, IL 60069.** Printed in the U.S.A.

Unlock the New **GPSWorld.com**

**A Universe of GPS/GNSS Resources,
Now Personalized**

**Your Name,
Your
Personalized
Content**



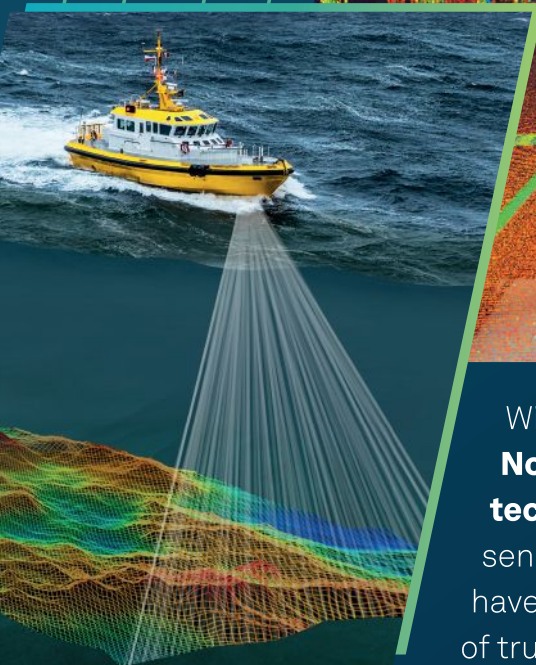
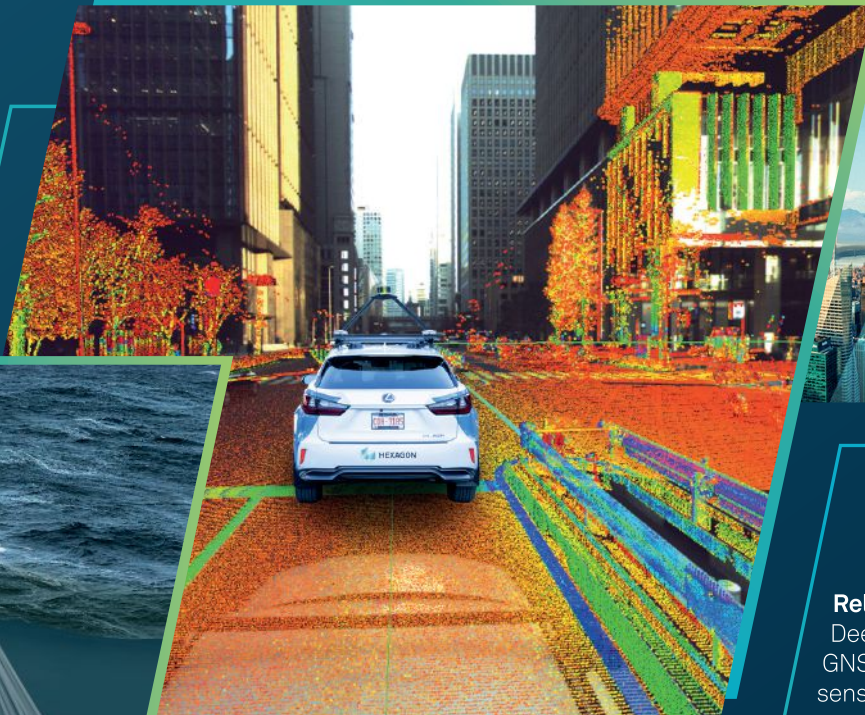
- Listen to Audio Articles
- Create Reading Lists
- Get Tailored Content
- Manage Your Subscriptions



Start exploring at [GPSWorld.com](https://www.gpsworld.com)

Contact Michelle Mitchell at mmitchell@northcoastmedia.net or 216.363.7922 for details

Your trusted source of truth—anywhere



Reliable
Deeply coupled
GNSS+INS
sensor fusion delivers
accuracy with reliability.



Available
Continuous positioning
in any environment,
including GNSS-denied
or degraded.



Flexible
Choose the IMU
that fits your
performance needs,
and your budget.

With almost 25 years in field,
**NovAtel's SPAN GNSS+INS
technology** is the best-in-class
sensor fusion engine that leaders
have counted on as their source
of truth for precise, continuous
position, velocity, attitude,
and timing.

Whether you're mapping the
world, surveying from land, sea,
or air, or developing the future
of autonomous vehicles,
SPAN provides the most
reliable, available, and flexible
positioning solution.



[Learn more](#)



HEXAGON

