GPS WORLD

GNSS
POSITIONING
NAVIGATION
TIMING

THE INDUSTRY'S MOST TRUSTED TECHNICAL RESOURCE SINCE 1990

WHO RUNS GPS? *UPDATED*

NO DRIVER OR PILOT NEEDED

Autonomous Systems for Land, Air and Sea

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A RESPONSE TO THE BROADCAST POSITIONING SYSTEM PROPOSAL

MAY 2025 | Vol 36 | No 5
GPSWORLD.COM
A NORTH COAST MEDIA PUBLICATION

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MAY 2025

Qinetiq/Pratt Miller

ON THE COVER

SBG Systems' INS Ellipse-D powers Leo Drive's autonomous cars. (Credit: Leo Drive)

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Flawed Spectrum Proposal Could Cause Disruption and Risks to Public Safety

BY JAKE PARKER
SENIOR DIRECTOR OF GOVERNMENT RELATIONS FOR THE SECURITY INDUSTRY ASSOCIATION

On March 27, 2025, the Federal Communications Commission (FCC) launched a proceeding on commercial technologies that would complement GPS. "Although GPS is indispensable to America's economic and national security, it represents a single point of failure that can be vulnerable to disruption or manipulation by our adversaries," said the FCC's announcement, highlighting the federal government's bipartisan call to develop complementary systems that provide positioning, navigation and timing (PNT) data to better achieve PNT resilience nationwide and protect America's economic and national security.

The Security Industry Association (SIA) commends the FCC's commitment to protecting America's economic and national security and exploring available PNT options. We believe the docket will show there is a wide array of PNT technologies that can complement GPS, and we look forward to providing information to the Commission about tradeoffs among these emerging PNT offerings and encouraging the Commission to avoid taking action that could disproportionately disrupt valuable public safety technologies.

Read more at **gpsworld.com/category/opinions/**.

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Celebrating a 35-year Journey

BY *GPS WORLD* STAFF

GPS World is celebrating its 35th birthday in 2025! Over the years, we have helped advance the development and deployment of GPS/GNSS and other positioning, navigation and timing (PNT) solutions.

We continue to evolve to meet the needs of our readers and industry partners. This month marks an exciting new development on our journey. We have recruited former Senior Editor Tracy Cozzens to the team to serve as Editor-at-Large. She will support Editor Diane Sofranec, Associate Editor Jesse Khalil and Digital Media Manager Joey Ciccolini in shaping and creating the editorial and online content. Cozzens amassed 20 years of experience with *GPS World*, where she built wonderful relationships with many technology innovators, until her retirement in 2023. We wooed her out of retirement as a 35th birthday gift to our loyal family of *GPS World* marketing partners and readers.

Tracy Cozzens

Diane Sofranec

Jesse Khalil

Joey Ciccolini

Our newly shaped editorial staff will continue to provide all the information and content our readers have come to expect: interesting and timely deep-dive features, GNSS agency news and entertaining sections such as "Mapping Marvel" and "Seen & Heard." We will continue to reach out to our industry partners to share their stories of product development and customer satisfaction.

For now, our cover story this month focuses on autonomous systems for land, air and sea. They continue to evolve, with more sensors, greater capabilities and greater range. We'll take a look at the current state of navigation for autonomous systems and a select few of the latest projects and products in this area.

In addition, "Evolution" examines artificial intelligence (AI), as columnist Sunil Bisnath focuses on the impact AI is directly having and could potentially have on GNSS hardware and PNT solutions, including receiver signal acquisition, measurement processing, position estimation, integrity and mitigation of jamming and spoofing.

Plus, we revisit our authoritative reference "Who Runs GPS?" that aims to clarify who does what to maintain GPS as a fantastic global utility. It also highlights the latest updates and changes in the system.

On that note, we encourage readers like you to submit story ideas and news items to any member of our team. See the masthead to the left for our contact information. We look forward to hearing from you!

What are the main challenges facing GNSS/GPS-based autonomous solutions in terms of signal integrity, jamming and spoofing, and how are these being addressed?

“Outside of the military, interference is the most common threat to GNSS, with the dominant source being cellular transmission harmonics. It is commonly addressed with out-of-band filters. Non-terrestrial networks (NTN), like Global Star uplink at 1.6 GHz, are gaining traction in more mobile and wearable devices to fill gaps in cellular availability. However, it can create coexistence issues for devices for concurrent L1 GNSS reception during NTN uplink.

In military cases, while intentional interference is effective, the increasing number of GNSS bands to cover requires more transmission power. Modernized GNSS signals with wider bandwidth signals require more jamming power, which risks detection by radiofrequency emission satellite systems such as Hawkeye 360. The frequency of spoofing events will likely continue to increase and spill over into civilian domains.

Thanks to the increasing number of test ranges being made available to commercial GNSS developers, anti-spoofing technology is making some gains, at least in the high-end systems used for autonomous GNSS.”

“Ride sharing and transport are the likely winners in exploiting the cost savings of driverless systems with autonomous navigation. The past 15 years’ investments in the development of augmented navigation systems — mainly lidar and vision-based — are finally paying off as we see Waymo in service, and soon Uber and Tesla in commercial deployments. Still, these systems depend solely on GNSS as the absolute positioning system, used for navigation in non-urban environments, but also fallback in certain cases where the sensors are problematic, as well as system calibration.

Agriculture, being one of the first segments to exploit autonomous solutions, can still see incremental gains as GNSS corrections systems move RTK from local to regional, allowing some monthly service margin improvements. High-precision consumer products like robotic lawn mowers will be enabled with similar infrastructure. Data services are a key part of infrastructure, for communication as well as precision navigation enablement. Companies such as Swift Navigation, Point One Navigation and RxN networks are expanding their networks and competing with the likes of Trimble and Hexagon.”

What are the most impactful use cases and sectors benefiting from recent advancements in autonomous solutions?

ADVERTORIAL

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In an era where unmanned systems are transforming the battlefield and the civilian world alike, precision, reliability, and secure synchronization are not optional, they are mission critical.

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Secure. Trusted. Built for the Future.

With integrated anti-jam and anti-spoofing capabilities, VersaSync is prepared for today's contested and congested GNSS environments. In defense operations, that means secure synchronization even in GPS-denied zones. In civilian use, it ensures resilience against malicious interference or system faults.
Built with flexibility and modularity, VersaSync evolves with your systems—supporting current and emerging communication protocols and allowing seamless integration into new unmanned designs as the technology matures.
With Safran Electronics & Defense proven legacy in aerospace, defense, and high-performance navigation, you gain not just technology but a partner in innovation.
Ready to Unleash the Full Potential of Your Autonomous Platform?
Discover how VersaSync can become the reliable heartbeat of your unmanned solution.

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U.S. Space Force Photo by Senior Airman Joshua Hollis

THE LOCKHEED MARTIN GPS IIIA, Space Vehicle 08 (SV-08), was successfully transferred on April 2, 2025, through a coordinated effort between Lockheed Martin, the U.S. Space Force's Space Operations Command and the USAF's Air Mobility Command.

Space Force Prepares for Accelerated GPS III Mission

The U.S. Space Force's Space Systems Command and Space Operations Command are preparing to launch the National Security Space Launch GPS III-7 mission, designated Space Vehicle 08, aboard a SpaceX Falcon 9 rocket. The launch is planned to take place from Space Launch Complex 40 at Cape Canaveral Space Force Station, Florida, no earlier than late May 2025.

This mission follows the successful Rapid Response Trailblazer launch in December 2024 and represents another accelerated effort. It involves a coordinated operation across multiple Space Force organizations to retrieve a GPS III satellite from storage, integrate it with the launch vehicle and prepare it for launch on a compressed timeline.

The GPS III satellite is equipped with M-Code technology, which offers three times greater accuracy and eight times more resistance to jamming compared to earlier systems. This capability aims to enhance precision, navigation and timing services for the joint force, ensuring modernized support for military operations.

This effort builds on lessons learned from the previous Rapid Response Trailblazer mission and demonstrates the Space Force's ability to reduce standard launch preparation timelines. While such preparations typically require up to 24 months, this mission is set to be completed within three months.

Mission Delta 31 of Space Operations Command is overseeing pre-launch processing in collaboration with Lockheed Martin in Colorado. On April 2, 2025, the satellite was transported to Florida aboard a U.S. Air Force C-17 Globemaster III and is now undergoing final launch preparations. Col. Andrew Menschner, commander of Mission Delta 31, emphasized the teamwork involved in rapidly deploying an M-Code-capable satellite and advancing traditional launch timelines. Key aspects of this mission include space vehicle-to-launch vehicle integration, satellite control preparation and expedited contracting efforts.

The satellite is named in honor of Katherine Johnson, whose mathematical contributions were pivotal to early U.S. spaceflight missions. Once operational, it will enhance communication capabilities critical to national security and align with the secretary of defense's strategic objectives by supporting military readiness with anti-jamming technology.

EUSPA Secures Continuity of EGNOS Navigation Services

The European Union Agency for the Space Programme (EUSPA) has awarded Thales Alenia Space — a joint venture between Thales and Leonardo — a €51 million ($56 million) contract to extend the operational life of the European Satellite-Based Augmentation System (EGNOS).

Named Life Extension Phase 1 (LIFEX 1), this contract will ensure that EGNOS V2 continues to provide reliable, secure and high-performance navigation services for Europe's aviation, maritime, land transport, mapping and agricultural sectors beyond 2028.

EGNOS system is designed to enhance the accuracy, reliability and integrity of positioning signals by improving the performance of GNSS, such as GPS and, in the future, Galileo. As part of this contract, Thales Alenia Space will address EGNOS V2 critical system upgrades and infrastructure improvements, reinforcing the system's resilience and operational durability. These updates will focus on enhancing security measures, modernizing components and ensuring the ongoing reliability of EGNOS's Safety of Life Service, which plays a key role in aviation, enabling accurate approaches at European airports without requiring ground guidance systems. Operational since 2011, this service has significantly improved operational safety and efficiency for the greater benefit of European operators.

EUSPA

EUSPA SIGNED A CONTRACT with Thales Alenia Space — named LIFEX 1 (Life Extension Phase 1) — to ensure that EGNOS V2 continues to provide reliable, secure, high-performance navigation services.

Sierra Space Demonstrates Resilient GPS Technology

Sierra Space has successfully demonstrated its Resilient GPS (R-GPS) technology for the U.S. Space Force (USSF). This milestone, achieved in collaboration with General Dynamics Mission Systems, involved generating all GPS navigation signals required for the R-GPS mission. The technology seeks to address the growing need for resilient GPS systems capable of countering threats such as jamming and spoofing, which pose risks to the current GPS infrastructure.

GPS technology is integral to modern life, supporting civilian applications from smartphone navigation to critical military operations. However, as adversarial threats become increasingly advanced, there is a pressing need to enhance GPS resilience. To tackle this challenge, the USSF's Quick Start program is focused on integrating smaller, cost-effective satellites into the existing GPS framework. These satellites would provide a rapidly deployable layer of protection against emerging threats, according to the USSF.

The demonstration evaluated hardware, firmware and software performance, including the generation of P(Y), M-code and C/A signals at L1 and L2 frequencies. These capabilities ensure that R-GPS satellites can produce accurate and secure navigation signals compatible with devices used globally.

USSF Space Systems Command granted Sierra Space an R-GPS contract in September 2024 to develop design concepts for smaller and more affordable satellites. Following an internal systems requirements review later that year, the company demonstrated its technological capabilities within months of the program's inception.


digitalmazdoor digitalmazdoor / iStock / Getty Images Plus / Getty Images

GNSS GLOBAL NAVIGATION SATELLITE SYSTEM **PNT** POSITIONING, NAVIGATION AND TIMING

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3

1. INTEGRATED NAVIGATION SOLUTION

IDEAL FOR INSPECTION AND SURVEY APPLICATIONS

Teledyne Compact Navigator is an ultra-compact autonomous integrated navigation system engineered for subsea and surface vehicles. It is ideal for small vehicles, enabling inspection and survey operations on compact platforms. The system is offered in two depth-rated models, one capable of operating at 4,000 m and another at 300 m. The Compact Navigator consumes less than 7 watts of power, extending mission duration by conserving energy. The system operates fully autonomously, eliminating the need for external aiding or operator intervention. Advanced phased array Doppler Velocity Log technology enhances performance while allowing the device to be mounted on an autonomous underwater vehicle or ship hull.

The Compact Navigator supports a broad range of applications, including autonomus underwater vehicles, shallow water surface navigation, operations in GNSS-denied environments and dynamic positioning for surface vehicles. The system provides true North-seeking gyrocompass-grade performance, and its web-based user interface supports integration, operation and troubleshooting. It is factory-calibrated and offers a battery backup option for reliability in demanding conditions. The system operates independently of satellite signals, making it resistant to jamming or signal loss. This capability is significant for shallow water navigation, where GNSS-based systems may be unreliable.

teledynemarine.com

2. 3D REALITY CAPTURE SOLUTION

CAN BE USED ACROSS VARIOUS INDUSTRIES

FARO Blink, a new 3D reality capture solution, is designed to make collecting and utilizing 3D data more accessible and efficient. It centers on software-driven technology integrating advanced visualization and automated workflows through the FARO Sphere XG Digital Reality Platform. This integration aims to simplify operations and deliver faster, more actionable insights for users across various industries.

FARO Blink is tailored for professionals in fields such as surveying and construction. It offers high-quality visualization and can streamline workflows, allowing teams to efficiently capture, view and share 3D data, thereby enhancing project progress and collaboration.

faro.com

3. MULTIBEAM ECHOSOUNDER

FOR BATHYMETRIC SURVEYING

The MS400C is a fully integrated multibeam echosounder designed for uncrewed surface vessels. The new system combines sonar processing, inertial navigation, GNSS positioning and sound velocity sensing into a single unit.

The MS400C seeks to address deployment challenges faced by USV operators during hydrographic surveying. Its compact, lightweight design allows direct mounting on small platforms. Installation involves connecting a few cables to the IPC and power supply and to the primary and secondary GNSS antennas. With preconfigured spatial relationships, operators can deploy and start surveying quickly, reducing configuration errors and ensuring consistent data quality.

Equipped with Auto Survey functionality, the system calibrates parameters based on water conditions, which streamlines pre-survey procedures. Real-time roll compensation and attitude data from the internal measurement unit, combined with sound velocity profiling, ensure high-fidelity depth measurements, even in dynamic conditions. Designed for autonomous and remotely operated survey platforms, the MS400C supports data collection in confined waterways.

hydro-techmarine.com

4. RTK/PPK GNSS SYSTEM

WITH TILT COMPENSATION

The SurveyPod RTK/PPK GNSS system is built for professionals in surveying, agriculture, mining and construction. The system integrates GPS, GLONASS, Galileo and BeiDou signals for improved satellite visibility and accuracy, even in harsh environments.

Powered by a CORS Network, SurveyPod offers real-time, centimeter-level positioning ideal for high-precision applications. The device supports tilt compensation for reliable data collection at angles and boasts up to 16 hours of battery life, making it ideal for extended field operations. With this launch, Nibrus Technologies is expanding its survey equipment portfolio, offering a Made-in-India GNSS solution to the global market.

surveyaan.com 🌐

1. NORTH-SEEKING IMU

OPERATES INDEPENDENTLY OF GNSS

This MEMS-based north-seeking inertial measurement unit (IMU) operates independently of GNSS. It can achieve a heading accuracy greater than 1° secant latitude without GNSS assistance. When integrated with GNSS and SBG Systems' navigation algorithms, it can achieve INS heading accuracy greater than 0.01°.


①

Measuring 52 x 52 x 36 mm and weighing less than 150 g, it consumes only 2 watts of power. It offers long-term reliability in demanding conditions, and its ITAR-free status allows unrestricted global deployment. SBG Systems also has developed a new pure north-finding algorithm capable of rapid initialization in both static and dynamic conditions within one minute, as well as an advanced GNSS/INS fusion algorithm that delivers exceptional single-antenna heading accuracy even in low-dynamic environments.

The IMU is particularly suited for subsea applications, including remotely operated vehicles and autonomous underwater vehicles, as well as geospatial and marine surveying tasks requiring precise single antenna heading accuracy.

The first off-the-shelf solutions are expected to be available by early 2026.

sbg-sysrems.com

2. POST-PROCESSING SOFTWARE

WITH UPGRADED FEATURES

Qinertia 4.2 is an updated version of SBG Systems' post-processing software for GNSS and INS data. One of the notable additions is the beta version of Precise Point Positioning Fixed Ambiguity, which offers centimeter-level accuracy processing without the need for a base station. The update also includes a new RTS smoothing option, the Trajectory Smoother, which enhances INS processing by removing artifacts while maintaining precision. Another feature is the standalone Lever Arm Estimation Tool, now available as a separate application with a simplified interface. The Advanced Virtual Base Station Network Creation has been enhanced with improved base station quality indicators to increase reliability.

It is compatible with the New Ellipse series and supports Teledyne Intrepid INS. The software now offers faster processing speeds, enhanced geodesy functionalities such as base station velocity analysis, and updated tools for assessing processing quality through new status plots. It also supports the latest firmware versions of Ekinox, Apogee, Navsight and Quanta systems.

sbg-systems.com 🌐

②

LAUNCHPAD | MACHINE CONTROL

1. GNSS RECEIVER AND INS SYSTEM

FOR MACHINE GUIDANCE

The AsteRx RB3 GNSS receiver and the AsteRx RBi3 GNSS/INS system are designed to operate in extreme environments. They feature IP69K-rated housings and components that have undergone ISO-standard testing.

The technology offers durability under heavy shocks, vibrations and challenging environmental conditions, making it suitable for demanding applications such as construction, mining and port automation.

The AsteRx RB3 and RBi3 utilize multi-frequency GNSS technology to deliver precise, centimeter-level positioning even in environments where GNSS signals are typically difficult to maintain. The receivers can be mounted externally on heavy machinery or integrated into chassis systems, offering flexibility in placement and simplifying installation.

The AsteRx RBi3 incorporates FUSE+ technology, which combines a high-performance GNSS engine with an industrial-grade inertial sensor. This integration provides accurate orientation data, such as heading, pitch and roll, alongside reliable positioning. In dual-antenna configurations, the receivers deliver sub-degree GNSS heading accuracy immediately upon initialization. The AsteRx RB3 and RBi3 are ideal for machine guidance in industries requiring rugged equipment to maintain precision under extreme conditions.

septentrio.com

2. HANDHELD REALITY CAPTURE SOLUTION

FOR MAXIMUM MOBILITY

Designed for mass data solutions, the CR-H1 utilizes PIX4Dcatch, a specialized application with integrated lidar that runs on iPhone devices. It collects images and employs photogrammetry to create detailed, full-color 3D point clouds. The iPhone connects to Topcon's HiPer CR receiver, enabling the application to collect georeferenced images. The receiver and iPhone are mounted on a specialized handle designed and manufactured by Topcon so that users can capture point clouds without a tripod.

The CR-H1 can be used for utilities and subsurface mapping, construction verification and earthworks, civil engineering and site verification, land surveying and forensics and 3D data capture. Topnet Live subscriptions are available for the CR-H1, providing real-time GNSS corrections that deliver higher-quality point clouds.

topconpositioning.com

LAUNCHPAD | MOBILE

1. HANDHELD GPS DEVICE

CAN PROVIDE UP TO 200 HOURS OF GPS NAVIGATION ON A SINGLE CHARGE

The Garmin eTrex Solar is a handheld GPS device with a built-in solar charging feature. This feature allows for potentially unlimited battery life in optimal sunlight conditions. Even without direct solar input, the device can provide up to 200 hours of GPS navigation on a single charge, making it suitable for extended trips with limited access to power.

The device supports GPS, GLONASS, Galileo, QZSS, IRNSS and Beidou. It features a rugged design, an IPX7 water resistance rating, and a compact, lightweight body that can be attached to a backpack or worn around the neck. Users can import GPX files and navigate to waypoints, courses and geocaches. It also includes a three-axis compass and can store up to a thousand waypoints, 50 courses and 200 activities.

Users can connect the eTrex Solar to their smartphones through the Garmin Explore app, which enables additional features such as geocaching details, weather updates, software updates, trip planning, and cloud storage syncing.

garmin.com

2. NEW PRODUCT OFFERINGS

NOW FEATURING MARINE GNSS ANTENNAS

Geo-matching has expanded its product database to include GNSS antennas. The initial marine GNSS antennas featured in this new category are the VP6300 from Calian GNSS, formerly Tallysman, and the AV34 from Trimble.

Geo-matching features detailed information on more than 1,300 products across 63 categories for surveying, navigation and machine guidance. The website is designed to guide users through complex product specifications, offering access to brochures, case studies, product videos and professional reviews. Among the many categories available on Geo-matching.com are hydrographic processing software, GNSS receivers, GIS software, inertial navigation systems, total stations, UAVs, sidescan sonars, imaging sonar and more. The platform encourages users to browse its extensive catalog, upload new products, leave reviews and register their companies to add products to the database.

geo-matching.com

1. MAPPING UAV

WITH A NEW "SMART RETURN-TO-HOME" FEATURE

Flyability has introduced a "Smart Return-to-Home" (RTH) feature for its Elios 3 UAV, designed to enhance its autonomous capabilities. This feature allows the UAV to return to its take-off point using the shortest available path while avoiding obstacles in real time.

During flight, Smart RTH monitors battery levels through a new flight management gauge, notifying the pilot when it is time to return. The feature is activated via Flyability's Cockpit flight app, and pilots can take manual control at any point. By automating the return process, the system helps pilots focus on inspections without concerns about battery management or navigation in complex environments. Smart RTH uses lidar scans to generate a flight plan that the UAV executes independently.

flyability.com

2. DRONE DETECTION SOFTWARE

FAA COMPLIANT

The AirWarden Remote ID Receiver detects and decodes Remote ID signals broadcast by UAVs. It is designed for organizations and authorities that need to monitor UAV activity for safety, security and compliance with regulations.

It decodes the information transmitted by UAVs in accordance with FAA and other regulatory standards. The data it captures includes the UAV's identification number, its precise location (latitude, longitude and altitude), the takeoff location, operator location if available, timestamps, and other relevant metadata. The AirWarden can be deployed as a standalone unit or integrated into larger security and monitoring systems. Users interact with the system through a web-based or software interface that facilitates live monitoring, alert management, and data analysis.

Additionally, the AirWarden can integrate seamlessly with other security infrastructure, such as video surveillance and access control systems. This integration seeks to improve how security teams automate responses and coordinate actions when unauthorized or suspicious drone operations are identified.

aerodefense.tech

MEETING THE AUTONOMY PROMISE

Advanced Navigation for Sea, Land and Air

BY TONY MURFIN, CONTRIBUTING EDITOR

Qinetiq/Pratt Miller

THE RCV-L is a purpose-built hybrid-electric unmanned ground combat vehicle integrating technology from QinetiQ and Pratt Miller Defense.

A 2019 RAND report for the U.S. Navy concluded that autonomy could still be in the distant future. The Navy should take care that a number of claimed autonomy applications could be more aspirational than practical, the report stated, with the applications nowhere near to operational capability. The authors wrote that huge investments may be required to achieve autonomous naval weapon systems, not only in autonomy.

Around the world in recent years, most armed forces and many advanced technology companies, along with government agencies, have been investing in AI and automation. Perhaps now, just six years later in 2025, we already are looking foward to unmanned vehicles that display not just fundamental autonomy, but also quite advanced "auto-capability."

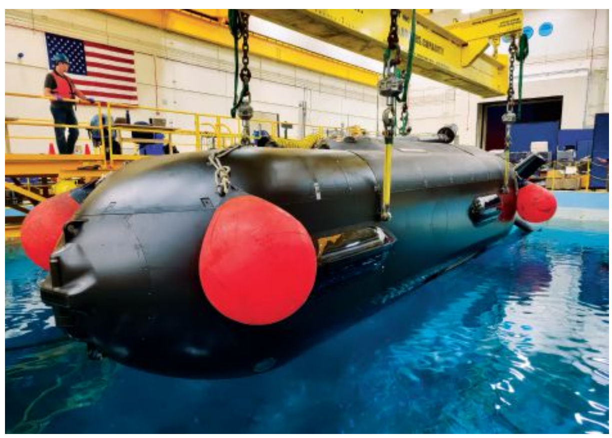
Read the full RAND report, *Advancing Autonomous Systems: An Analysis of Current and Future Technology for Unmanned Maritime Vehicles* at **rand.org/pubs/research_reports/RR2751.html**.

In the World's Waters

The U.S. Navy (USN) has been operating a number of unmanned surface vessels (USV) over the past several years. In a 2023/2024 Pacific Fleet exercise, four USV models (Sea Hunter, Sea Hawk, Mariner and Ranger) were mostly operated autonomously. Ranger has a small bridge manned only for harbor maneuvers.

The USN has unmanned autonomy programs for large, small and underwater vehicles. The Orca submarine program is slated to consist of five 51-foot-long vehicles, and includes variants fitted with an added 30-foot payload section. To operate for several months underwater, it is likely that a similar degree of autonomy has been incorporated. ORCA surfaces regularly and can be given new routing if required.

Other types of vessels collect ocean and seafloor data. The environmentally friendly Saildrone can operate independently — we could say autonomously — for more than a year. The Saildrone company, based in Alameda, California, contracts out its USVs, providing its technology to agencies and governments and taking on the risks of ocean surveying to acquire valuable data. Saidrones are equipped with satellite communications, GNSS navigation, weather sensors and sub-surface sensors.



Boeing

AN ORCA EXTRA LARGE UUV (XLUUV) is tested in a tank. With a range of 6,500 nautical miles, the submarine can perform long missions. Its navigation system features a Kalman-filtered inertial unit supported by Doppler velocity logs and depth sensors.

Navsight Enables Detailed Surveys at Sea

BY TRACY COZZENS, EDITOR-AT-LARGE

The UK-based company Uncrewed Survey Solutions (USS) has created an unmanned surface vessel called the "Accession Class USV" using SBG' Navsight inertial navigation system. The Ascension incorporates a modular design that offers three variable boat lengths depending on the desired application. The base boat length of 3.5 m can be extended to 4.25 m or 5 m by adding additional hull sections.

The standard hydrographic payload includes an SBG Apogee Navsight INS/GNSS solution, a Sonic 2024 multibeam sonar from R2Sonic and Teledyne Valeport MiniSVS and Swift SVP for measuring sound velocity. These sensors acquire data using Hypack or QINSy Hydrographic software for mission planning, acquisition, post-processing, and final products.

The standard configuration can be enhanced with a mobile lidar system such as the Carlson Merlin laser scanner for mapping terrestrial structures to create a full 3D point cloud above and below water. This is only achievable by using the embedded SBG INS — capable for both shallow and deeper water regions in either open sky or challenging GNSS environments such as under bridges and tree canopies. In such situations, the centimeter-level RTK position accuracy is greatly improved using SBG's Qinertia post-processing software.

Uncrewed Survey Solutions (USS) via SBG Systems

SBG SYSTEMS provides Navsight equipment for multi-beam and laser survey vessels such as the Ascension by Uncrewed Survey Solutions.

Oshkosh Defense

OSHKOSH DEFENSE integrated autonomous technology onto Palletized Load System vehicles as part of the Expedient Leader Follower program.

Wheels on the Road

Autonomy applications on land are dominated by commercial self-driving cars, Tesla being the leading manufacturer in the U.S. However, full autonomy is still a considerable way from being ready. At the full-autonomy level, known as Level 6 in the auto industry, the vehicle does all the driving, including obstacle avoidance, under all conditions, without any geographic limitation. Nevertheless, we appear to have progressed from basic manual control (Level 0) to somewhere around Level 3, where the vehicle is largely aware of its environment, and does most of the driving. Even so, human monitoring and control are still required.

Tesla's autopilot technology in its Model S and Model X electric vehicles could be referred to as an advanced driver assistance system — or as Tesla calls it, "Full Self-Driving (Supervised)" — and is reported to handle emergency steering and braking, autonomous steering, lane changing, vehicle following, curve negotiation, and automatic parking. Autopilot sensor inputs are provided by 12 ultrasonic sensors and eight cameras providing a 360° field of view.

Tesla Autopilot intelligence can identify more than 250 traffic signs in 50 countries, including turn signs and speed limits. It can identify and interpret traffic lights and road markings, and decide what to do when coming across things such as traffic cones and pedestrians.

Nevertheless, Teslas have been involved in quite a few accidents, the cause of which has been analyzed to be mostly a lack of driver attention (supervision), and in a number of cases, a failure of the autonomous system to recognize unusual road conditions.

Another company, Leo Drive, specializes in providing scalable software and hardware solutions, offering an end-to-end, one-stop service for integration of autonomous systems. Its mission is to make autonomous technology more accessible and widely adopted across various industries.

Just a Bus Ride Away

BY TRACY COZZENS, EDITOR-AT-LARGE

TIER IV, based in Japan, has developed open-source software for autonomous driving and is developing vehicles suitable for autonomy in urban areas. On March 9, 2025, the city of Komatsu in Japan launched an autonomous bus service with the technology. The service already has moved more than 10,000 passengers.

TIER IV's navigation solution combines an array of advanced sensors including long- and short-range lidar, object-detection cameras, radar, an inertial measurement unit and a high-accuracy GNSS receiver.

The receiver needs to operate accurately with a high level of integrity even in challenging environments. TIER IV chose the AsteRx SB3 Pro+ receiver by Septentrio, which ensures optimal performance for autonomous operations in demanding conditions.

TIER IV video screenshot

IN MARCH, KOMATSU launched an autonomous bus service powered by TIER IV and Septentrio technology.

The GNSS technology of the AsteRx SB3 Pro+ is multi-frequency and multi-constellation, using all available signals from GPS, Galileo, QZSS and more. Its high-integrity positioning warns the system when positioning reliability may be compromised. APME+ technology reduces the effect of multipath and enables reliable operations in urban environments, and LOCK+ algorithms provide optimal tracking performance even under shocks and vibrations.

For its autonomous test vehicle, Leo Drive is using the Ellipse-D, a dual-antenna RTK inertial navigation system (INS) from SBG Systems. The company chose the Ellipse-D for its accuracy, reliability, and advanced features — all essential for autonomous vehicle development and testing. The Ellipse-D INS was integrated into Leo Drive's, a passenger car converted for autonomous operations.

The U.S. Army has been using automation in its weapon systems for some time. How much autonomous behavior, of which these systems are truly capable, may be difficult to determine. The General Atomics Reaper unmanned aerial vehicle (UAV) is largely controlled over long-distance satellite links by operators in control stations. It's possible that the same set up is true of most of the Army's automated weapons — probably motivated by the need to avoid systems independently determining their own targets and firing without human confirmation.

It's difficult to determine just what army programs are underway, other than to acknowledge that programs have been launched in the past. There doesn't appear to be any open, clear indication of the degree of autonomy to be included. A couple of programs have produced at least visible hardware, but how much or little human control is involved is unclear.

Taking Flight

Up in the air, new autonomy contender Mayman Aerospace is offering the Razor, a jet-powered vertical take-off and landing (VTOL) UAV. Development of Razor is funded by private investment and U.S. Department of Defense contracts.

Razor is imbued with a degree of AI that enables autonomous decision-making, as well as navigation. Its autonomous AI brain — the SkyField flight-control system — navigates independently in a GPS-denied environment, possibly involving ground beacons and eventually integrating with battlefield management systems. With an airframe of less than 10 ft and sculpted shape, it presents a low radar cross section and has a degree of stealth to assist in the penetration of enemy defenses. Its top speed of 500 mph provides new options for both military and commercial applications, according to Mayman.

Mayman Aerospace

THE RAZOR VTOL with gimbled jet pods passed tests at a military base in California in September 2024.

Razor also can aid disaster recovery, rescue operations, and the delivery of urgently needed life-saving cargo.

Many VTOL unmanned aircraft have struggled with the transition from vertical to horizontal flight. On its first vertical lift-off and climb-out on four jet engines, Razor paused briefly at altitude. Then its jet pods tilted slightly toward horizontal before the aircraft went directly into horizontal flight. An earlier flying testbed may have assisted the development of transition

Attacking the Weed Invasion

BY TRACY COZZENS, EDITOR-AT-LARGE

Surveying invasive acquatic plant species with non-aerial methods is expensive and time-consuming, preventing frequent monitoring and effective management. Not enough study has gone into testing survey drone methods, and too few people know how to approach them. Plus there's so much to monitor, AI will be needed.

One solution, the Wingtra aerial survey platform, provides efficient, high-resolution data capture across all major data types: multispectral, RGB and lidar. The Wingtra company touts its easy setup, versatile take-off and landing, guided safety checks, and reliable automated flight. New pilots can be trained quickly, and the survey platform itself can collect enough data in a short time to train AI.

The University of Vermont Spatial Analysis Lab and Mississippi State University teamed up and used three types of Wingtra aerial survey data to demonstrate a proof of concept to capture data, train AI models and easily train teams. Their target was mapping invasive species, which can clog and throw off the natural balance of wetlands and waterways. The project conducted 119 flights at six sites in Vermont and New York, collecting 163 datasets and training 10 pilots.

Wingtra

USING THE WINTRA UAV, the research team was able to gather data from wetlands that would normally require a boat.

software, perhaps with a boost from machine learning.

Designed for deliveries, the EHang 216 heavy cargo, 16-rotor unmanned aircraft can carry a payload of 551 pounds over almost 22 miles with a top speed of 80 mph, according to the EHang company. The UAV is fully autonomously operated while being monitored over a 4G/5G data link at a manned control center. The system has an automatic fail-safe mode in which the UAV will return to base if the communications link goes down or if battery power drops too low.

EHang also uses a redundant design, with two GPS receivers and double rotors, ensuring a low likelihood of failure during a delivery run.

More In Development

So while land vehicle autonomy is moving forward — with Tesla cars and Army vehicles that apparently can take control with close human monitoring — we still have some distance to go to achieve fully independent autonomous behavior on the road.

Autonomous applications on the sea are more common, with U.S. Navy applications showing substantial progress. Still, precise navigation in crowded harbors remains under human control. Humans are still watching and monitoring, ready to intervene should military or commercial UAV applications make untoward execution errors.

We will continue to follow developments of significant autonomy programs such as the U.S. Air Force Collaborative Combat Aircraft (CCA), a new type of uncrewed weapon system. The CCA and other programs are maintaining high investment levels, so it's possible that we may see full autonomy fielded quite soon. Perhaps then our belief in its capability will become fully justified.

Ehang video screenshot

THE EHANG 216 HEAVY-CARGO UAV EHANG 216L is designed for deliveries, including life-saving ones.

Is There a Silver Bullet for Resilient PNT?

Still Searching for a GPS Backup

BY JULES MCNEFF
OVERLOOK SYSTEMS TECHNOLOGIES

Rick_Jo / iStock / Getty Images Plus / Getty Images

Merriam-Webster defines a “silver bullet” as a magical weapon, one that instantly solves a long-standing problem. Well, it’s been about 30 years. Despite studies, analyses, tests, demonstrations and much hand-wringing, no silver bullet technology has been identified to back up the myriad GPS dependencies that now permeate U.S. critical infrastructure (CI).

The President, members of Congress, Deputy Secretaries and the President’s National Space-Based PNT Advisory Board have all weighed in to insist that such a backup be put in place to preserve the operational continuity of domestic CI, all to no avail. As a participant in or observer of virtually all these efforts over the past 20 years, I am as familiar with and frustrated as anyone by the lack of progress or urgency.

Now, the Federal Communications Commission (FCC) is the latest to join the fray in late March with a public hearing preceded by a *Notice of Inquiry (NOI) on Promoting the Development of PNT Technologies and Solutions,* as well as a separate but related *Notice of Proposed Rulemaking* on improving wireless E911 location accuracy. As with many of the preceding efforts, the NOI is comprehensive and seems all-inclusive regarding both technologies and governance, and it is timely, as it follows many recent press reports on both GPS and CI vulnerabilities. One can hope that its findings will be compelling and capable of implementation, though the sheer range of responses it invites in light of numerous recent industry initiatives for PNT services may only confuse the situation further.

The NOI reflects the recent marketing of PNT services to the government by NextNav, the National Association of Broadcasters (NAB), various commercial SATCOM providers and others. NextNav proposes a commercial PNT service, potentially in conjunction with cellular communications providers, and the NAB proposes a Broadcast Positioning System (BPS) that would include PNT information with television signals using a proposed new broadcast standard. Both entities have separately petitioned the FCC for consideration of rulemaking changes to facilitate their planned solutions. However, their proposals highlight the confusion that can be created by commercial interests that do not take account of some fundamental differences between PNT and communications services.

PNT services have unique requirements for coverage, availability, continuity, integrity and time management that differ from those for communications services, and which dictate how PNT services are provided and employed, particularly when nationwide service is required. This is not to say that the noted PNT initiatives involving market-focused communications providers should not be considered as viable complements to space-based GPS service. However, a viable backup to GPS must be able to provide service in rural and remote portions of the country, where commercial markets are lacking and robust commercial services are not available.

There are significant differences among civil and military PNT service requirements. The Department of Defense (DOD) recognized the reality of this common variation in services, and in its *2019 Department of Defense PNT Enterprise Strategy* envisioned a multi-layered PNT architecture consisting of global, regional and local sources of PNT information to support U.S. and allied military systems worldwide. The global PNT layer is space-based and ubiquitous, with 3D position and precise time available worldwide. The regional PNT layer may be space-based or terrestrial with national or international coverage where PNT resiliency must be assured. The local layer may be space-based, terrestrial, and/or autonomous using manmade and natural PNT sources over a limited area based on source design and performance.

In proposing to back up GPS use in domestic CI, both NextNav and the proposed BPS seem to be positioning themselves to serve as the regional layer for the entire country, though both are fundamentally focused on urban markets. NextNav proposes PNT services in urban areas using a network of beacons, potentially partnering with cell phone service providers to provide broader reach, primarily for timing. NextNav also offers a special precise vertical location service for first responders in select metro areas.

The BPS proposal envisions mesh networks of television broadcast antennas, where one TV station is the lead for timing and provides a timing signal to other (follower) stations in a metro area. The PNT information (time, tower location) is contained in a small portion of each main TV broadcast message frame. In effect, it is a new instantiation of a technology demonstrated in 2008 by Naval Academy Midshipman David Taweel in collaboration with Johns Hopkins APL. Using time-managed TV transmissions in Washington and Baltimore, he designed and executed a closed-course UAV flight profile to demonstrate use of signals of opportunity (SOO) for navigation in the absence of GPS. In the same period, a company called Rosum briefly marketed similar PNT services using TV and other SOO transmissions. The technology was stymied by the lack of a nationwide broadcast standard for time-synchronized TV transmissions, which are essential to enable receivers to calculate PNT solutions. This is apparently still a problem today, as the NAB petition to the FCC requests

> **"Unless our government accepts responsibility, there will be no PNT silver bullet for domestic CI."**

that the latter mandate adoption by TV broadcasters of a new standard that will enable the BPS signal but will also require changes to TV sets and converter boxes. The end user market for a TV-based service is undefined, as is the willingness of station operators nationwide to accept a new standard.

Both NextNav and BPS technologies have performed well within structured demonstrations conducted independently and by the government, and I don't doubt their technical viability as local layer complements to GPS, particularly for timing. However, as complete backups to GPS positioning and timing services nationwide, issues of adding necessary infrastructure and coordinating precise time management among the range of broadcast system partners and cell network providers become cost prohibitive to serve remote and rural areas where relevant markets don't exist. Also, TV towers, are sited to provide optimum reception of TV signals in their service areas but not to optimize geometric separation among them that is necessary for positioning services, particularly beyond the margins of metro areas. Finally, neither provider would be able to back up GPS in supporting national security and economic activities in the Alaskan Arctic region and over the northern ocean areas abutting the United States and Canada, where GPS may realistically be threatened in the face of growing competition from U.S. adversaries.

In that context, and with respect to all the studies assessing GPS backups, NextNav stated in an FCC filing, "No one else has proposed a credible solution to the widely recognized and increasingly urgent problem that the United States has no wide-scale [terrestrial PNT] service to complement and back up GPS where the GPS signal is obstructed or when outages occur."

This is simply not correct, as government studies over years have identified enhanced Loran (eLoran) as the most viable and affordable backup to GPS, and eLoran remains the only terrestrial PNT service that can efficiently back up GPS nationwide, including the Alaskan Arctic and northern oceans. However, since 2015, and despite Congressional support, deliberate political resistance within OMB and resulting DOT/DHS inaction and attempts to shift responsibility to industry have allowed much of the legacy Loran infrastructure to degrade. Costs have risen, and the government is now considering selling the system off, losing access to the valuable sites where eLoran transmissions would be most useful to back up civil GPS use. At the same time, our adversaries in Russia, China and (reportedly) Iran, continue to build out eLoran networks of their own to back up their use of space-based PNT services.

Unless our government accepts responsibility, there will be no PNT silver bullet for domestic CI. Experience shows that industry will not solve this problem alone.

JULES MCNEFF has been supporting national and DOD GPS and PNT interests for more than 40 years. He participated in the development of the first Presidential Decision Directive on GPS and a National PNT Architecture and in the adoption of the U.S. National Grid (USNG) as a federal geo-addressing standard and drafted a strategy for the DOD PNT Enterprise. He is a graduate of the U.S. Air Force Academy and of Harvard Business School and retired from the U.S. Air Force. He has been a member of *GPS World*'s Editorial Advisory Board for 35 years.

2025 Updated

WHO RUNS GPS?

The Global Positioning System (GPS) is a vast and mostly unknown enterprise. This section aims to clarify who does what to maintain GPS as a fantastic global utility. It also highlights the latest updates and changes in the system.

BY MATTEO LUCCIO WITH CONTRIBUTIONS FROM MIKE DUNN, POSITIONING, NAVIGATION AND TIMING TECHNICAL DIRECTOR, SSC/CG

LEADERSHIP

National Executive Committee for Space-Based Positioning, Navigation and Timing (EXCOM)

The EXCOM, an interagency body, guides and preserves whole-of-government interests in providing space-based PNT services, augmentations and space-based alternatives. The EXCOM is co-chaired by the deputy secretaries of the departments of Defense and Transportation or its designated representatives. The EXCOM coordinates GPS-related matters across multiple federal agencies to ensure that the system addresses national priorities as well as military requirements. It includes leadership from the Departments of State, Treasury, Justice, Interior, Agriculture, Commerce, Energy and Homeland Security; the Office of the Director of National Intelligence; the Joint Chiefs of Staff; and NASA.

National Coordination Office for Space-Based Positioning, Navigation and Timing (NCO)

A permanent staff hosted by the Department of Commerce in Washington, D.C., this small office plans, schedules and prepares agendas for the EXCOM and the Executive Steering Group. The NCO also maintains *GPS.gov*, an invaluable website.

PNT Oversight Council

Operating through the PNT Executive Management Board, it provides GPS guidance for U.S. military and defense-only subjects. Planning and orchestration are provided by the Department of Defense (DOD) chief information officer (CIO/C3I). Participation includes key OSD, JCS and Space Acquisition staff members, and other invitees depending upon the topic at hand.

ACQUISITION AND SUSTAINMENT

DOD US Space Force (USSF) Space Systems Command (SSC)

HQ: Los Angeles AFB, El Segundo, California
Commander: Lt. Gen. Philip Garrant

SSC identifies, prototypes and fields resilient space capabilities for joint warfighters. It delivers sustainable joint space warfighting capabilities to defend the nation and its allies while disrupting adversaries in the contested space domain. Its key roles are:

- **Acquisitions.** Develops and acquires USSF space systems.
- **Capability development.** Drives innovation and develops future technologies through collaboration with allies and industry in support of the joint warfighter.
- **Talent development.** Builds and maintains a diverse pool of space systems talent.
- **Launch.** Assures access to space with launch capabilities for both commercial and military assets.
- **Systems architecture.** Contributes to the development of a resilient, integrated national security space architecture that outpaces current and future threats.
- **Sustainment.** Supports space system development and launch capabilities.

The following SSC units are directly responsible for developing and deploying GPS:

- **SSC Military Communications and Positioning, Navigation, Timing Directorate (MilComm & PNT)** HQ: Los Angeles AFB, El Segundo, California; Commander: Program Executive Officer Cordell DeLaPena Jr.

- Develops, produces, delivers and maintains military communications and PNT systems.
- **Space Launch Delta 45 (SLD 45)** HQ: Patrick SFB, Florida Commander: Brig. Gen. Kristin Panzenhagen
  - Conducts all space launch operations from the East Coast, including GPS.

Integrated Mission Deltas (IMDs) and System Deltas (SYDs): The USSF has introduced SYDs and IMDs to streamline operations and enhance efficiency. System Deltas focus acquisition activities within mission areas to further enhance delivery and collaboration. SYDs consolidate program offices in SSC that design, develop and deliver mission systems under a mission-focused command structure for acquisitions. IMDs are designed to bridge the gaps among operations, engineering and capability development specialists, ensuring rapid capability development and focused combat effects. IMDs consolidate all aspects of mission-area readiness into a single organization, combining units in Space Operations Command (SpOC) that perform mission generation, intelligence support and cyber defense with program offices at SSC that handle sustainment.

- **PNT System Delta -** Commanded by Col. Matthew Spencer: This SYD focuses on developing and delivering GPS and other PNT capabilities.
- **Mission Delta 31 -** Commanded by Col. Andrew Menschner: Mission Delta 31 has two missions: positioning, navigation and timing and the Satellite Control Network. It consists of six squadrons and 12 detachments/operating locations across geographically separated locations. Squadrons include:
  - **2nd Navigation Warfare Squadron (2 NWS):** Operates the GPS satellite constellation delivering positioning, navigation and timing data to military and civilian users globally (formerly 2 SOPS).
  - **31st Capability Development Squadron (31 CDS):** Responsible for development and fielding of next-generation software for all modernized and legacy GPS satellites.
  - **31st Sustainment Squadron (31 STS):** Provides sustainment support, delivering updates and modifications to improve operational capabilities of fielded systems.
  - **21st Space Operations Squadron (21 SOPS), 22nd Space Operations Squadron (22 SOPS) and 23rd Space Operations Squadron (23 SOPS):** Schedule satellite contacts through the Satellite Control Network for more than 190 Department of Defense, Allied, and national agency satellites; publish the daily Space Access Tasking Order; and provide real-time support for satellite anomaly resolution.

OPERATIONAL CONTROL

USSF Space Operations Command (SpOC)

HQ: Peterson SFB, Colorado Springs, Colorado
Commander: Lt. Gen. David Miller Jr.

SpOC generates, presents and sustains combat-ready intelligence, cyber, space and combat support forces for USSPACECOM Space Forces Space.

US Space Command (USSPACECOM) and US Space Forces-Space (S4S)

HQ: Vandenberg SFB, California
Commander: Lt. Gen. Douglas Schiess

S4S is the USSF service component field command to USSPACECOM.

- Mission Delta 31
  HQ: Peterson Space Force Base, Colorado
  Commander: Col. Andrew Menschner

Working together, the following squadrons are responsible for the day-to-day operation and maintenance of GPS, including its ground and space segments:

- **2nd Navigation Warfare Squadron (2 NWS)** is the Force Generation Squadron for the presented Navigation Warfare (NAVWAR) mission area. 2 NWS trains and develops combat-ready operators to operate the largest DOD spacecraft constellation via the Master Control Station and worldwide network of monitor stations and ground antennas. 2 NWS also assists with future planning for new spacecraft capabilities and ground segment components, including the Next Generation Operational Control System (OCX).

- **2nd Navigation Warfare Combat Squadron (2 NWCS)** is the combat-ready force presented to USSPACECOM S4S. 2 NWCS performs the command and control mission for the 37-satellite GPS constellation, providing precise PNT information and NAVWAR support to users globally. 2 NWCS also provides mission support and tactic development to support and defend the GPS constellation.
- **The 19th Space Operations Squadron (19 SOPS)** is an Air Force Reserve component that provides critical augmentation to current and future GPS operations. The squadron's members, alongside their 2 NWS counterparts, execute the day-to-day operation of the GPS constellation, support on-orbit engineering efforts and play a crucial role in the eventual adoption of OCX.
- **310th Operations Support Squadron (310 OSS)** is a reserve Air Force squadron nested under the 310th Operations Group. Just like the 19 SOPS, it trains active duty and reserve personnel.

▸ **GPS Master Control Station (MCS)**
HQ: Schriever Space Force Base, Colorado

Monitors and controls the GPS satellite constellation and its ground assets, GPS monitor stations and GPS ground antennas. GPS is managed 24 hours a day, 365 days a year by a crew of no less than 10 personnel primarily from 2 NWS and 19 SOPS.

KEY PARTNERS AND CONTRIBUTORS

Several other U.S. government departments and organizations play a role in shaping national GPS policy.

Department of Transportation (DOT)

DOT is the lead department for civil PNT. It coordinates, defines and validates requirements for the management and modernization of all civil applications. DOT represents all civil departments and agencies in GPS development, acquisition, management and operations. DOT provides PNT systems analysis and coordination throughout the requirements development process to ensure safe and efficient architecture deployment. Additionally, DOT serves as the lead federal agency in discussions with DOD regarding all GPS civil services and signals, including implementation of signal authentication capabilities. DOT has several different administrations that are active GPS users and developers of GPS applications, including:

- **Federal Aviation Administration (FAA),** which operates the GPS Wide Area Augmentation System to monitor the integrity of GPS signals and broadcast differential corrections for safety-of-life applications.
- **Federal Railroad Administration (FRA)**
- **Federal Highway Administration (FHWA)**
- **Maritime Administration (MARAD)**
- **DOT Volpe Center,** which houses a major research and development center of excellence.

The DOT also has civil engagement, responsible for communicating with international partners through analyses and subject matter expert contributions to working groups and other domestic and international fora, including:

- ICAO Navigation Systems Panel
- RTCA Special Committee 159 Working Groups
- European Organization for Civil Aviation Equipment
- U.S./EU GPS/Galileo Working Groups
- International Committee on GNSS
- Civil GPS Service Interface Committee (CGSIC) under the EXCOM.

Department of Commerce (DOC)

- **National Oceanic and Atmospheric Administration (NOAA):** Operates a network of continuously operating reference stations to provide GNSS data, supporting three-dimensional positioning, meteorology, space weather and geophysical applications throughout the United States.
- **National Telecommunications and Information Administration (NTIA):** Authorizes and protects federal uses of the radiofrequency spectrum, including the radionavigation bands used by GPS.
- **National Institute of Standards and Technology (NIST):** Publishes and promotes the Cybersecurity Framework, including a PNT Profile designed to shore up the resilience of critical infrastructures that use GPS.

Department of Homeland Security

- **U.S. Coast Guard GPS Navigation Center (NAVCEN):** Provides a navigation information service for civilian GPS users, coordinates and manages CGSIC in cooperation with DOT, publishes GPS data files and manages reports of GPS interference and inquiries from around the world.

National Aeronautics and Space Administration (NASA)

- **PNT Advisory Board:** Provides independent advice to the EXCOM from outside the U.S. government. The board focuses on making GPS and related PNT systems and services more accessible, reliable and robust.

Department of State (DOS)

- **GPS International Working Group (GIWG):** Facilitates outreach planning, coordination and interaction for U.S. engagement in a wide variety of multilateral and bilateral international forums, including leadership and active participation in United Nations forums such as the International Civil Aviation Organization.

CONGRESSIONAL FUNDING AND OVERSIGHT

The U.S. Congress plays a crucial role in funding and overseeing the GPS program. Through legislation, Congress allocates funds to ensure the continued development, operation and modernization of GPS. The program is supported fully by U.S. taxpayers and has no other source of funding.

Funding Overview

- **Fiscal year 2025:** The budget request had included over $464 million for the GPS program. This funding covers various aspects of the program, including procurement, research, development, testing and evaluation by the U.S. Space Force.
- **Defense appropriations:** The DOD receives the bulk of the funding, which supports GPS procurement, space segment development, operational control segment, and military GPS user equipment.
- **Transportation appropriations:** The Department of Transportation (DOT) receives funding to operate civil GPS augmentation systems like the Wide Area Augmentation System (WAAS) and investments to enhance positioning, navigation and timing (PNT) resilience and security.

Several congressional committees have provided strong support for GPS and have conducted hearings on GPS-related matters since 2009.

- **In the U.S. Senate**
  - Armed Services Committee
  - Foreign Relations Committee
  - Appropriations Committee
  - Committee on Commerce, Science and Transportation
- **In the U.S. House of Representatives**
  - Armed Services Committee
  - Transportation and Infrastructure Committee
  - Energy and Commerce Committee
  - Science, Space and Technology Committee
  - Oversight and Government Reform Committee
  - Small Business Committee

These committees ensure that GPS remains a priority in national defense, civil infrastructure and technological advancement. Their oversight helps maintain the integrity and reliability of the GPS system, benefiting both military and civilian users worldwide.

EDITOR'S NOTE: This article includes contributions from others including members of the SSC/CG Military Communications and Positioning, Navigation and Timing Program Executive Office, along with SSC Public Affairs and SpOC.

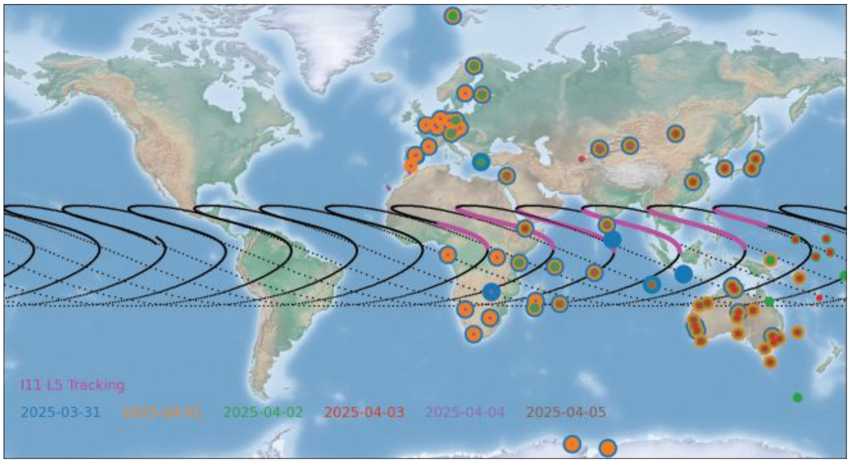
NVS-02: Navigation Signals from Transfer Orbit

BY PETER STEIGENBERGER, STEFFEN THOELERT, AND STEFAN HACKEL

NVS-02 is a second-generation navigation satellite of the Indian regional navigation satellite system NavIC. It was launched on Jan. 28, 2025, but could not reach its designated orbit due to a malfunction of a valve of the thrusters. Thus, the satellite is still in its transfer orbit. As of April 2025, the NVS-02 perigee is about 190 km, whereas the apogee is 37,400 km above the Earth's surface. The inclination is about 21° and the eccentricity is 0.74. The groundtrack of NVS-02 is illustrated in **Figure 1** and currently has a repeat cycle of about six days.

As of today, starting on Feb. 19, 2025, a decent number of receivers of the International GNSS Service are tracking the L5 signal of NVS-02 with the pseudo-random noise number I11. The L5 tracking of dedicated stations on individual days is indicated by different colors in Figure 1. Although the groundtrack has global coverage, no stations in Northern and Southern America have tracked I11 so far. The tracking is limited to periods when the satellite is near the apogee with altitudes between 23,000 km and 37,400 km and visible from the Indian Ocean region. During these periods, indicated in pink in Figure 1, the transmitter is active and the antenna is roughly pointing toward Earth.

Figure 2 shows the carrier-to-noise density ratio (C/N_0) of the NVS-02 L5 signal tracked by a Septentrio PolaRx5 receiver at the German Space Operations Center (GSOC) of the German Aerospace Center (DLR) in Oberpfaffenhofen, Germany. Sudden drops in the C/N_0 occur at about 8°, 28°, 46° and 52°. Here, the line of sight



All figures provided by the authors.

FIGURE 1: Groundtracks of NVS-02 for six consecutive days. The colored dots represent stations tracking the L5 signal on the day given in the legend. Pink ground tracks indicate tracking by any of the stations.

to the satellite is at the edge of the transmit antenna main lobe with a significantly lower gain, introducing the drop in signal power and, finally, the loss of lock.

The spectral flux density of NVS-02 in the L5, L1 and S band is shown in **Figure 3.** The L-band spectra have been measured with GSOC's 30 m high-gain antenna in Weilheim, Germany. As the feed of this antenna is limited to the L band, the S-band spectrum has been recorded with a 5 m dish antenna of DLR's Institute of Communication and Navigation.

The peak in the L5 spectrum at the center frequency of 1176.45 MHz is related to the civil Standard Positioning Service and introduced by a Binary Phase Shift Keying (BPSK) modulation with 1 MHz bandwidth. The two broader peaks with an offset of 5 MHz from the center frequency are caused by a Binary Offset Carrier (BOC) signal of the Restricted Service with a bandwidth of 2 MHz. Sidelobes of that signal are visible at the center frequency ±15 MHz and ±25 MHz.

For the L1 band, a Synthesized Binary Offset Carrier (SBOC) is used. It consists of two BOC signals with 1 MHz bandwidth and offsets of 1 MHz and 6 MHz, respectively. The two mainlobes of the BOC (1,1) component are visible at 1575.42±1 MHz, and the mainlobes

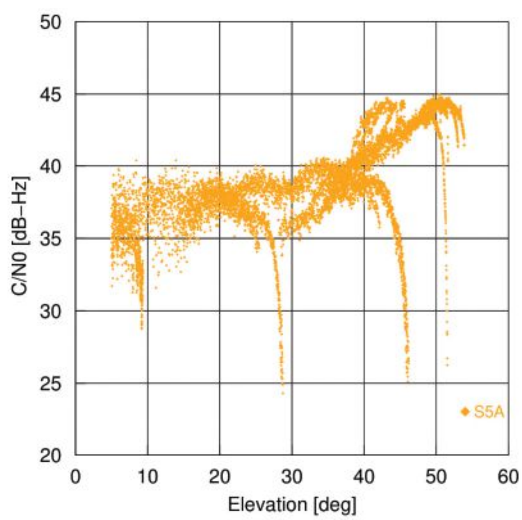


FIGURE 2: Elevation-dependence of the carrier-to-noise density ratio of the NVS-02 L5 signal at Oberpfaffenhofen, Germany.

of the BOC (6,1) component at 1569 MHz and 1581 MHz. The same type of signals, as in L5, are transmitted on the S-band carrier with a center frequency of 2492.028 MHz. Due to its different location in a less remote area, compared to the 30 m antenna in Weilheim, the 5 m antenna in Oberpfaffenhofen suffers from pronounced interference with other signals in the S band; the most prominent peak can be seen at 2480 MHz, several smaller and sharper peaks over the whole frequency range shown in the lower plot of Figure 3. Possible causes of these interferences are WiFi and civilian and military radiocommunication services.

Although NVS-02's mean orbit height is steadily decreasing due to the atmospheric drag around the perigee, the satellite will stay in orbit for at least a decade. However, navigation signal transmission might stop at any time due to operational constraints or unfavorable conditions in the non-nominal orbit. ◍

MANUFACTURERS

GNSS data in this article was collected with JAVAD and Septentrio PolaRx5 GNSS receivers. The spectral overviews were captured with a Rohde & Schwarz FSQ26 signal analyzer and an Aaronia Spectran V6 spectrum analyzer.

Peter Steigenberger is senior scientist at the German Space Operations Center of the German Aerospace Center (DLR) where he conducts research in the field of new satellite navigation systems.

Steffen Thoelert is an electrical engineer at DLR's Institute of Communications and Navigation. His research activities focus on signal quality monitoring and satellite payload characterization.

Stefan Hackel is a flight dynamics engineer at DLR's German Space Operations Center, where he works on software development and spacecraft operations.

Further Reading

GPS World (2025) Indian navigation satellite stranded in transfer orbit, *GPS World*, Vol. 36, No. 3, p. 10

ISRO (2022) NavIC Signal in Space ICD for Standard Positioning Service in L1 Frequency, Version 1.0. U.R. RAO Satellite Centre, Indian Space Research Organization, Bangalore, https://www.isro.gov.in/media_isro/pdf/SateliteNavigation/Draft_NavIC_SPS_ICD_L1_Oct_2022.pdf

S. Thoelert, O. Montenbruck, and M. Meurer (2014) IRNSS-1A: signal and clock characterization of the Indian regional navigation system, *GPS Solutions*, Vol. 18, No. 1, pp. 147–152, doi: 10.1007/s10291-013-0351-7

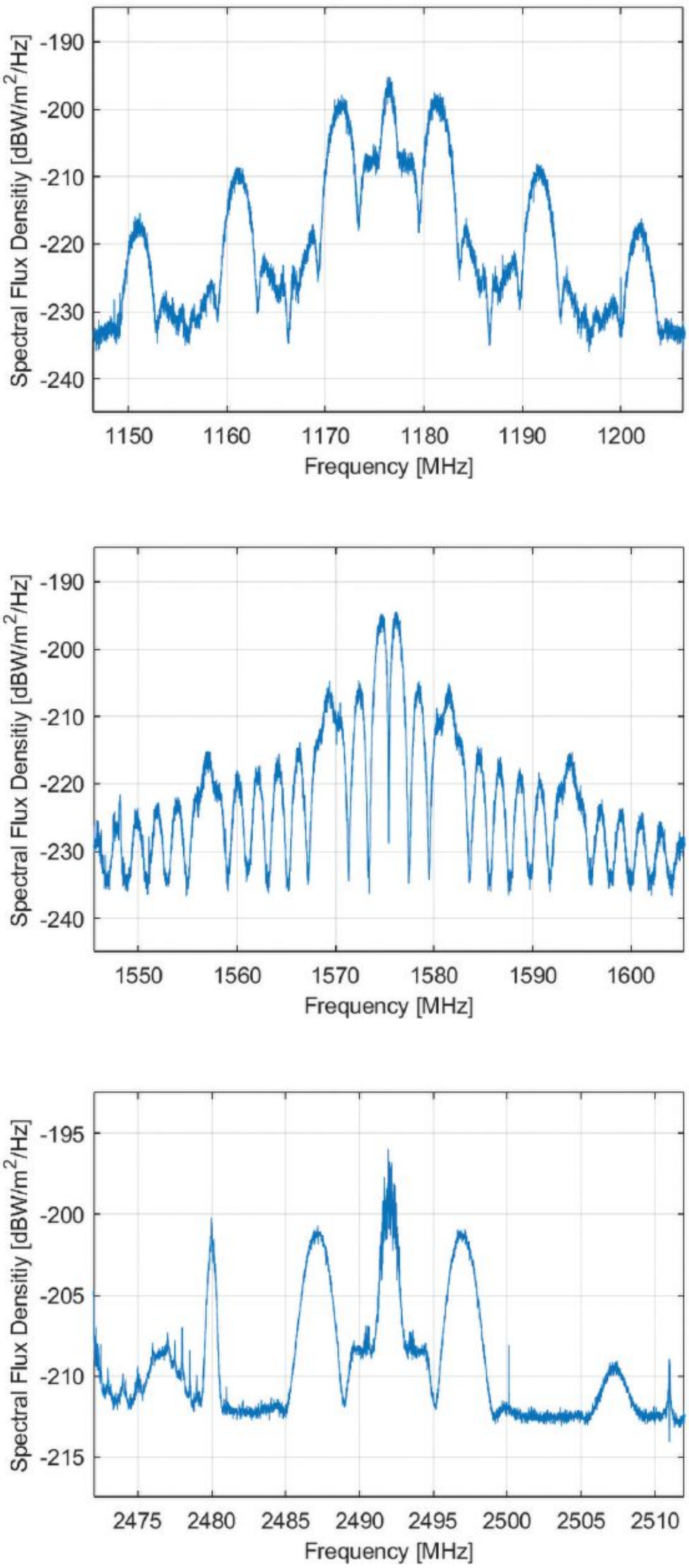


FIGURE 3: Spectral flux density of NVS-02 in the L5 (top), L1 (middle) and S-band (bottom).

DEFENSE

Advanced Navigation Expands US Operations by Recruiting Military Veterans

Advanced Navigation, an Australia-based company, is expanding its presence in the United States by actively recruiting military veterans. The company aims to leverage the unique expertise of former service members to enhance its mission-critical technologies and address the growing demand for assured positioning, navigation and timing (APNT) capabilities across defense, aerospace and critical infrastructure sectors.

Advanced Navigation

Wayne Prender, former U.S. Army captain and head of global defense at Advanced Navigation, believes warfighters-turned-technologists are central to this mission.

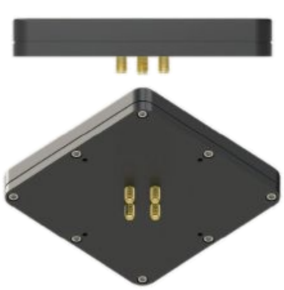
"Veterans bring more than technical expertise; they understand firsthand the urgency and complexities of navigation in contested spaces. Their experience directly informs how we design, test and implement solutions, delivering capabilities that genuinely enhance mission outcomes and warfighter safety," said Prender.

The company recruits veterans with operational backgrounds in submarines, special operations, aviation and electronic warfare to apply their expertise to APNT applications — including unmanned systems, advanced radar, precision strike platforms and secure battlefield communications. Advanced Navigation's veteran-led business development team collaborates closely with system integrators, program offices and military end users to deliver tailored APNT solutions that meet rigorous performance standards.

Inertial Labs Launches Anti-Jamming CRPA System

Inertial Labs, a VIAVI Solutions Inc. company, has introduced the M-AJ-QUATRO anti-jamming antenna system, designed to ensure assured positioning, navigation and timing in GNSS-challenged environments. The system incorporates controlled reception pattern antenna (CRPA) technology and digital processing capabilities, making it suitable for applications ranging from military operations to commercial aviation.

PNT services are increasingly critical for various sectors, including transportation, telecommunications, artificial intelligence, hyperscale data centers, energy, finance and defense. As GNSS jamming and spoofing threats grow, government agencies and industry leaders are working to address these challenges. For instance, the Federal Aviation Administration and Naval Air Warfare Center Aircraft Division are expediting approval processes for CRPA technology to enhance aviation safety and counter GPS interference.



Inertial Labs, a VIAVI Solutions company

The M-AJ-QUATRO supports the L1, L2 and L5 GNSS bands and offers robust interference suppression capabilities. Its adaptive digital nulling feature automatically mitigates jamming signals with over 34dB+ suppression in the export-free version and over 45dB+ suppression in the export-controlled version. Additionally, the system can identify and locate sources of interference through its jammer direction-finding capability, improving situational awareness.

It is compatible with multiple GNSS constellations to provide comprehensive global coverage. It employs dual FPGA-based encryption and anti-spoofing technologies for secure signal processing and data integrity. Built to meet stringent military standards like MIL-STD-810G and MIL-STD-461F, the M-AJ-QUATRO is engineered to withstand extreme conditions, making it an ideal solution for defense and aerospace applications.

SPACE & EARTH

Sergey Kuznetsov / iStock / Getty Images Plus / Getty Images

JAXA Selects Spirent's PNT Simulator for Lunar Navigation Program

The Japan Aerospace Exploration Agency (JAXA) has selected Spirent Communications to supply its lunar positioning, navigation and timing (PNT) simulation solution. The solution will support JAXA's lunar exploration efforts and aid in developing essential navigation infrastructure for future moon missions.

Spirent's PNT X solution allows JAXA to simulate lunar PNT services in a controlled laboratory setting before their deployment on the Moon. This capability is critical for testing and validating navigation equipment for lunar missions in accordance with the emerging LunaNet specifications, which include adaptable S-band frequency solutions. The system also ensures scalability for future space exploration.

Using the PNT X system, JAXA can experiment with novel S-band signals and evaluate the performance of receivers that rely on standalone S-band Lunar PNT signals or a combination of Lunar PNT and Earth-based L-band GNSS infrastructure. The simulation of these signal combinations demands high levels of precision, which Spirent's specialized architecture is designed to meet.

This collaboration builds on a longstanding relationship between Spirent and JAXA. In 2011, JAXA utilized Spirent's simulation technology to verify the performance of early Quasi-Zenith Satellite System (QZSS) receivers. Since then, Spirent simulators have supported multiple advancements in QZSS.

Spirent's lunar PNT simulation solution seeks to present new opportunities for space agencies developing lunar constellations, satellite and receiver developers and organizations planning lunar missions or seeking to establish additional PNT infrastructure on the Moon.

AUTONOMOUS SOLUTIONS

Saildrone USV Demonstrates GPS-Jamming Resilience in Middle East

Saildrone has equipped its Voyager platform with new hardware and software algorithms, allowing it to operate in areas affected by GPS jamming and spoofing.

The company successfully demonstrated these capabilities in the Middle East, showcasing its ability to function autonomously in GPS-denied environments. According to Saildrone, the tests addressed challenges posed by regional electronic warfare tactics, such as jamming and spoofing, which have disrupted unmanned systems in contested maritime zones.

US Navy Photo by Chief Petty Officer Arif Patani

A Saildrone Voyager USV equipped with hardware and software to operate in a GPS-denied environment at sea during IMX 2025.

Task Force 59, established by the U.S. Navy in 2021 under NAVCENT and the Fifth Fleet, has been instrumental in integrating unmanned systems and artificial intelligence into fleet operations. Saildrone engineers developed a localization solution that does not rely solely on satellite navigation, offering seamless operation even in denied environments. This capability was demonstrated during IMX 2025, where Saildrone's Voyager platform was the sole unmanned vessel capable of persistent surveillance under such conditions.

Saildrone USVs are actively conducting wide-area surveillance across the CENTCOM area of responsibility, enhancing maritime domain awareness and supporting U.S. Navy operations. These efforts align with Operation Prosperity Guardian, which has been safeguarding commercial shipping and countering regional threats since December 2023.

Saildrone is now in its fourth year of collaboration with the U.S. Navy. Its unmanned surface vehicles are deployed across various regions, including the Middle East, Atlantic, Caribbean and Pacific Oceans.

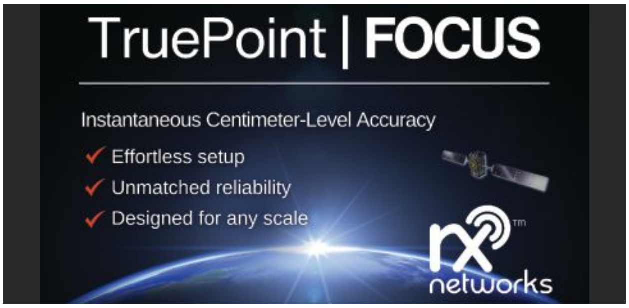
Rx Networks Launches GNSS Correction Service

Rx Networks has introduced TruePoint | FOCUS, a high-precision, cloud-based GNSS correction service that offers instantaneous centimeter-level accuracy for a variety of applications. This service is designed to address the needs of industries requiring real-time precision, such as micro-mobility, smart agriculture, robotics, UAVs, IoT and machine control.

TruePoint | FOCUS supports both real-time kinematic (RTK) and PPP-RTK modes to offer flexibility and high performance. The RTK mode is hardware-agnostic, ensuring compatibility with any RTK-enabled GNSS receiver. It uses standard correction protocols like RTCM v3 and supports access via NTRIP for seamless integration and rapid deployment. The PPP-RTK mode leverages state space representation to deliver high-accuracy positioning with optimized bandwidth usage. This mode combines the benefits of global coverage from PPP with the fast convergence times of RTK, making it suitable for applications requiring seamless operation over large areas.

The service is notable for its ability to process more GNSS signals than many competing solutions, enhancing its resilience and performance in challenging environments. It supports signals from GPS, Galileo and BeiDou constellations, offering comprehensive correction capabilities. According to the company, TruePoint | FOCUS guarantees consistent centimeter-level accuracy with a 99.9% service level agreement, ensuring reliability for users operating in regions such as North America, Europe and China.

TruePoint | FOCUS is available for trial in both RTK and PPP-RTK modes across covered regions, with plans to expand its geographic reach. Interested users can request a complimentary 30-day trial license to evaluate the service.



Rx Networks

GPS WORLD
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- The Future of Farming: Affordable Precision with GEODNET's RTK Network, sponsored by GEODNET
- AI and PNT: Driving Innovation, Safety, and Compliance in Autonomous Systems, sponsored by Safran Electronics & Defense
- The Path to Resilient GNSS: Anti-Jamming Solutions from Antenna to Receiver, sponsored by Calian
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AUTONOMOUS SOLUTIONS

Swift Navigation Expands RTK Positioning Across Western Europe

Swift Navigation's Skylark Precise Positioning Service now offers continuous 2-cm accuracy across Western Europe, enabling the deployment of reliable consumer robots and digital mapping solutions.

Autonomous robots and field mapping applications require precise positioning to operate efficiently; traditional RTK solutions can often struggle, forcing robotics manufacturers to use local base stations or fragmented networks, which can lead to coverage gaps and inconsistent performance. Field teams in utilities and construction also require survey-grade accuracy.

Skylark addresses these issues by delivering accuracy across geographic areas, eliminating the need for base stations or switching between providers. It uses a proprietary atmospheric model that compensates for ionospheric and tropospheric effects in real time. The carrier-grade network, operated by mobile network providers, ensures regional reliability.

Skylark is available in three variants — Nx RTK, Cx and Dx — designed to meet varying requirements for accuracy, power consumption, data transmission and cost. The Skylark Nx RTK delivers 1-to-2-cm accuracy across 28 Western and seven Eastern European countries. Compatible with standard RTK receivers and supported by portals for credential management, licensing and usage analytics, Skylark Nx RTK integrates high-precision positioning into existing devices and workflows.

Swift Navigation

MACHINE CONTROL

Trimble, PTx Trimble Enhance Ag Precision with IonoGuard


Trimble

Trimble and PTx Trimble have introduced Trimble IonoGuard, a new technology designed to enhance RTK GNSS signal reliability for precision agriculture applications. The system aims to improve positioning accuracy and reduce signal loss during challenging ionospheric conditions.

IonoGuard is now available for users of the PTx Trimble NAV-900 guidance controller and Trimble base stations equipped with the ProPoint positioning engine. The technology was developed to maintain RTK correction integrity and minimize positioning dropouts during periods of high solar activity.

Solar activity peaks every 11 years, with the next maximum predicted in 2025. This phenomenon can significantly impact GNSS signal stability, potentially affecting precision positioning. Solar Cycle 25, which began in 2024 and is expected to continue through 2026, may present substantial challenges with the possibility of global disruptions. While solar cycle disturbances often go unnoticed by the public, high-precision RTK GNSS users in equatorial regions frequently experience impacts from solar activity throughout the year, which can lead to costly interruptions in agricultural operations.

IonoGuard is accessible through the latest PTx Trimble Precision-IQ firmware release. When used with compatible GNSS hardware, the system aims to deliver improved RTK performance during both routine operations and periods of solar disturbance.

EVOLUTION

THE USE AND PROMISE OF AI IN GNSS PNT

BY SUNIL BISNATH

ESSENCE

Artificial intelligence (AI) has become part of the daily lexicon, and an endless stream of media reports assert that AI either has affected or will affect most aspects of human life. What is AI and what are its components? How is it being used in GNSS technology? What is the near-term potential of AI in GNSS/PNT? These are weighty, evolving questions for which this column attempts an initial synthesis.

AI definitions and descriptions vary widely. One general and broad definition from IBM (2025) is "Artificial intelligence (AI) is technology that enables computers and machines to simulate human learning, comprehension, problem solving, decision-making, creativity and autonomy." The idea of thinking machines (Turing, 1950) and the term "artificial intelligence" were introduced in the 1950s (McCarthy, 2007). The 1960s and 1970s saw the development of neural networks. The 1980s brought advances in neural network training and deep learning. The 1990s saw rapid advances in computing power. Big data and cloud computing developments in the 2000s allowed for the management and analysis of large datasets. The 2010s brought deep neural networks/deep learning, and the 2020s have seen the introduction and flourishing of large language models.

This column primarily focuses on the impacts that AI is directly having and could potentially have on GNSS hardware and PNT solutions, including receiver signal acquisition, measurement processing, position estimation, integrity and mitigation of jamming and spoofing. Due to space limitations, it will limit discussion to topics such as GNSS-based sensor fusion, navigation system routing, application-specific customizations, etc., all of which are undergoing significant AI-related infusions. A suitable guide to consider is the list of tasks for which evolving AI approaches can outperform existing methods in meaningful and efficient ways. For example, in error modeling or optimal estimation, can AI-based techniques fill gaps in non- or only partially-deterministic processes?

> To investigate the current and potential uses of AI in GNSS, it is essential to define its components, especially as some terms are misused or conflated.

ESSENTIALS

To investigate the current and potential uses of AI in GNSS, it is essential to define its components, especially as some terms are misused or conflated. The presented description is based on a wealth of Internet-based information, including from IBM (2025). **Figure 1** illustrates the current broad concepts within, or subsets of, AI based on a synthesis of nomenclature used. In the figure, AI — defined here as a machine that exhibits human-like intelligence — is the superset. Within AI, there are many concepts or subsets that can be categorized, though they can overlap. There is perception intelligence, such as text and space recognition, and there is the broad area of machine learning.

Sophisticated processes have been developed and continue to rapidly evolve to give machines the ability to sense, learn and make decisions. *Natural language processing* (NLP) allows machines to recognize, understand and generate text following human language. *Voice recognition* is similar, in that the machine transcribes speech to text and back. *Computer vision* enables machines to interpret and analyze imagery. While *robotics* is a field of its own, within the superset of AI, it can be seen as an application of AI to motion. *Planning* refers to autonomously solving planning and scheduling problems. And *expert system* is the field of AI dedicated to simulating human expertise, judgment and behavior. All of these AI subsets are typically enhanced with *machine learning* (ML).

ML involves the development of algorithms and statistical models that can infer patterns (i.e., learn) from existing data without explicit instructions (i.e., rote training) and apply this knowledge to new data. Based on the learning approach, there are four types of machine learning algorithms: supervised, semi-supervised, unsupervised and reinforcement. (ML can also be classified by functionality.) *Supervised learning* uses manually labeled datasets to accurately train algorithms to classify data or predict outcomes. In *semi-supervised learning* and *unsupervised learning*, relationships are found with less or no explicit human interaction, respectively. *Reinforcement learning* combines these approaches with goal optimization. There are many types of ML techniques/algorithms, such as linear regression, logistic regression, decision trees, random forest, support vector machines, k-nearest neighbor and clustering, each designed for different types of problems and data.

Neural networks (NNs) or artificial neural networks are modeled after the human brain. A neural network model contains a given input layer and output layer, each with a set of nodes. These layers and nodes are interconnected with a set of hidden layers of nodes, with each node having a weight and bias, determined (i.e., estimated) based on the specified network inputs and outputs by utilizing one of a selection of optimization techniques. NNs can work well for tasks that involve identifying complex patterns and relationships given large amounts of data, though the details of specific parameter interrelationships cannot necessarily be determined by such models — therefore sometimes referred to as "black box" models. There are several types of neural networks, including convolutional NNs, long short-term memory networks, autoencoders, recurrent NNs, transformers, etc.

Deep learning refers to the depth of layers in a neural network. A deep learning model neural network contains at least three, but typically hundreds of hidden layers. Having many layers allows for unsupervised, fast and accurate identification of complex patterns and relationships. *Generative AI* can be described as deep learning models that generate new/original content, e.g., text, image or audio data through a variety of training, tuning and generation processes. Finally, *large language models* can read, understand and generate human language (refer to NLP), making use of all the functionality of ML.

ELEMENTS

How machine learning is used in GNSS

So, when should AI be used in GNSS/PNT tasks? A rudimentary answer is whenever AI can perform better (in some specified and measurable sense) than existing methods. The determination of this answer for a particular scenario requires research. From the descriptions of AI and its subsets, GNSS/PNT output is used in myriad AI applications such as sensor fusion, autonomous vehicle navigation, route planning, etc. However, it is primarily the ML subset of AI that is being researched for use in GNSS signal and measurement processing.

ML models can be categorized by their fundamental

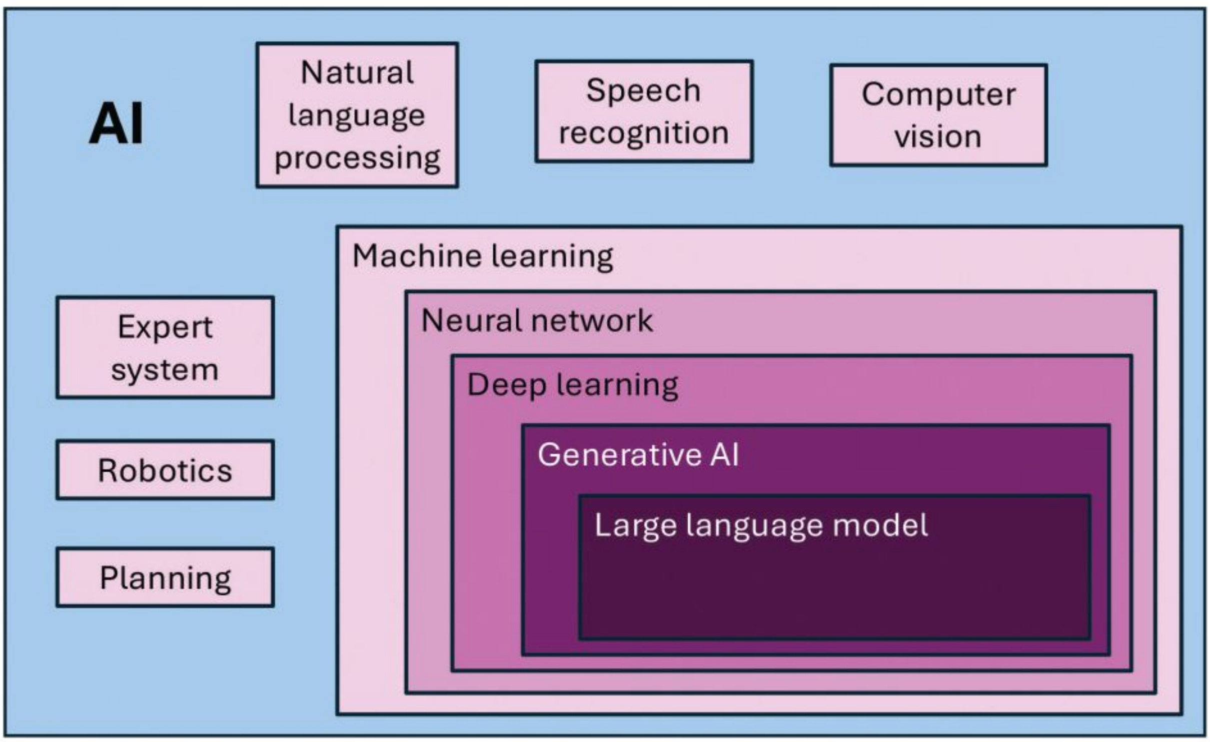

FIGURE 1 **Concepts within/subsets of AI.**

methodology, as either generative or discriminative, or by the tasks for which they are used: either regression or classification (IBM, 2025). Generative algorithms model the distribution of data points with the goal of predicting the joint probability of a data point appearing in a particular space, whereas discriminative algorithms model the boundaries between classes of data with the goal of predicting the conditional probability of a given data point being in a specific class. Regression models predict continuous values and are mainly used to determine the relationship between one or more independent variables and a dependent variable, whereas classification models predict discrete values and are mainly used to determine a category or class, e.g., binary or multi-class.

Siemuri et al. (2022) provide a comprehensive review of recent research (from 2020 through 2021) in which ML techniques are used in GNSS problem solving and provide a categorization of GNSS use cases. Relevant key findings include: 1) ML is proposed to increase GNSS/PNT robustness under degraded signal environments; 2) more than 200 studies were assessed; 3) in most cases, the ML approaches outperformed (at varying levels of significance) the traditional GNSS models; and 4) industry adoption of ML in GNSS so far appears limited. The analysis found that neural networks were used in more than half of the studies (55%) — including some deep learning, while support vector machine and decision tree/random forest techniques were used in 19% and 10% of the studies, respectively. Use cases for machine learning in GNSS were categorized as: i) signal acquisition; ii) signal detection and classification; iii) Earth observation and monitoring; iv) navigation and positioning; v) denied environments and indoor navigation; vi) atmospheric effects; vii) spoofing and jamming; viii) GNSS/inertial integration; ix) satellite selection; and x) LEO satellite orbit determination and positioning.

So, how is machine learning used in these GNSS/PNT use cases — and in general? How ML is applied can be described as a set of steps or a cycle with a varying number of components. **Figure 2** presents a graphical synthesis from the literature, with a grouping of five core steps.

Step 1 — problem definition: understanding the problem(s) and goals, defining the available data, defining the problem inputs and outputs, determining the category of ML to use and selecting evaluation metrics.

Step 2 — data preparation: collecting the data, editing them, and labeling them if employing supervised classification.

Step 3 — model development: selecting the algorithm, selecting the model, building the model and training the model.

Step 4 — model evaluation: validating the model, tuning the model, analyzing the results, cross-validating the results and applying the evaluation metrics.

Step 5 — model deployment: finalizing the model, applying the model in prediction, and, if necessary, feeding back into the start of the cycle.

The scikit-learn (2025) library is a popular resource for Python-based ML information, tools and examples. An illustrative example of how ML can be used in GNSS for signal classification and measurement weighting is given by Li et al. (2023). The authors describe the process for designing the ML problem-solving scenario, selecting the models that are either of the regression or classification type and comparing the performance of many popular

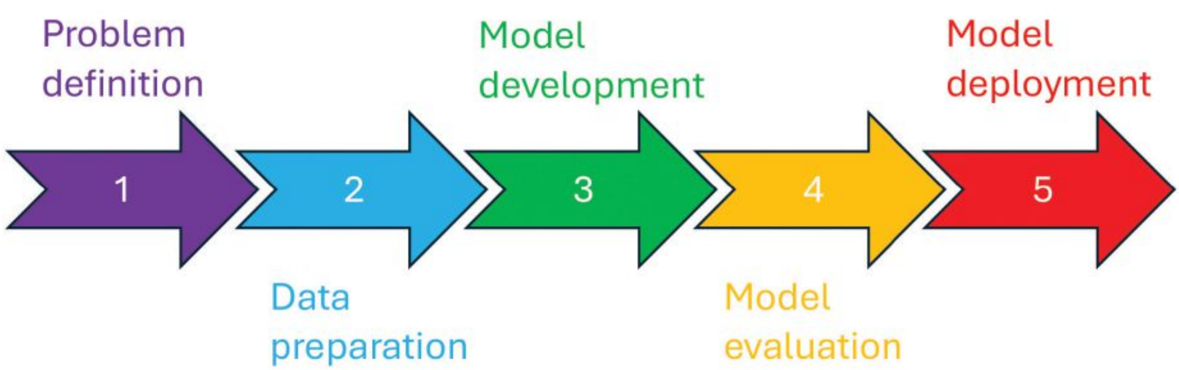

FIGURE 2 **Steps in, or cycle of, machine learning implementation.**

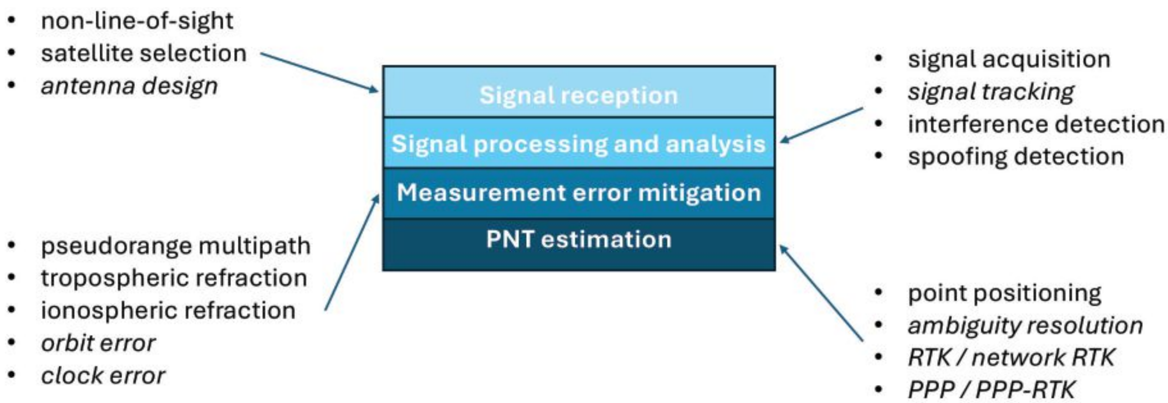

FIGURE 3 Application themes of machine learning in GNSS with initially studied and potential research areas.

ML models to detect direct line-of-sight versus non-line-of-sight and multipath signals in urban environments. Note that most applications of machine learning in GNSS involve some form of supervised classification.

Initial and potential machine learning uses in GNSS

For this column, a brief synopsis is given of the use of machine learning in GNSS in the context of the application themes of signal reception, signal processing, measurement error mitigation and PNT estimation, as illustrated in **Figure 3**. Correspondingly, potential ML uses are also considered.

Signal reception

Studies including Tsu (2017) and Li et al. (2023) have used various machine learning models to differentiate between line-of-sight, non-line-of-sight and pseudorange multipath GNSS signals in urban environments. Various input features, such as signal strength, are used to train models, resulting in majority accurate classification. ML has been used to optimize satellite selection (rather than using all available tracked satellites) for efficient PNT processing. Radio frequency hardware and software simulators can use ML to improve the realism of propagated signals in various environments and under different dynamics, including multipath, interference and spoofing. There is also the potential for ML to be used to improve antenna design, including for controlled radiation pattern antennas that generate one or multiple nulls.

Signal processing and analysis

Deep learning models have been used for signal acquisition and show improvement over current methods with simulated data (Borhani-Darian et al., 2023). There may be potential for the use of ML in signal tracking or in the design of new tracking algorithms and processes. Studies have shown that ML can be used to detect natural and intentional radio frequency interference. Various ML models have successfully been used to produce accurate classification of radio frequency interference jammer types (e.g., Morales Ferre et al., 2019). ML has also been used to detect signal spoofing with simulated and real signals with high levels of validation (e.g., Semanjski et al., 2020).

Measurement error mitigation

As GNSS multipath is a non-deterministic (and non-zero mean) process, it is a strong candidate for machine learning-based mitigation, especially meter-level pseudorange multipath (compared to centimeter-level carrier-phase multipath). Such studies, combined with non-line-of-sight classification, have been described in the previous section.

Initial investigations of the use of machine learning in the mitigation of tropospheric refraction appear promising (e.g., Łoś, et al., 2020). The wet tropospheric delay on GNSS signals is irregular, making it difficult to predict. Therefore, there is great potential for improved anomaly detection, refraction modeling and more accurate severe weather nowcasting.

As with tropospheric refraction, ionospheric refraction, while well understood, is difficult to model accurately, especially during periods of high solar activity. Machine learning has been shown to accurately detect anomalies and scintillation (e.g., Linty et al., 2018) and potentially for nowcasting.

There is the potential to improve GNSS satellite orbit and clock estimation with ML, as these are both well-defined processes, but also contain levels of process uncertainty. For example, it is usual to include once-per-orbital revolution empirical accelerations in orbit estimation states, and satellite force models can always be improved. Consequently, ML studies may aid in such GNSS network processing to improve the accuracy of real-time and post-processed correction products.

PNT estimation

Well-established optimal estimation techniques such as least-squares and Kalman filtering work extremely well for most GNSS/PNT estimation cases. However, hardware limitations and environmental conditions can lead to measurements not meeting the technical assumptions of these conventional approaches, e.g., the use of independent measurements, the absence of systematic errors, the absence of gross errors, the use of realistic measurement variances, etc. Deep learning models have the potential to improve GNSS point positioning (e.g., Kanhere et al., 2022) in test data, if poor model numerical conditioning, changing satellite visibility and model overfitting are managed. There is potential research in the use of machine learning methods to improve carrier-phase ambiguity resolution, and in the centimeter-level positioning techniques of real-time kinematic (RTK)/network RTK, and precise point positioning (PPP)/PPP-RTK.

Broader AI/ML use within GNSS-based PNT

Clearly, GNSS/PNT outputs are used in a broad spectrum of applications, for which AI and ML are currently being used or have the potential of being used to attain and enhance goals. Machine learning has been used to improve GNSS-derived position time series analysis for many Earth science applications, including in plate tectonics, tsunami monitoring, vulcanology, subsidence monitor, GNSS reference station monitoring, overall measurement integrity, etc. and in diverse GNSS-enabled techniques such as radio occultation and reflectometry (Siemuri et al., 2022).

ML has the potential to allow for improvements in sensor fusion, chief amongst these being GNSS/inertial measurement unit (IMU) integration. Improvements can be found in IMU calibration and in managing functional and dynamic mismodeling for specific user applications. Wider, multi-sensor fusion, such as for simultaneous location and mapping solutions, rely heavily on ML approaches, such as reinforcement learning.

Finally, GNSS-based PNT is used in most of the non-ML subsets of AI. GNSS-based position information is central to many outdoor robotics, planning and computer vision algorithms, providing either seeding localization information for other sensors or processes, or core position information for the overall AI-driven system.

RESOURCE CONSIDERATION
Applicability / reliability
Significance of improvement
Data availability
Data storage
Computing power
Equipment and electrical power budgets
Hardware and software implementation

TABLE 1 **Resource considerations for machine learning use in GNSS.**

Machine learning resource considerations

As with all technology, a cost/benefit analysis is required when considering the application of ML in a specific GNSS use case. **Table 1** summarizes the broad considerations. Can the problem at hand be reliability mitigated with ML, in the sense that there are complexities that are difficult or impossible to physically model, but sufficient patterns in the data to be modeled by ML? If ML can outperform a conventional approach using specified metrics, is the improvement significant to the user? Are there large enough, i.e., sufficient and varied, datasets to train a model for prediction over expected data variations? As most ML algorithms require large amounts of computing storage for large datasets, typically from data servers, can the necessary computing power be brought to bear? Similarly, given that most ML algorithms require large amounts of computing power for myriad computational operations, typically utilizing graphics processing units (GPUs), is such computing power available? As storage servers for large datasets and GPUs for processing are expensive and require large amounts of electrical power, are the financial and electrical power, environmental and security resources available? And finally, how practical is it to implement the ML model on user equipment or via servers?

EVOLUTIONARY

AI is a broad field that is rapidly developing and entering service in most technologies. While AI includes many subsets such as computer vision, natural language processing and robotics, the ML subset (which includes neural networks, deep learning and generative AI) has the most direct applicability to GNSS/PNT. Of the available ML models used in GNSS, most are supervised (i.e., they use labeled training data), and the majority use neural networks. Initial studies of applications such as signal classification and interference detection indicate that supervised ML models perform better than traditional approaches.

Many subsets of AI, such as computer vision and robotics, rely heavily on ML, while GNSS/PNT has only recently seen investigations in ML use. For many applications, it can be that conventional deterministic models, physics-based models or optimal estimation techniques work well and reach desired performance standards. However, as GNSS/PNT continues to trend to lower cost hardware, harsher environmental conditions and increasing safety-of-life usage, PNT outliers and corner cases grow in importance, and ML can potentially provide solutions, as outlined in **Figure 3**. These are the early days of investigating and applying ML in GNSS/PNT. To use ML or not to use ML — that is the question. There are many factors to consider, as described in Table 1. Performance improvements over current approaches and operational practicality (i.e., costs) will dictate ML adoption. Much more research is required in many GNSS/PNT applications, followed by significant widespread testing and tuning of developed ML models. It is difficult not to predict the near-term adoption of ML in at least some GNSS/PNT use cases, if they will benefit our daily lives. Look for future columns that will examine and investigate ML implementations in specific GNSS/PNT applications that prove its efficacy.

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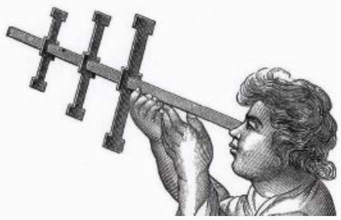

FREE NAVIGATION HISTORY COURSE

Harvard University offers *PredictionX: Lost Without Longitude,* a free online course that examines the evolution of navigation from ancient methods to modern technologies. The program explores the science and history of navigation, focusing on the challenges of determining longitude before GPS existed. It highlights key advancements, such as John Harrison's marine chronometer and the Longitude Prize. Through multimedia content — including videos, infographics and Worldwide Telescope tours — the course is designed to demonstrate how centuries of advancement in navigation enabled humanity to achieve milestones such as landing on the moon.

SELF-DRIVING CARS COLLECT GEOSPATIAL DATA

In Finland, self-driving cars are being used to collect geospatial data to address urban challenges. The ARVO autonomous vehicle from the Finnish Geospatial Research Institute is equipped with high-precision sensors that map its environment in real-time, collecting information on road conditions, urban vegetation as carbon sinks and factors influencing flood risks. In partnership with Aalto University and funded by the European Regional Development Fund, this initiative seeks to explore various uses of this data, such as city planning, environmental monitoring and infrastructure management.

STOPPING SCAMMERS

Google has taken legal action against a network of scammers responsible for creating more than 10,000 fake business listings on Google Maps. The scammers fabricated profiles targeting urgent service industries and bolstered them with fake reviews to appear credible. Victims were misled into contacting these fake businesses, which then sold their personal information as "leads" to legitimate service providers without consent. Google has removed the fake listings and is suing individuals involved in the scheme, *CBS News* reported.

MAPPING UGANDA'S DISAPPEARING TROPICAL GLACIERS

Project Pressure, in collaboration with UNESCO and the Uganda Wildlife Authority, conducted an expedition to the Rwenzori Mountains to map the region's disappearing tropical glaciers. The team created the first 3D model of Mt. Stanley's glaciers and installed monitoring equipment, revealing that Mt. Speke and Mt. Baker have lost their glaciers entirely, while the Stanley Plateau Glacier has shrunk by 29.5% since 2020 and is heavily fragmented. The project aims to continue monitoring the glacial retreat, develop mitigation strategies and engage the local community in ongoing research.

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