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EVOLUTION

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FEBRUARY 2025 | Vol 36 | No 2
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CONTENTS

VOL. 36 NO. 2 GPSWORLD.COM

FEBRUARY 2025

ComNav Technology

COVER STORY

24 MACHINE CONTROL

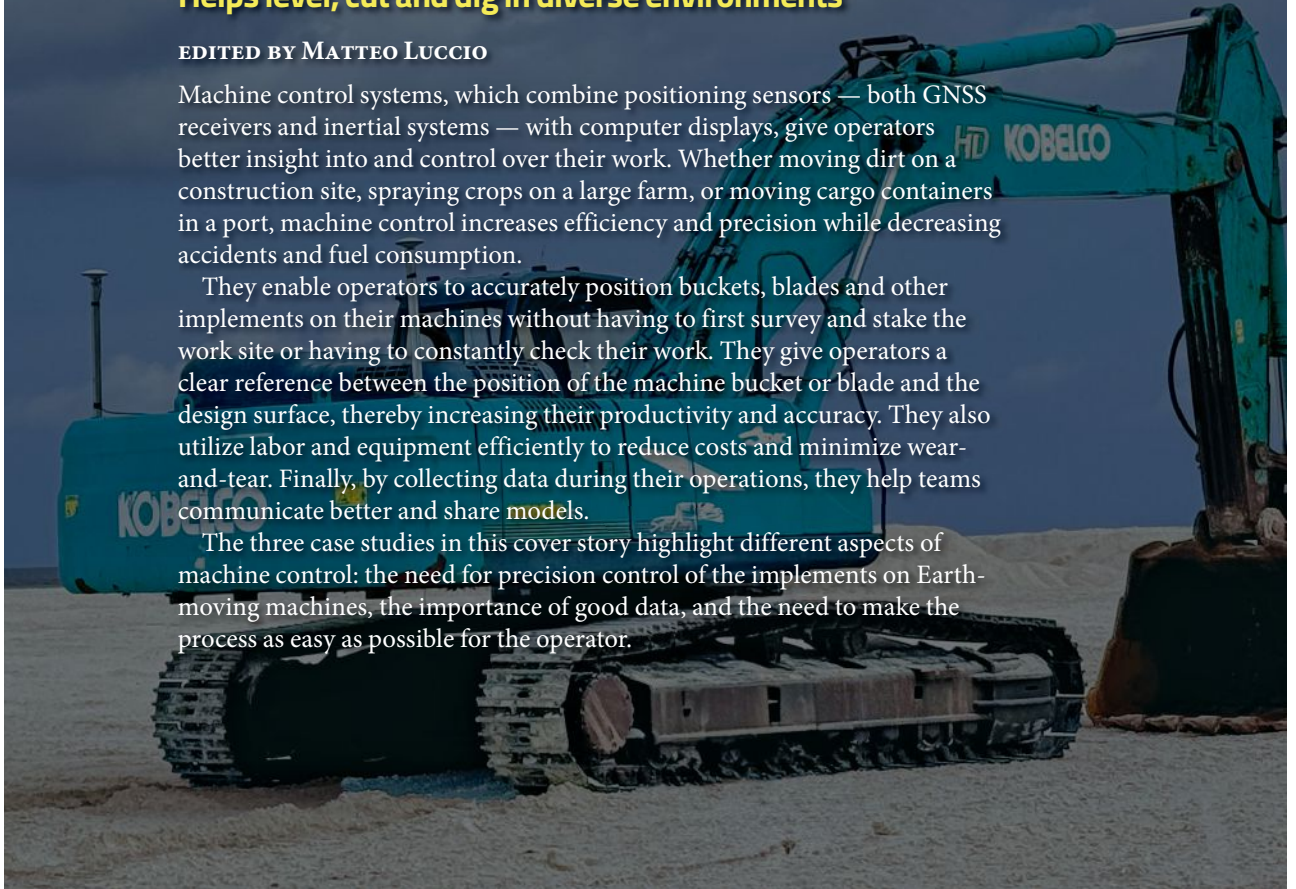
Helps level, cut and dig in diverse environments

EDITED BY MATTEO LUCCIO

Machine control systems, which combine positioning sensors — both GNSS receivers and inertial systems — with computer displays, give operators better insight into and control over their work. Whether moving dirt on a construction site, spraying crops on a large farm, or moving cargo containers in a port, machine control increases efficiency and precision while decreasing accidents and fuel consumption.

They enable operators to accurately position buckets, blades and other implements on their machines without having to first survey and stake the work site or having to constantly check their work. They give operators a clear reference between the position of the machine bucket or blade and the design surface, thereby increasing their productivity and accuracy. They also utilize labor and equipment efficiently to reduce costs and minimize wear-and-tear. Finally, by collecting data during their operations, they help teams communicate better and share models.

The three case studies in this cover story highlight different aspects of machine control: the need for precision control of the implements on Earth-moving machines, the importance of good data, and the need to make the process as easy as possible for the operator.



EVOLUTION

35 The Evolution of Precise Point Positioning

BY SUNIL BISNATH

ON THE COVER

Leica Geosystems' alpine machine control solution is used in partnership with Prinoth's snow groomers to prepare ski resorts and snow parks for the next ski seasons. This solution measures and visualizes snow depths on the snow groomer's display using a digital terrain model created from bare summer terrain without snow. (Credit: Leica Geosystems)

SPECIAL SECTION

20 Mapping the Flames

GIS technology plays crucial role in wildfire management and response

BY JESSE KHALIL & MATTEO LUCCIO

OPINIONS AND DEPARTMENTS

5 FIRST FIX

Freeing CRPAs

BY MATTEO LUCCIO

6 EAB PNT Q&A

When we discuss the security of GNSS/PNT systems, we nearly always focus on interference — i.e., meaconing, intrusion, jamming or spoofing. However, GNSS/PNT systems are embedded in systems of systems that also offer many other opportunities for cyberattacks. What should we do about it?

WITH ELLEN HALL & MITCH NARINS

7 UPCOMING EVENTS

2025 Conferences and Trade Shows

10 SYSTEM OF SYSTEMS

GPS III SV-07 Becomes Operational - L3Harris Selected to Design Resilient GPS Satellites - Galileo Gets Emergency Alert System Upgrade

17 INSIDE THE BOX

What's Going on with These UAV Sightings?

BY TONY MURFIN

41 AD INDEX

42 SEEN & HEARD

Autonomous Vessel Completes Sea Trials in Norway - ESA in Search of Very Low-Earth Orbit Technologies - Car Tracking Leads to Successful Arrest - 3D Mapping of New Zealand Coastline

LAUNCHPAD

12 OEM

14 UAV

15 SURVEYING

16 TRANSPORTATION

16 MACHINE CONTROL

MARKETWATCH

30 AUTONOMOUS SOLUTIONS

31 DEFENSE

32 MACHINE CONTROL

33 SPACE & EARTH

ONLINENOW

NEWSLETTER EXCERPT



NGS to Release Components of the Modernized NSRS in 2025

BY DAVID B. ZILKOSKI
CONTRIBUTING EDITOR, SURVEY SCENE

The modernization of the National Spatial Reference System (NSRS) is scheduled to occur in 2025/2026.

National Geodetic Survey (NGS) intends to release associated tools and services within five years of the modernization. The following details from the Federal Register outline the process for the rollout of the modernized NSRS:

- NGS plans to roll out components of the modernized NSRS in 2025 or 2026. As each component is released at beta.ngs.noaa.gov, it can be publicly tested with feedback provided to NGS. The testing will continue for at least six months after the final component is released on beta.ngs.noaa.gov.

While the modernized NSRS is being rolled out and tested, the current NSRS will remain the official NSRS of the United States. Only one major improvement to the current NSRS is expected during this time: ITRF2020 will be integrated into all products and services.

Once testing is complete and all modernized NSRS components appear stable and correct, the Federal Geodetic Control Subcommittee will be asked to vote to approve the modernized NSRS. 🗳️

Read the full column at gpsworld.com/category/opinions/.

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Published monthly



Freeing CRPAs

DDTC has dropped CRPAs from ITAR! What does that mean and why does it matter?

Controlled Reception Pattern Antennas (CRPAs, pronounced “serpers”) are still the single most effective counter to the threat to GNSS from jamming and spoofing — a growing problem in and near conflict areas, such as Ukraine and the Middle East. CRPAs, which make use of the fact that the desired satellite signals and the unwanted jamming signals generally arrive from different directions, reduce the effective range of jammers by up to five orders of magnitude. They are attractive because they replace existing antennas on GNSS receivers without requiring any other changes — though they are generally larger than typical GPS antennas because they contain several antenna elements and some associated electronics.

Beginning on Sept. 15, 2025, CRPAs will no longer be covered by the International Traffic in Arms Regulations (ITAR), which prohibit the sale outside of the United States of defense articles, services and technical data and impose very large penalties for violators. ITAR is managed by the Directorate of Defense Trade Controls (DDTC) in the Bureau of Political-Military Affairs at the U.S. Department of State, which announced the rule change in mid-January. It removes items that “no longer warrant inclusion” from the U.S. Munitions List (USML), which defines the “defense articles” that fall under ITAR jurisdiction. CRPAs for PNT will instead be classified as dual-use commercial items and fall under the Export Administration Regulations list managed by the Department of Commerce. The Directorate removed CRPAs for PNT from the USML because they “no longer provide a critical military advantage, with increasing commercial utilization applicable to civil GPS resiliency” and because the department “intends to facilitate civil global navigation

system resiliency.”

This is a seismic shift that many in the GNSS/PNT community — including the National Space-Based Positioning, Navigation and Timing Advisory Board (PNTAB) — have been advocating for years. While U.S. manufacturers have been prohibited from exporting CRPAs, TUALCOM, a Turkish company based in Ankara, has been selling 4- and 8-element CRPAs for GNSS applications, as have some Canadian companies.

Airlines and manufacturers of autonomous vehicles will be among the early beneficiaries of this policy change, as will many safety-of-life applications. Presumably, the vast expansion in the market for CRPAs also will quickly lead to a sharp drop in their cost.

In a November 2022 presentation to the PNTAB, Brad Parkinson listed the use of CRPAs among the major techniques that can make GPS receivers “virtually immune” to jamming and spoofing, recalling that they were first tested in 1978. However, he pointed out, they had been neglected because they were perceived as too expensive and large for many applications, because of delays in implementing the L5 signal, and because ITAR prohibited beam-steering antennas with more than three elements. He argued that restrictions on GNSS CRPAs were no longer effective at preventing potential enemies of the United States from using them.

Barring a reversal from the new administration, U.S. CRPA manufacturers can now help protect GNSS worldwide from jamming and spoofing. 🌐

Matteo Luccio | EDITOR-IN-CHIEF
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Professor Washington Ochieng proposed the following question

When we discuss the security of GNSS/PNT systems, we nearly always focus on interference — i.e., meaconing, intrusion, jamming or spoofing. However, GNSS/PNT systems are embedded in systems of systems that also offer many other opportunities for cyberattacks. What should we do about it?

“The key is platform architecture, specifically ensuring robust spatial and temporal partitioning between safety-critical and non-safety-critical functions. Safety-critical functions, such as navigation and autopilot, must be isolated from non-safety-critical functions, such as mission compute, where artificial intelligence typically operates. This partitioning minimizes the scope and effort required to produce design assurance artifacts for airworthiness certification. Additionally, it enhances security by reducing potential attack vectors through the isolation of safety-critical and mission-critical capabilities.”



After serving for many years on this board, **Clem Driscoll**, **Greg Turetzky**, **Jean-Marie Sleewaegen**, **Terry Moore**, and **Ellen Hall** have recently resigned, due to changes in their professional lives. I want to express my deep gratitude to them for their contributions to GNSS/PNT and their long-standing support of this magazine. I look forward to still occasionally hearing from them or seeing them at conferences and wish them the best in the next phase of their careers.

Paul McBurney, Co-Founder and CTO of oneNav, has joined the board. I look forward to his contributions to these pages.

— Matteo Luccio, Editor-in-Chief

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Racelogic Ltd.

Rob Van Brunt
Spirent Federal Systems



“An old mariner’s proverb is: ‘The prudent mariner never relies solely on any single aid to navigation.’ A more recent

statement offers: ‘With so many pieces of sophisticated electronic equipment at our beck and call it would seem some are lulled into complacency and are ignoring basic seamanship.’ In September 2018, the U.S. Naval Institute published an article titled, ‘Professional Mariners Cannot Rely on Electronics Alone.’

The recent news that the U.S. ITAR restrictions on multi-element antenna arrays will be lifted (thanks to many in our community who have lobbied hard for this for many, many years) is excellent news. It will help and was a necessary change — but it is not sufficient. It certainly does not remove the need to pursue complementary, PNT solutions that will ensure the safety, security, and economic well-being of PNT users and their PNT-dependent systems worldwide. From a basic systems engineering perspective, incorporating multiple solutions with independent failure mechanisms is ultimately the end product that we in the PNT community should all be seeking.

We must not forget, however, a key element of many of these systems: the human in the loop, who, if continually provided the opportunity to train in PNT-challenged environments, often can be the ultimate system safety element. This will require the design of our PNT services to ensure that the human factors designed into these systems include sufficient information for the human component to understand an off-normal situation and have the training and skills to take the appropriate corrective actions.”

UPCOMING EVENTS

2025 Conferences and Trade Shows

GEO WEEK
Feb. 10-12, Denver



Los Angeles Geospatial Summit
Feb. 28, Los Angeles



AUVSI XPONENTIAL
May 19-22, Houston



ION Joint Navigation Conference (JNC)
June 2-5, Greater Cincinnati Area



Hexagon LIVE Global
June 16-19, Las Vegas



Esri User Conference
July 14-18, San Diego



Commercial UAV Expo
Sept. 2-4, Las Vegas



ION GNSS+
Sept. 8-12, Baltimore



INTERGEO
Oct. 7-9
Frankfurt, Germany



Trimble Dimensions User Conference
Nov. 10-12, Las Vegas



Dates and locations are subject to change.

GNSS | CRPA | INERTIAL | JAMMING

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castnav.com

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Safran Electronics & Defense

Empowering Defense Operations with Safran's Precision Timing Solutions

In defense operations, every nanosecond counts in critical detection missions, particularly in missile defense radar and distributed sensor systems. However, ensuring synchronized data exchange with highly-precise time and frequency across vast distances has long been challenging. Safran Electronics & Defense offers innovative navigation & timing solutions to tackle this pressing issue head-on.

The Problem

Missile defense radar and distributed sensor systems often suffer from data synchronization issues due to long distances between components. Traditional methods involving coaxial cables are cumbersome and present scalability issues. Maintaining accurate timing is essential for C5ISR systems to detect and track threats in real time.

The Solution

Safran introduces two groundbreaking solutions: HATI and the Z-Family. HATI, a licensable firmware, seamlessly integrates with existing FPGA designs and distributes time and frequency signals through



standard optical fiber cables. It requires no additional hardware and ensures sub-nanosecond timing accuracy over distances of up to 50 miles. Alternatively, the White Rabbit Z-Family offers dedicated hardware for precise time distribution, implementing the White-Rabbit protocol to ensure high-accuracy timing within Metro Area Network distances and beyond.

Why Choose Safran

- **Easy Integration:** HATI can be installed on existing FPGA or PTP cards, eliminating the need for additional hardware.
- **Versatility:** Compatible with 1GB or 10GB Ethernet links, HATI adapts seamlessly to your existing network infrastructure.
- **Ruggedness:** Dynamic compensation of weather-induced asymmetries ensures reliable performance in any conditions.
- **Accuracy:** Achieve stunning sub-nanosecond resolution for timing synchronization, which is necessary for mission-critical applications.
- **Reliability:** Safran's solutions can manually distribute time and frequency over long distances without requiring amplifiers or frequent calibration.
- **Resiliency:** Incorporating failover mechanisms, our solutions ensure

uninterrupted operation despite timing source failures.

- **Intuitive Management:** A user-friendly web UI, extensive SNMP monitoring and advanced management features streamline operations and maintenance.
- **Advanced Management:** Smart alerts, SNMP monitoring, topology discovery, and comprehensive logging ensure seamless integration with existing network management tools.

HATI sub-nanosecond time sync in phase array antennas also eliminates separate clock cables for each element, cutting costs and weight, and enhancing reliability. This is crucial for large systems with numerous cables.

Conclusion

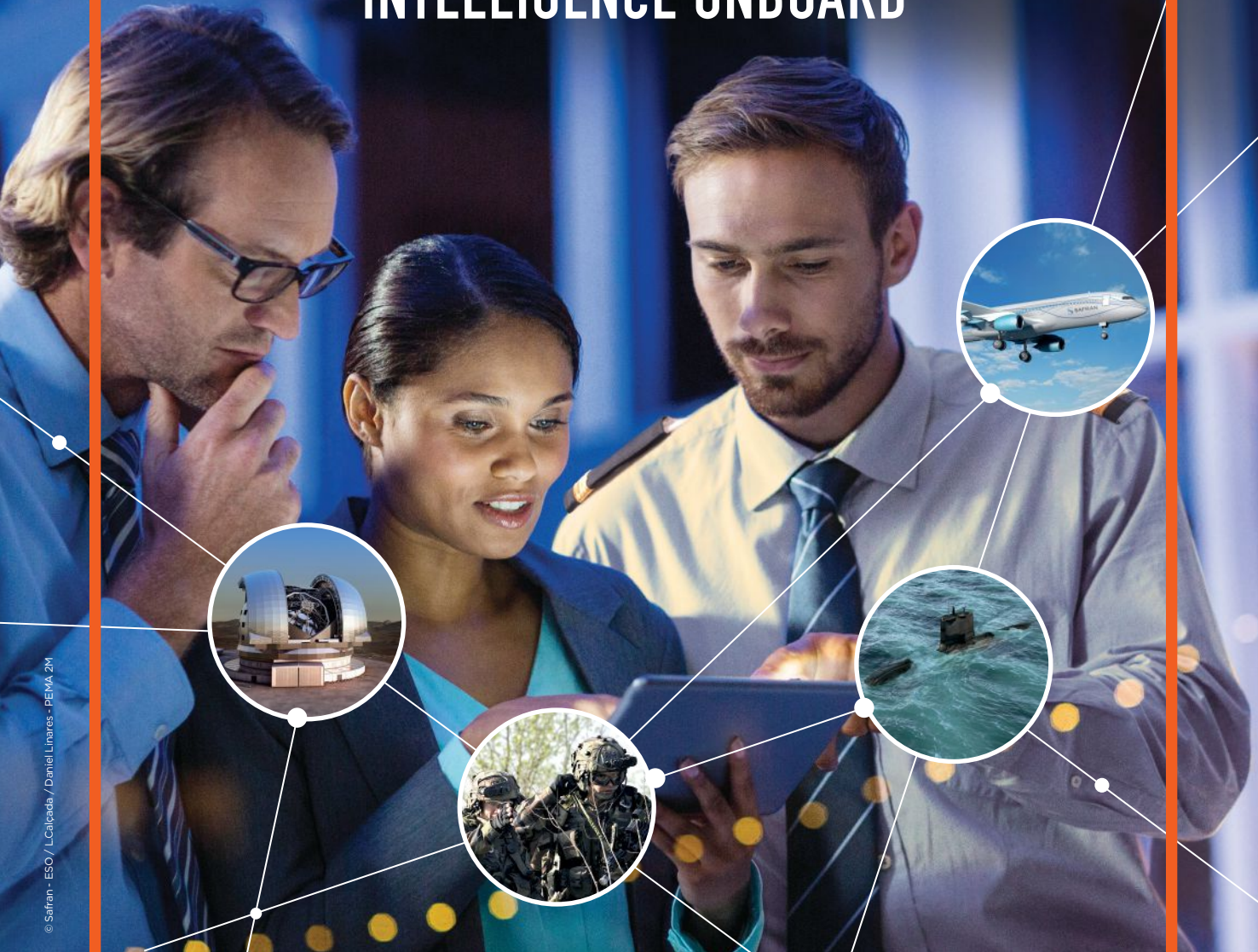
Safran's precision timing solutions modernize defense operations, providing unmatched accuracy, reliability, and versatility. With HATI and the White Rabbit Z-Family, your systems are always synchronized, empowering you to stay ahead of threats in today's dynamic defense landscape. For more information, visit www.safran-navigation-timing.com.



ELECTRONICS & DEFENSE

OBSERVE, DECIDE, GUIDE

INTELLIGENCE ONBOARD



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 **SAFRAN**

SYSTEM OF SYSTEMS

POLICY AND SYSTEM DEVELOPMENTS IN GNSS AND OTHER PNT TECHNOLOGIES



Lockheed Martin

GPS III SV-07 Becomes Operational

The U.S. Space Force transferred Satellite Control Authority of the GPS III Space Vehicle 07 (SV-07) to the 2nd Navigation Warfare Squadron, Mission Delta 31, at Schriever Space Force Base, Colorado. The satellite became operational and available to global users on Jan. 22, 2025 — expanding the GPS constellation to 31 active vehicles. The transfer is the first instance in which the Satellite Control Authority moved from the acquisition program to the operations squadron within a single Delta, reflecting the new mission delta structure.

The GPS III satellite was launched on Dec. 16, 2024, from Cape Canaveral

Space Force Station, Florida, aboard a SpaceX Falcon 9 rocket as part of a

The satellite became operational and available to global users on Jan. 22, 2025 — expanding the GPS constellation to 31 active vehicles.

Rapid Response Trailblazer mission. The operation involved retrieving an existing GPS III satellite from storage, expediting integration and launch vehicle preparation, and swiftly processing the satellite for launch.

The entire process, from initiation to launch, was completed in approximately three months, significantly shorter than the typical six-month pre-launch processing timeline. This accelerated timeline was possible through collaboration between multiple Space Force organizations and partner agencies. The GPS III SV-07 satellite is equipped with M-code, designed to improve anti-jamming and anti-spoofing capabilities, enhancing secure access to military GPS signals. 🌐

L3Harris Selected to Design Resilient GPS Satellites

L3Harris Technologies has received a contract from the U.S. Space Force's SSC to develop design concepts for Phase 0 of the Resilient Global Positioning System (R-GPS) program.

This initiative aims to enhance the existing GPS constellation by integrating cost-effective small satellites, providing increased resilience for both military and civilian users. The R-GPS program seeks to augment the current 31-satellite GPS constellation with up to eight additional satellites. The new satellites are designed to counter various threats, including jamming, spoofing and more, ensuring uninterrupted PNT services.

L3Harris has provided navigation technology for all GPS satellites launched to date. The company has also contributed to the development of control systems, monitoring receivers and user equipment for GPS. This experience serves as the basis for their proposed R-GPS solution.



L3Harris is leveraging its investments in transformational PNT technology to meet the Space Force's evolving requirements by using commercial form factors and interfaces to create a modular, scalable solution, the company said. Additionally, L3Harris is collaborating with the Space Force as the prime contractor for the experimental Navigation Technology Satellite-3 program, which focuses on developing innovative technologies and accelerating development timelines. 🌐

Galileo Gets Emergency Alert System Upgrade

The European Union Agency for the Space Programme (EUSPA) has awarded GMV a framework contract to deliver new Galileo functionalities under the Emergency Alerting System (ERAS). This four-year contract, valued at approximately \$6 million, will enable significant advancements in Europe's disaster response capabilities. The GMV-led consortium includes Ineco, ALTEN Spain and Kinton as subcontractors.

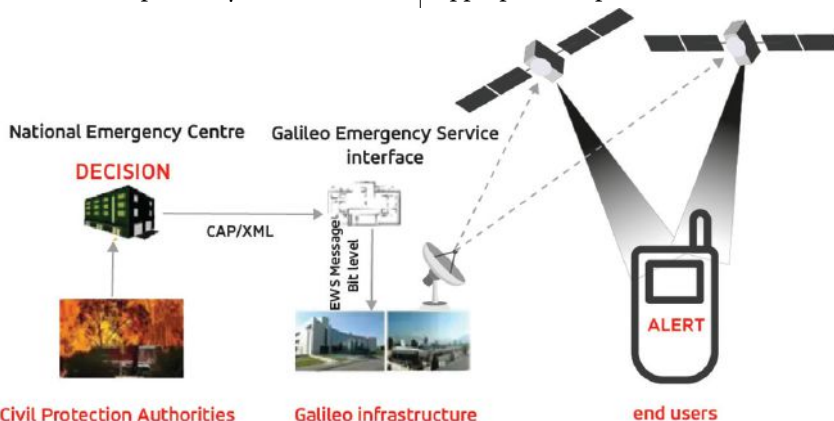
ERAS will primarily allow Member

States' National Civil Protection Authorities to broadcast emergency warning messages directly to populations in at-risk or affected areas. These alerts will be transmitted via Galileo satellites to smartphones and other Galileo-enabled devices. According to EUSPA, the messages will contain crucial information about the hazard, including its type, severity, affected area, expected onset and duration, as well as guidance for appropriate responses.

The Galileo Emergency Warning Satellite Service and ERAS seek to enhance Galileo by offering resilience and complementarity to existing public warning systems, independence from terrestrial and mobile networks, rapid communication with global reach and particular benefits for remote areas with limited mobile coverage.

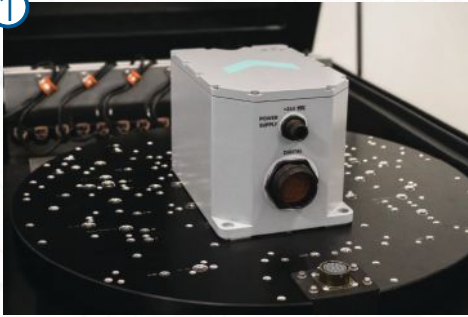
The system is designed to provide a robust and versatile solution for emergency communications, ensuring that critical alerts reach populations even in challenging scenarios. ERAS is expected to be fully operational in the first half of 2026.

The joint use of Galileo ERAS and the Copernicus Emergency Management Service seeks to enhance the European Union's and its Member States' disaster management capabilities. This integration will provide a comprehensive approach to alerting populations about risks such as the recent disasters in Valencia, Spain, and other parts of Europe. 🌐

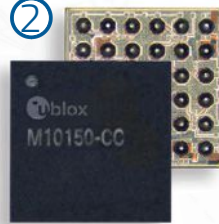


GMV

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1. AHRS GYROCOMPASS

FOR VARIOUS MARITIME OPERATIONS

Octans 9 is an attitude and heading reference system gyrocompass. This model seeks to enhance operational performance across various applications, including dynamic positioning, vessel navigation and offshore platform stabilization. The Octans 9 is designed to meet the needs of maritime operations.

Octans 9 offers a heading accuracy of 0.1° secant latitude and a heave measurement accuracy of 5%. Additionally, the system can maintain uninterrupted operations even during GNSS outages, essential for continuous performance in challenging environments.

It incorporates advanced capabilities such as improved filtering and alignment-in-motion features for precise stabilization in dynamic applications.

Utilizing Exail's fiber optic technology, which utilizes light spinning in a fiber coil with no moving parts, the Octans 9 system offers reliability and durability.

Exail, exail.com

2. GNSS CHIP

INTEGRATES INTO SMALL WEARABLE DEVICES

UBX-M10150-CC is a GNSS chip designed for wearable devices. It offers advancements in size, power efficiency and performance for battery-powered devices.

The chip measures 2.39 mm x 2.39 mm x 0.55 mm, making it suitable for integration into small wearable devices such as sports watches and smartwatches — it also includes a mode specifically designed for open water swimming. The UBX-M10150-CC utilizes low energy accurate positioning technology, which achieves power consumption as low as 10mW. This technology, combined with smart adaptation to signal conditions, allows for a 50% reduction in power consumption compared to previous M10 chips, according to u-blox.

It incorporates multipath mitigation technology, which enhances position accuracy, particularly in urban environments where signal reflections are common. This feature can be beneficial for maintaining accurate tracking in challenging signal conditions, u-blox said.

u-blox, u-blox.com

3. INERTIAL MODULE

WITH A NINE-AXIS IMU

The IM19 fuses gyro and accelerometer data with GNSS data for high-precision attitude measurement and inertial navigation.

It features a nine-axis IMU with a gyroscope range of $\pm 1,000$ deg/s and an accelerometer range of $\pm 8g$. When integrated with GNSS, IM19 offers better than 0.02° pitch and roll and better than 0.25° yaw accuracy in real time.

With easy integration and proven reliability, it has been adopted worldwide for diverse applications such as tilt compensation, machine control, laser/lidar/radar-assisted RTK and attitude stabilization. IM19 is a miniature SMD device measuring only 14.8 mm by 18.4 mm, operating in temperatures from -40°C to 85°C and has a low power consumption of 130 mA at 3.3 V.

Feyman Technology (FMI), feymani-global.com

4. FMCW LIDAR SENSOR

DESIGNED TO IMPROVE MACHINE PERCEPTION CAPABILITIES

The Carbon frequency modulated continuous wave (FMCW) lidar sensor features lidar on a chip with solid-state beam steering integrated into a fingernail-sized silicon photonic chip. The Carbon sensor offers high-resolution imaging with millimeter precision and object detection capabilities up to 200 m.

FMCW technology enables instant velocity measurement at each point, in addition to distance, reflectivity and intensity data. This 4D capability allows for high-fidelity point cloud data generation, providing a real-time view of the environment up to 20 times per second, according to Voyant Photonics. It can operate effectively through dust, fog, rain and snow and is immune to sunlight interference. Additionally, it is not affected by highly reflective objects such as street signs, traffic cones and safety vests.

The Carbon sensor seeks to enhance machine perception capabilities across various industries, including industrial automation, robotics and security applications. Its software-defined lidar feature allows users to modify the frame rate and adjust the field of view during operation.

Voyant Photonics, voyantphotonics.com

5. NAVIGATION SOLUTION FOR MARINE OEMS

Savvy Integrated is a comprehensive hardware and software integration platform specifically designed to provide advanced navigation solutions for original equipment manufacturers (OEMs) in the marine industry. This solution combines digital charting technology with hardware integration capabilities, addressing critical navigation challenges for boat manufacturers.

The Savvy Integrated platform provides OEMs with a navigation solution featuring a comprehensive digital marine chart with real-time geographical data and seamless integration with multifunction displays. The platform, which is compatible with a range of marine system architectures, offers extensive depth mapping and navigation details, as well as support for various types and configurations of vessels.

savvy navvy, savvy-navvy.com

5



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1. ROTOR UAV CAN HANDLE DIVERSE PAYLOADS

The X500 rotor UAV is designed for precision aerial operations such as surveying, urban monitoring, emergency response, disaster relief and infrastructure inspection.

It features a dual GNSS and triple inertial measurement unit redundancy to enhance positional accuracy and reliability, while integrated millimeter-wave radar provides precise obstacle detection. The UAV's video transmission system supports HD feeds over distances of up to 20 km and its visual SLAM positioning offers accurate landing on moving platforms.

The X500 is designed to handle diverse payloads, with a capacity of up to 5 kg and flight durations of up to 58 minutes — or 50 minutes when equipped with the CHCNAV AA10 lidar system. Its open SDK and compatibility with the Mavlink protocol allows for seamless integration with both CHCNAV sensors and third-party equipment. Built for demanding conditions, the X500 features an IP55 rating and can operate in winds up to 12 m/s.

Complementing the X500's hardware is CHCNAV's SmartGo ground control software, which simplifies mission planning and offers real-time flight monitoring. With various flight path options and beyond visual line of sight capabilities, SmartGo ensures safe and efficient operations while providing full control over mission parameters.

CHC Navigation, chcnav.com

2. MARITIME INS FOR AUTONOMOUS SURFACE AND UNDERWATER VESSELS

Maritime inertial navigation system (INS) integrates ANELLO's Silicon Photonic Optical Gyroscope (SiPhOG) technology with an advanced sensor fusion engine, offering high-precision navigation for autonomous surface and underwater vessels.

It combines optical gyroscope performance and silicon photonics technology, resulting in a compact, low-

power consumption device designed for GPS-challenged environments. Its capabilities include reference-grade position, velocity and attitude data output at 100 Hz, and a high-precision three-axis SiPhOG with less than 0.5°/hr unaided heading drift.

This system incorporates dual triple-frequency GNSS receivers with static heading capability and an AI-powered sensor fusion engine with GNSS spoofing detection. The INS provides accurate dead reckoning and is designed to withstand harsh maritime conditions, being waterproof and resistant to corrosion, salt spray, and chemicals. The system's applications extend beyond maritime use, with potential benefits for industries such as construction, agriculture, robotics and defense.

ANELLO Photonics, anellophotonics.com

3. RTK-GNSS MODULE IDEAL FOR UAVS

The Wren Mini is a compact and high-precision RTK GNSS module suited for UAVs. It utilizes the DroneCAN protocol for communication, offering enhanced robustness and resistance to electromagnetic interference.

This module features multi-band RTK capabilities with quick convergence times for reliable performance and simultaneous reception of signals from multiple GNSS. The Wren Mini is equipped with a Quectel LC29H RTK chip that supports L1/L5 frequencies for centimeter-level positioning accuracy.

The Wren Mini features a high-quality antenna with a built-in low-noise amplifier. This integration aims to simplify installation and improve overall performance. Additionally, the module incorporates a magnetometer to improve its orientation and heading determination. While primarily targeted at UAV applications, the Wren Mini can also serve as a rover or base station for other RTK positioning needs. It is part of a line of open-source products, allowing for community-driven development and customization.

Systork, systork.ioz

SURVEYING LAUNCHPAD

1. LIDAR SCANNING SOLUTION OPERATES IN CHALLENGING ENVIRONMENTS

YellowScan and Ventus-Tech Robotics (VTR) have released a lidar scanning solution that combines a sophisticated payload with a UAV featuring a tailsitter vertical takeoff and landing design. This integration aims to enhance aerial mapping and surveying capabilities across various industries.

The VTR UAV — weighing 3,950 g — can operate in challenging environments, making it particularly suitable for construction, forestry, agriculture and environmental monitoring applications.

The system includes YellowScan Mapper+ OEM payload, which allows users to collect 3D data accurately. The Mapper+ utilizes a Livox AVIA laser scanner and an Applanix APX-15 UAV GNSS inertial solution, offering a precision of 3.5 cm and an accuracy of 4 cm. It can operate at a maximum altitude of 100 m above ground level and has a laser range of up to 230 m.

Yellowscan, yellowscan.com



2. RUGGED ANDROID TABLET FOR SURVEYING, UTILITIES AND LOGISTIC INDUSTRIES

The ZX10 10-inch, fully rugged Android tablet is designed for professionals working in challenging environments. The tablet is powered by Qualcomm's QCS6490 processor and Neural Processing Unit and offers artificial intelligence (AI) capabilities and high performance in a compact form factor.

It meets MIL-STD-810H certification and IP66 standards, with the ability to operate in temperatures ranging from -29° C to 63° C. The device features a 1,000-nit LumiBond screen that remains readable in direct sunlight and supports operation with gloves.

The device offers strong connectivity options, featuring dual SIM technology, WiFi 6E, Bluetooth 5.2, and optional 5G support. Its innovative hot-swappable dual-battery design allows for continuous operation, and it comes with configurations that can accommodate up to 256GB of storage and 8GB of LPDDR5 memory. The tablet can be used for surveying, public safety, utilities and logistics industries.

Getac, getac.com



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GPS NETWORKING

1. 3D NAVIGATION SYSTEM

WITH ADVANCED DRIVER-ASSISTANCE CAPABILITIES

Mapbox and Hyundai AutoEver, a software affiliate of Hyundai Motor Group, have developed an integrated AI-driven 3D navigation

①



system with advanced driver-assistance (ADAS) capabilities. This system, powered by Mapbox 3D Live Navigation and MapGPT, operates on Hyundai Mobis' cockpit domain controller.

The Mapbox 3D Live Navigation system offers 3D lane-level guidance, augmented reality overlays and real-time driver assistance. It integrates Mapbox's navigation technology with Hyundai AutoEver's software-defined vehicle platform and Hyundai Mobis' AR-enabled cockpit domain controller. This integration provides drivers with turn-by-turn navigation enhanced by ADAS alerts, including collision warnings and lane departure notifications.

MapGPT, an AI-powered location assistant, complements the navigation system. It facilitates voice-driven interactions for dynamic routing, real-time traffic updates and hyper-local search. The system also allows voice-activated controls for in-car functions such as climate control and music. For electric vehicles, MapGPT includes features such as real-time range monitoring and charging station recommendations.

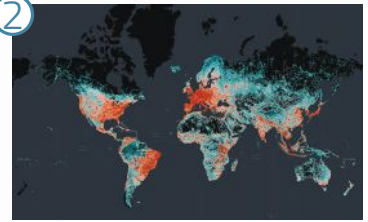
Hyundai Mobis, mobis.com

2. TRANSPORTATION DATASET

COVERS 86 MILLION KM OF ROADS WORLDWIDE

The Overture Maps Foundation has announced the general availability of its global transportation dataset, covering 86 million km of roads worldwide, offering support for a wide range of industries,

②



including automotive, logistics, navigation, urban planning and humanitarian response. The transportation dataset incorporates detailed aerial imagery for accurate road representations, clear road routes with recognizable highway signs, comprehensive rail and ferry route information and complex traffic rules and restrictions.

It introduces the Global Entity Reference System, which provides unique identifiers through a linear reference system for users to attach external data, such as accident reports or road construction updates, to specific road segments with precise location information. Future enhancements are expected to leverage artificial intelligence and other open data sources to maintain and expand the dataset's accuracy and completeness, according to the Overture Maps Foundation.

Overture Maps Foundation, overturemaps.org 🌐

AUTONOMY KIT

IMPROVES MACHINE NAVIGATION

John Deere has introduced the second generation of its autonomy kit, which integrates advanced computer vision, AI and camera technology to enhance machine navigation in various environments.

①



The new autonomy kit is being implemented across various machines, including the 9RX tractor for large-scale agriculture, the 5ML orchard tractor for air blast spraying, the 460 P-Tier autonomous articulated dump truck for quarry operations and an autonomous battery electric mower for commercial landscaping. These machines feature advanced camera systems, lidar sensors and improved depth calculation capabilities, allowing for more efficient and precise operations.

John Deere offers multiple adoption paths for users, with select machines being autonomy-ready and retrofit kits available for certain existing machines. The autonomous machines are managed through the John Deere Operations Center Mobile, a cloud-based platform that allows users to control and monitor the machines remotely, access live video and data and receive notifications about job quality or machine health issues.

John Deere, deere.com

AUTOSTEER SYSTEM

FOR PRECISION AGRICULTURE

②



The AG501 Pro autosteer system offers improved accuracy and efficiency for various farming operations. The AG501 Pro features a streamlined design, incorporating the A100 Pro Smart Antenna, which integrates a GNSS antenna, GNSS module, gyroscope and datalink functionalities into a single unit.

The system utilizes ComNav's high-performance GNSS module, which supports full-constellation tracking. By employing GNSS+INS terrain compensation technology, the AG501 Pro can achieve a pass-to-pass accuracy of 2.5 cm across diverse terrains, minimizing skips and overlaps. It also includes free signal options, such as Galileo-HAS and BeiDou-B2B services, allowing 5 cm to 10 cm accuracy without the need for mobile RTK base stations or RTK service subscriptions. This is particularly beneficial in areas with poor internet connectivity.

The AG501 Pro offers a variety of guideline options, including parallel straight lines, curves, A+ Heading and automatic U-turns. It operates within a speed range of 0.1 km/h to 20 km/h and is compatible with various machine types, including tractors, sprayers and combine harvesters. The system's user-friendly software interface seeks to simplify configuration and task management, the company said. The AG501 Pro software also supports multiple languages, making it accessible to farmers worldwide.

ComNav Technology, comnavtech.com 🌐

What's Going on with These UAV Sightings?



TONY MURFIN
CONTRIBUTING EDITOR,
AUTONOMOUS ARENA

It cannot be denied that people are seeing more objects flying in the night sky. It is suspected that these are unauthorized UAVs collecting information over U.S. and international military bases and, well, also over people looking up at the sky in their backyards at night. It is unlikely that these unidentified flying objects are causing much harm to the civilian population other than being a curiosity. However, it remains unclear what they might be doing over military installations.

In November and December 2024,

numerous reports emerged of UAVs surveilling residential neighborhoods, restricted zones and critical infrastructure across the Northeast United States. This includes areas such as water storage facilities, transmission lines, railway installations, police departments — both local and federal — and military bases.

Military bases reporting UAV overflights included Wright-Patterson Air Force Base in Ohio, Picatinny Arsenal and Naval Weapons Station in New Jersey and Ramstein Air Base in Germany. In the UK, Royal Air Force (RAF) bases at Lakenheath, Mildenhall, Feltwell and Fairford in the South of England all reported

unauthorized UAV overflight activity, which is somewhat concerning for nuclear weapons bases in Europe. Lakenheath appears to have scrambled F-15s to investigate one such UAV incursion.

Detecting and Mitigating Threats

In the United States, the increased intensity of UAV sightings has residents and Congress concerned, while various authorities claim that most of these incidents are harmless. A joint statement by the Department of Homeland Security, the Federal Bureau of Investigation, the Federal Aviation Authority (FAA) and the Department of Defense stated:

“Having closely examined the technical data and tips from concerned citizens, we assess that the sightings to date include a combination of lawful commercial drones, hobbyist drones, and law enforcement drones, as well as manned fixed-wing aircraft, helicopters, and stars mistakenly reported as drones. We have not identified anything anomalous and do not assess the activity to date to present a national security or public safety risk over the civilian airspace in New Jersey or other states in the Northeast.”

Nevertheless, these agencies reported, “Local commanders are actively engaged to ensure there are appropriate detection and mitigation measures in place.”

No other major announcements have followed these incidents, but it would seem logical that military bases have begun activating existing detection and defensive systems. Known countermeasures may include specialized radar, laser, optical, acoustic and radio frequency (RF) detection and defensive systems.

Radar always has been employed to detect airborne intruders, and the reflections from them appear on a display, which the ground user can then align with a range of potential defenses. However, UAVs are generally small, while conventional radar is designed to pick up hefty reflections from the surface of full-size commercial and military aircraft.

Robin Radar Systems

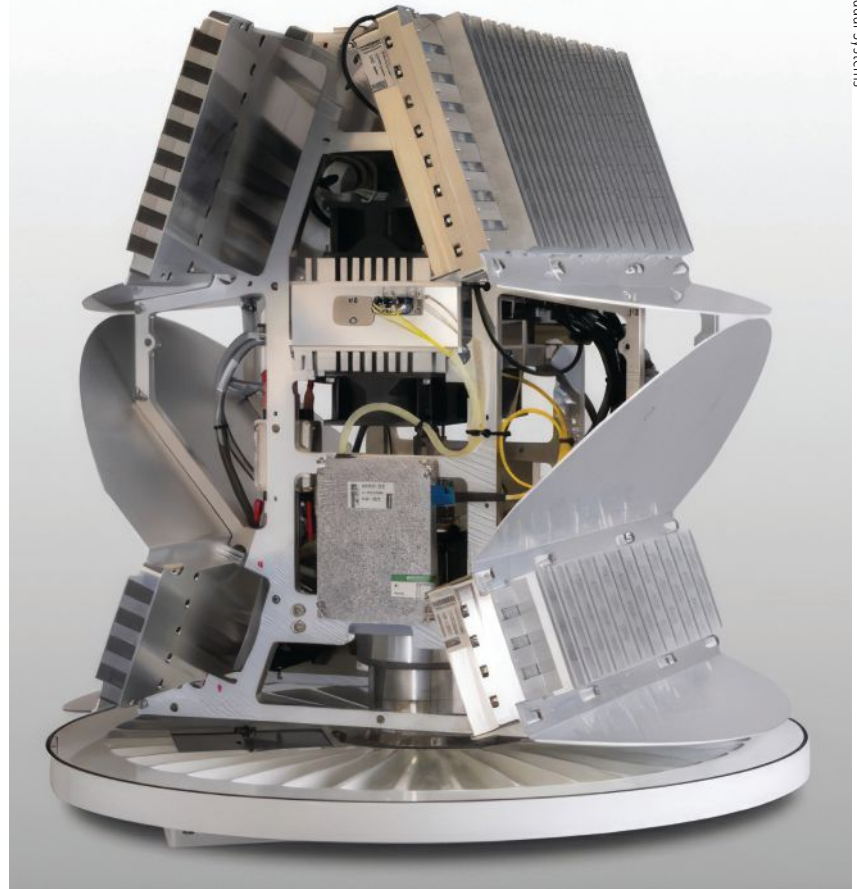
Robin Radar Systems in Holland has worked to refine radar that can detect small flying objects. Birds can cause havoc at airfields where aircraft take off and land at high rates, so detecting birds for airfield operators is one angle for which Robin Radar Systems has developed a reflection capability. A large bird and a UAV might be very similar in size. To differentiate the

two, the company found a way to see a Doppler effect (speed differences) within a radar return, which indicates the spinning rotors of a UAV rather than flapping wings — a system they term micro-Doppler radar. This detection system works to find objects many miles away and at well-defined approach angles from the radar antenna. Therefore, these X-Band radars are mostly based at the places you want to protect, such as airfields. Some radars also can be packaged to be transportable, perhaps for military applications, where a temporary base needs to know if enemy attack UAVs might be on their way.

Other principal detection systems include “sniffing” RF frequencies to

detect UAV control signals, but this has a shorter range than radar and does not easily determine distance or approach angle without several triangulating bases. Additionally, of course, UAVs without control signals cannot be detected with this particular RF technology. Optical systems using still/video/infrared (IR) cameras are good in daylight, but not so good in the dark. Acoustic systems use microphones or an array of microphones to listen for rotor sounds but have a shorter range (less than 1/3 of a mile).

Then, if you have suitable defensive capabilities, you could either take down an unwanted UAV by flying a counter-UAV to collide with and destroy it or by trapping it in a net. In



Robin Radar Systems

Inside Robin IRIS radar dome.

a military situation, many UAVs have been shot down by various types and calibers of guns — and even by very expensive missiles. Electronic defenses include jamming guidance and/or control signals by transmitting signals that overcome and scramble the GNSS and/or control signal or by frying its electronics using high-power microwave transmissions or high-powered laser(s) — these last two systems are expensive and heavy, which makes them cumbersome. Spoofing the on-board GNSS receiver by transmitting false satellite signals to steer the UAV away from its target recently has been used by Ukrainian forces to steer attack UAVs back into neighboring countries.

GNSS jamming is widely used, and there are numerous equipment suppliers; however, spoofing systems are less common due to their additional complexity and cost. Some RF systems can collect data from the opposing UAV and even detect where the operator might be located.

Of course, not all UAVs straying into restricted airspace come from operators with bad intentions — some might be “Sunday-driver” recreational UAV flyers who have allowed their UAVs to stray into the wrong area. This is another reason the FAA requires formal UAV operator training and certification for commercial operations, but this is not required for recreational UAV flyers.

FAA Regulations

The FAA regulations for UAVs are fairly easy to understand, and it would probably take an intentional effort to fly unauthorized into restricted airspace. Otherwise, stay at or below 400 ft,



DroneHunter drone net capture system.

Fortem Technologies

by fines and/or years in prison. Yet they still fly, so are they nuisance operators who don't care or is the activity criminally motivated or orchestrated offshore?

Utilizing UTM

Would the coming unmanned aircraft system traffic management (UTM) have been able to

keep these intruders away? I am not sure, but UTM is designed to manage UAV traffic, so presumably, it could manage these UAVs to comply with traffic requirements. However, these intruders are already ignoring existing laws, so UTM may more readily enable the identification of rogue UAVs and operators. Recent tests at the FAA/NASA UTM test range in North Texas have drawn huge interest from Walmart and Amazon, as they push to get UAV package delivery working. Wing now delivers for Walmart using a production UTM system in Dallas and Fort Worth, Texas.

To wrap this up, amongst many recently reported unidentified flying objects, several have been identified as probable UAVs, and some of those over restricted areas could be detected and managed with existing technologies. FAA regulations ban flights in restricted airspace unless approved — i.e., working in coordination with those ground facilities. There are UTMs for UAVs already being used commercially, which could assist in managing all UAVs. 🌐

Tony Murfin is managing consultant for GNSS Aerospace LLC, Florida. Murfin provides business development consulting services to companies involved in GNSS products and markets and writes for *GPS World* as the Professional OEM & UAV contributing editor.

“The FAA regulations for UAVs are fairly easy to understand, and it would probably take an intentional effort to fly unauthorized into restricted airspace.”

don't exceed 100 mph, don't go where you shouldn't, file a flight plan — ask permission using the automated FAA LAANC online tool — but always stay within visual range of the UAV. Those are most of the basics. Additionally, to operate a UAV commercially, you must also register it with the FAA and install an electronic device to tell everyone in the surrounding airspace the drone's registration number, which is traceable to the owner/operator. Never fly near clouds, comply with local rules when flying recreationally, and never, ever fly into restricted airspace, particularly around airports, without prior authorization.

These multiple reported UAV incursions violate FAA regulations, so it is reasonable to assume the operators are deliberately flying illegally. Recreational flying requires the operator to see the UAV at all times — so flying at night is not legal either, as the rules state not to fly an hour after sunset or an hour before sunrise. Operators in restricted airspace are committing a crime punishable



Mapping the Flames

GIS technology plays crucial role in wildfire management and response

BY JESSE KHALIL, ASSOCIATE EDITOR AND MATTEO LUCCIO, EDITOR-IN-CHIEF

The Palisades and Eaton fires devastated parts of Los Angeles in January 2025 and are largely contained as of Jan. 20. Fueled by extreme Santa Ana winds and dry conditions, these fires have left a mark on the region's landscape and community.

The Palisades Fire, which originated in the Pacific Palisades on Jan. 7, ultimately burned 23,448 acres, resulted in 12 confirmed fatalities and destroyed or damaged more than 6,800 structures, according to the California Department of Forestry

and Fire Protection, known as CAL FIRE. The fire's rapid expansion was particularly alarming, growing from a small brush fire to a massive conflagration within an hour.

Simultaneously, the Eaton Fire, which began near Altadena and Pasadena, consumed 14,117 acres. This fire proved even more deadly, with 17 confirmed fatalities and significant damage to more than 10,000 structures, according to CAL FIRE. Both the Palisades and Eaton fires have now been classified among the most destructive wildfires in

California's history.

During times of emergency, geographic information systems (GIS) specialists come together to create real-time mapping tools to provide critical support to first responders and keep communities well-informed. These tools have become indispensable in modern disaster management, particularly in wildfire response.

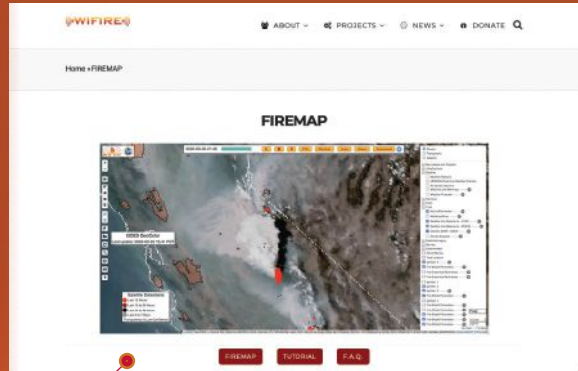
Interactive 3D Maps

Firefighters and other specialists from federal, state, and local agencies



CAL FIRE

Interagency GIS teams use the Fire Integrated Real-Time Intelligence System (FIRIS) to watch for fire starts, then receive alerts from dispatch centers and satellite imagery. After locating the point of ignition, they create fire behavior models using a program called WIFIRE from UC San Diego. This tool allows them to predict the fire's probable trajectory and size.



work together to fight wildfires. GIS specialists develop interactive 3D maps to display fire perimeters, evacuation zones and other critical data. The geospatial data serves as the foundation for effective communication and decision-making, allowing firefighters and incident management teams to access information in near real-time to make informed decisions.

Fire GIS specialists Peter Rowland, Brett Agler and Dawn Hutchinson shared insights into their teams' strategies for wildfire management. They emphasize the crucial role of geospatial tools in disaster response by delivering actionable intelligence. *GPS World* interviewed them during the California wildfires. Rowland and Agler were based at the Palisades fire, while Hutchinson, who is a member of a California Interagency Incident Management Team (CIIMT), was located near the Eaton fire. 🌐



CAL FIRE

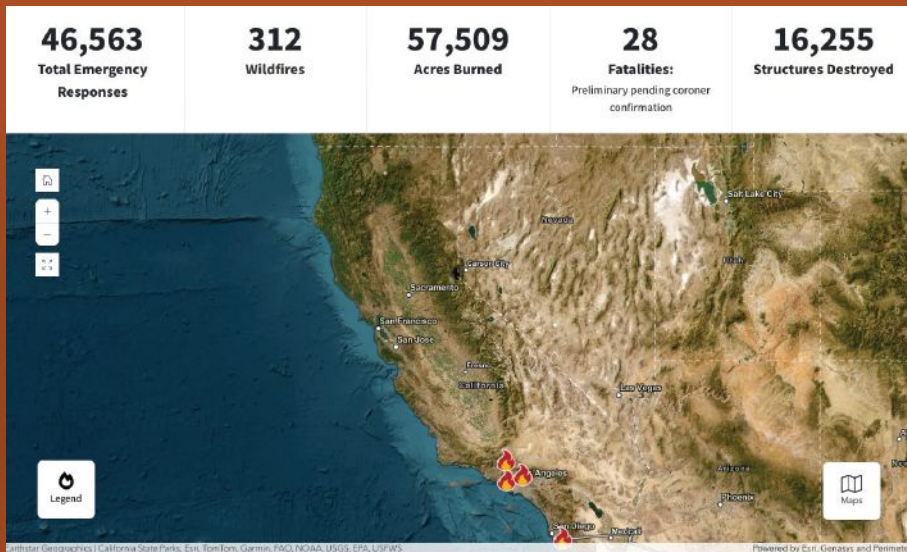
The team will alert the state if the data show the fire is likely to spread. Hutchinson explains that, within minutes of the start of the Eaton fire, her team produced a fire behavior model that illustrated where the fire was most likely to go and how big it would likely get within the next three hours.

The frequency of IR flights depends on the fire's size and intensity. Occurring anywhere from once to three times daily, including nighttime, these flights comprehensively map the landscape based on the fire's specific traits. The decision on how often to fly the planes and collect the IR data depends on the fire's behavior and potential threat level.

Field observers also are deployed daily to collect data down to the debris. They walk the fire's edge and move along specific paths created for wildfire management and containment. Once a fire is contained, GIS specialists try to verify ground truth for the perimeter of the entire fire.

GIS specialists constantly update fire perimeters as they get data from the field and the planes. Once a fire is contained, they create final maps to hand over to the local agencies or the Forest Service.

Most of the data that GIS specialists use to map fires comes from field observers and infrared (IR) thermal imagery. The IR data is collected by third-party contractors, by CAL FIRE's Intel shift team, or by the FIRIS program by flying manned aircraft.



www.fire.ca.gov

IR data and information collected by field observers are then uploaded into the National Incident Feature Service (NIFS) for GIS specialists to use to map fires.

Field observers download the maps onto their devices, go out into the field, and ground truth — physically walking the perimeter of the fire and using GPS on their devices to map the fire boundaries accurately.



CAL FIRE

Paper maps are good to have “just to get everybody on the same page without having to worry about battery life or the glare while you’re working out in the field,” said Rowland.

Along with online maps, the Interagency GIS teams print PDF maps for fire personnel in the field. The field observers use Esri ArcGIS Field Maps to record their tracks. They pair their mobile devices with Avenza or other geolocating applications.

Using ArcGIS Pro, GIS specialists create online maps and dashboards, which are then distributed in print and/or digitally to the agencies that need them, such as sheriff and police departments and departments of public works. The Interagency GIS teams create different map products for different end users. For example, it works with law enforcement to create evacuation maps and zones. Local public information officers also can distribute these maps or post them on their websites.

CAL FIRE



Crews also have online access to the maps through wildfire FTP (<ftp.wildfire.gov>). Crews load data and maps there that contain public information. Many agencies plug into the National Interagency Fire Center (NIFC), where the CAL FIRE team edits and analyzes mobile data.

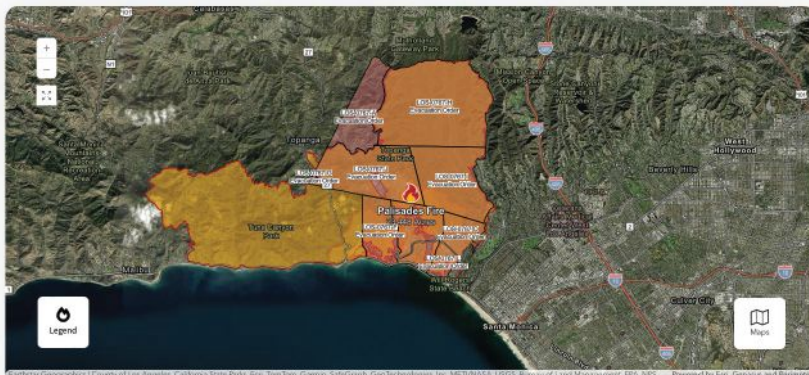
CAL FIRE



Thanks to Esri ArcGIS Field Maps and the NIFC, the Interagency GIS teams can see what field observers are tracking “pretty close to real-time,” said Agler. The field data undergoes a structured review process in which ground observers submit their findings, which are then reviewed and validated by command-level personnel before being officially downloaded and distributed. The maps distributed to the Interagency GIS teams display geographical areas of responsibility, including assigned divisions and branches. This allows crew members to efficiently identify their designated work areas and understand the overall incident organization.

Palisades Fire

95% Contained | 23,448 Acres | 1 County: Los Angeles



www.fire.ca.gov



MACHINE CONTROL

Helps level, cut and dig in diverse environments

EDITED BY MATTEO LUCCIO, EDITOR-IN-CHIEF

Machine control systems, which combine positioning sensors — both GNSS receivers and inertial systems — with computer displays, give operators better insight into and control over their work. Whether moving dirt on a construction site, spraying crops on a large farm, or moving cargo containers in a port, machine control increases efficiency and precision while decreasing accidents and fuel consumption.

Machine control systems enable operators to accurately position buckets, blades and other implements on their machines without having to first survey and stake the work site, or having to constantly check their work. They give operators a clear reference between the position of the machine bucket or blade and the design surface, thereby increasing their productivity and accuracy. They also utilize labor and equipment efficiently to reduce costs and minimize wear-and-tear. Finally, by collecting data during their operations, they help teams communicate better and share models.

Machine control, which first began to be implemented in the 1990s, is being increasingly adopted across a variety of different types of construction equipment — including graders, dozers, and, more recently, excavators. Now, beyond simply providing operators with a visual guide to the position of their buckets or blades, automated machine control moves the blade to grade by talking directly to the machine's hydraulics, enabling new or less-skilled operators to perform like long-time professionals and increasing the speed and precision of even the most experienced operators.

The three case studies in this cover story highlight the need for precision control of the implements on earth-moving machines, the importance of good data, and the need to make the process as easy as possible for the operator.



ComNav Technology

Enhancing Construction Projects in the Maldives

The Maldives consists of numerous coral reef islands with low soil-bearing capacity. Using heavy machinery in such an environment requires careful management of movement and precise operations while avoiding damage to local coral reef ecosystems, thus preserving marine life and the natural landscape of the islands.

As an advanced construction solution, ComNav Technology's XE100 Guidance System for Excavator employs high-precision GNSS positioning and heading technology coupled with inertial sensors. In construction projects in the Maldives, the XE100 not only provides precise guidance for operators on land but also enables efficient and precise underwater operations in complex marine environments while minimizing ecological impact. Its excellent performance has brought significant benefits to construction projects in the Maldives.

The Maldives' construction environment is complex and variable, requiring precise equipment to adapt to diverse terrain. The XE100 supports multi-constellation multi-frequency GNSS, delivering centimeter-level accuracy. This ensures that, whether for levelling, slope cutting, or digging, the system delivers precise instructions for bucket operations and guarantees accurate excavator positioning, even in challenging conditions.

For scenarios requiring underwater operations or mixed land and water tasks, the XE100 overcomes the



COMNAV TECHNOLOGY'S XE100 GNSS machine control system delivers centimeter-level accuracy in complex and variable environments.



USING HEAVY MACHINERY among sensitive coral reefs requires careful movement and precise operations to avoid damaging them.

traditional challenge of locating exact coordinates. The GNSS tablet's intuitive display of coordinate points helps operators identify work areas and select appropriate excavation actions. This ensures safety, reduces technical barriers, minimizes the need for rework, and significantly enhances construction quality while maintaining high efficiency and precision.

Construction projects in the Maldives often face challenges such as high humidity, high salinity and frequent vibrations. Each component of the XE100 is designed to withstand harsh environments with excellent durability. The system's modular design also supports expansion to other construction machinery, enhancing flexibility and paving the way for future technological upgrades.

As a nation abundant in marine resources and dependent on tourism, ongoing infrastructure development and maintenance are critical to the Maldives' economy. The XE100 system improves construction accuracy, reduces operation time, ensures safety, and lowers costs, thereby accelerating project timelines. 🌐

Both images from ComNav Technology



Leica Geosystems

Machine Control and Automation for Snow Management

The allure of pristine slopes and perfectly crafted terrain parks has always drawn adventurers to the mountains, but the landscape of snow management is shifting dramatically. With rising temperatures and unpredictable weather patterns, climate change poses a significant challenge to the snow sports industry. Natural snowfall is becoming less reliable, leaving resorts dependent on costly snowmaking systems that strain resources and budgets.

For snowparks, these challenges are even more acute. Crafting intricate features such as halfpipes, jumps and rails requires precision and significant amounts of snow — an increasingly scarce resource. Amid these difficulties, the need for sustainability has never been more pressing.

The Tech That's Changing the Game

Leica Geosystems' snow management solution, the Leica iCON alpine, paired with Prinoth snow groomers, is helping resorts get more out of less, making the construction of snowparks more efficient and sustainable.

The Leica iCON alpine system leverages GNSS and advanced inclination sensors and inertial measurement units (IMUs) to measure and manage snow depth accurately. Mounted on any snow groomer, this system continuously collects data, ensuring that operators can see the exact snow depth beneath the blade and tracks — accurate to within ± 3 cm. In other words, it's like X-ray vision for your snowcat.

Need a perfect jump? Create a 3D model and import the data, which can be read on the screen inside the groomer's cab. It even handles tricky terrain with features like avoidance



zones and anchor point searches. This setup doesn't just make slopes look good; it helps operators work smarter, not harder.

Snow Measurement for World Cup Slalom Course

For the past two years, Killington Mountain Resort in Vermont has been utilizing the Prinoth Connect Snow Measurement system powered by the Leica MC1 software.

Killington is one of the first resorts in North America to invest in snow measurement, and it has been vital to executing the Women's Slalom and Giant Slalom World Cup builds in 2023 and 2024. Killington has the snowmaking capability to cover the race trail, Superstar, with snow in about 100 hours. With the software, the teams can read the snow depth to ± 3 cm, using snow measurement sensors instead of long metal probes. The software helps increase the efficiency of both snowmaking and

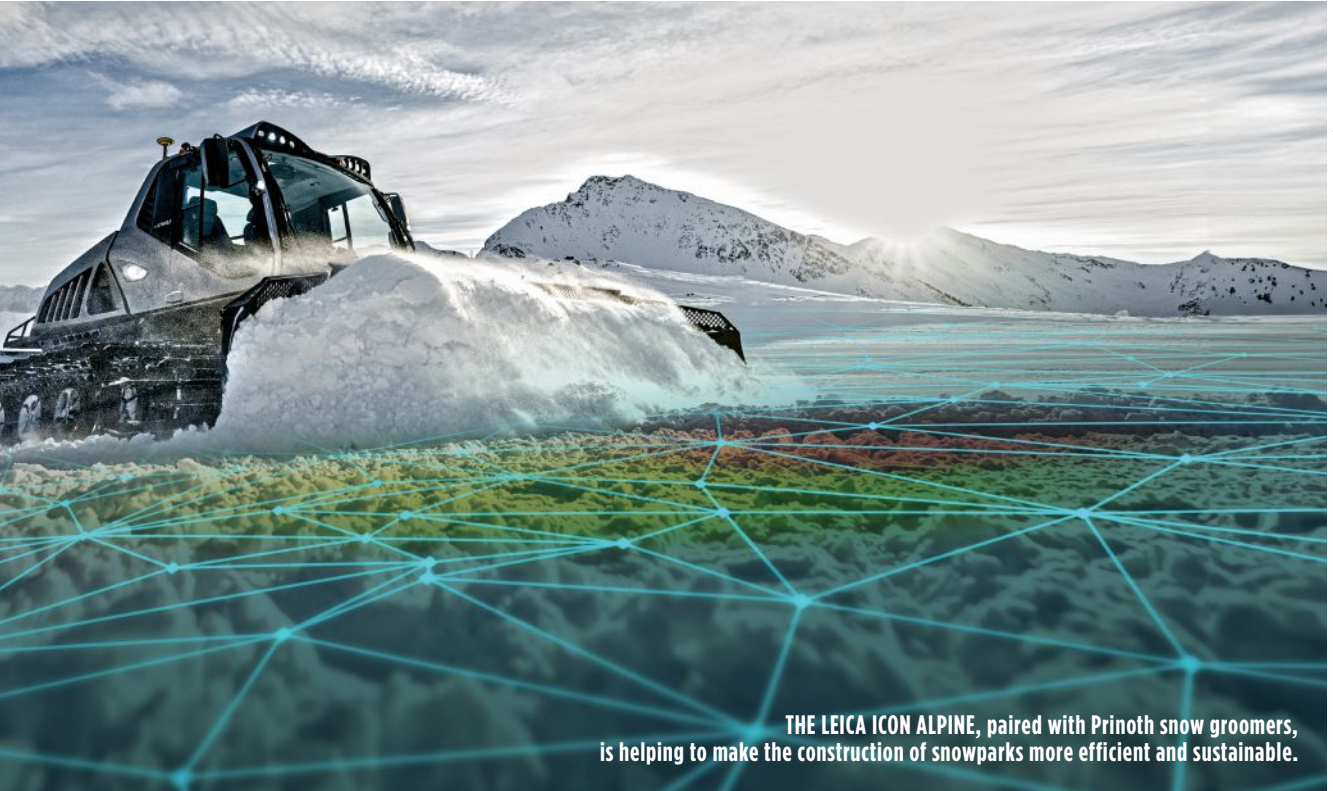


Leica Geosystems

LEICA ALPINE OFFICE enables resorts to achieve operational goals while safeguarding the environment by precisely managing snow management and reducing waste.



Prinoth, Leica Geosystems



THE LEICA ICON ALPINE, paired with Prinoth snow groomers, is helping to make the construction of snowparks more efficient and sustainable.

grooming, making the build easier for the grooming operators, more straightforward for officials, and safer for the racers.

From the Snow to the Dirt

However, Leica Geosystems machine control technology is a year-round solution thanks to its versatile Leica MC1 platform, which allows the same

hardware used for snow grooming to seamlessly transition into off-season applications such as summer earthworks, trail construction and road maintenance. With a single investment, resorts get a multipurpose tool that eliminates the need for separate systems, cutting costs and complexity.

For instance, in the summer

months at the Rieberalp in Davos Rinerhorn, the Leica MC1 solution powers excavation work for projects such as creating a reservoir and ensuring precise and efficient earthmoving. In the winter, the same system transitions to snow groomers, optimizing snow management on the slopes. This effortless switch between applications highlights the adaptability and value of the Leica MC1 platform, enabling ski resorts to get the maximum out of their investment while maintaining top performance year-round.

Technology for More Sustainable Snowparks

With precision snow management and reduced waste, resorts can achieve operational goals while safeguarding the environment. Adopting digital solutions such as these ensures that ski resorts and snowparks can continue to deliver world-class experiences for generations to come. 🌐



Prinoth

LEICA'S MACHINE CONTROL solution has been vital to precisely executing the Women's Slalom and Giant Slalom World Cup builds.



Trimble

Across Digital Dimensions on Te Ara Tupua

Te Ara Tupua is an initiative by the New Zealand Transport Agency aimed at enhancing transport resilience while establishing a walking and cycling route between Wellington and Lower Hutt. The Te Ara Tupua Alliance includes the NZ Transport Agency and its design and construction partners: Downer NZ, HEB Construction and Tonkin + Taylor. To execute this project, the NZ Transport Agency is collaborating with Taranaki Whānui ki te Upoko o te Ika and Ngāti Toa Rangitira as iwi mana whenua. This collaboration inspired the name Te Ara Tupua, referencing the Māori creation story in which Ngake and Whāitaitai, two tupua (ancient beings), formed Te Whanganui-a-Tara (Wellington harbor).

The Ngā Ūranga ki Pito-One section of Te Ara Tupua will be built on the harbor's edge, from Ngā Ūranga Interchange to Honiara Te Puni Reserve in Pito-One and connect with the new Pito-One to Melling section. The project will deliver a new resilient coastal edge protecting the road and rail while providing transport options and a safe route for walking and cycling between the two cities.

The solutions involved include:

- Trimble Marine Construction System
- Trimble SketchUp
- Trimble Stratus Software

The benefits of the project include:

- reduced project timeline
- improved safety for construction crews and the public
- increased productivity
- higher precision placement of embankment blocks
- reduced environmental impact
- real-time progress visibility for stakeholders.



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TE ARA TUPUA will deliver a new resilient coastal edge protecting the road and rail while providing new and safer transport options.

Te Ara Tupua is currently under construction along the western coastline of Te Whanganui-a-Tara with the aim of being completed in 2026. The Pito-One to Melling section of Te Ara Tupua is the first completed section of the project and was delivered by the contractors, Fulton Hogan.

The Pito-One to Melling section is a 3 km separated cycling route stretching from Pito-One to the Hutt River Trail near Bridge Street. The new path eventually will join the Ngā Ūranga to Pito-One section of Te Ara Tupua, which connects to the Hutt Road and Thorndon Quay.

The construction of Ngā Ūranga to Pito-One section of Te Ara Tupua includes a 4.5 km shared path, shared path bridge, rock revetments, seawalls and landings. To protect the shared path, road and rail line against wave action, erosion and sea-level rise, an essential part of the new pathway is the construction of embankments (or revetments).

Underwater Resilience

Te Ara Tupua is the first project where seismic performance has been considered and tested in the design elements, including the new seawall built over a large active faultline.

Two main types of material are required for this project. Rock is being used for the revetment (the sloping rock seawall), which will protect the reclamation and the path from the sea while the remaining material is general fill. These are being sourced in Taranaki and Golden Bay with rock from Golden Bay being transported by barge, greatly reducing the number of truck movements.

XBlocPlus units are a unique cost-effective solution for Te Ara Tupua. These blocks are poured in the shape of an 'X,' which interlock and stack on top of each other to create a seawall with a steeper incline.

Using these interlocking concrete blocks reduces the seawall's physical footprint and impact on the marine environment, enabling the project to use less material at a lower cost compared to a rock revetment.

Through this innovation, the project team of engineers and ecologists (Te Ātiawa, Ngāti Maniapoto, Ngāti Tūwharetoa and Ngāti Apa) worked alongside lead cultural designer, Len Hetet to combine cultural and environmental design, which resulted in Te Ripowai, the unique Te Ara Tupua ecological XblocPlus unit. Te Ripowai speaks of the rippling water and connects to a Te Ātiawa whakatauki of guardianship. The guardians must



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keep the ripples occurring, else water becomes still and life will cease to exist. Te Riopowai includes surface patterns and textures to encourage growth of marine plants.

The Ngā Ūranga to Pito-One pathway shoreline ultimately will have 6,663 of these blocks of varying shapes.

Block Placement

Placing these blocks with precision and speed initially created some concern for the project team. Operators in excavators equipped with grapple attachments needed to move the units into place, initially about 4 m underwater, to a tolerance of about 80 mm to assure embankment strength. To further complicate the construction, there are eight different block shapes.

It's a task purpose-built for real-time digital twins and machine guidance, according to the Alliance. With help from SITECH, the survey team looked to its digital assets.

First, Jan du Preez, survey manager with the Te Ara Tupua Alliance, relied on Trimble SketchUp to accurately model the individual blocks. Then, the team combined the Trimble Marine Construction (TMC) System with a digital model of the excavator. Laser scans along the shoreline provided a digital record of the existing conditions. Even the sequential placement of the blocks is planned in the digital space.

On the job, an operator selects a designated block for placement on the screen, then uses the excavator grapple attachment to pick it up. TMC provides real-time feedback on the block's position, rotation and tilt as the operator navigates to the appropriate position, even underwater.

Du Preez added, "With TMC, the operators can 'see' where they are placing them under the water. Because they're working in an active tidal area with most of the blocks sitting underwater, the idea was to make the process as easy as possible for the operator with highly visual markers on the screen. Every step is color coded, which allows operators to just focus on the colors, rather than trying to see underwater with the naked eye."

As the block is placed within the 80 mm tolerance required to interlock with the blocks above, the operator records the as-built position, and the screen shows green. The operator then releases the grapple and moves on to the next block.

When asked about efficiency, du Preez noted, "The initial program specified placing 15 blocks per day. We are currently placing between 35 to 45 blocks per day depending on site conditions. We estimate that we're seeing about three times the productivity compared with more conventional methodology — though I'm still not sure how we would have done this without TMC. We would have had to come up with some kind of visual



OPERATORS OF EXCAVATORS with grapple attachments needed to move eight different block shapes into place with an 80 mm tolerance.

marker and then perform quality checks with divers. It would have been time consuming and very costly."

Shared Progress

The benefits of the digital workflows to stakeholders, according to du Preez, are many, with transparency being the overarching benefit.

Unlike a traditional contract where owner and project team are separate, in an alliance model the client is an integral part of the team. That said, while NZ Transport Agency, Waka Kotahi, et al., are involved in the everyday running of the project as part of the alliance, they also have a board. "Every time the Alliance board of directors sees our solution, they are completely blown away by what we've been doing and how we're doing it," du Preez said. They particularly like the regular drone flights that capture progress updates. "All survey data, models and regular flight imagery are loaded and stored in Trimble Stratus for sharing so that stakeholders always see the latest project status. The entire Alliance really appreciates this level of real-time digital visibility into the project."

Ngā Ūranga ki Pito-One is on track for completion in 2026. When complete, the Te Ara Tupua will deliver a safe, connected and resilient route, enabling more people to walk or bike, and connect with local paths in both Wellington and the Hutt Valley. 🌐

MARKET WATCH

SEGMENT SNAPSHOT:
APPLICATIONS, TRENDS & NEWS

AUTONOMOUS SOLUTIONS

Honeywell and NXP expand aviation partnership

Honeywell and NXP Semiconductors have expanded their partnership to advance aviation technology and autonomous flight capabilities. This collaboration merges Honeywell's aerospace expertise and Anthem avionics system with NXP's high-performance computing architecture to develop AI-driven aerospace technologies.

The partnership aims to enhance operational efficiency in flight planning and management while facilitating smoother transitions to new chipsets and technologies. The companies will focus on developing next-generation cockpit displays with improved visual clarity and




Company officials gather at the Honeywell and NXP partnership signing ceremony.

system efficiency. They also are working on simplifying migrations to newer avionics technologies and extending the lifecycles of critical aviation systems, according to Honeywell and NXP.

NXP's domain-based architecture, which includes high-compute capabilities, integrated cybersecurity and functional safety, will be adapted for aviation applications on Honeywell Anthem, the company's cloud-connected cockpit system. This builds upon the companies'

collaboration in building management, fire safety and security products.

For aerospace applications, Honeywell will utilize various NXP processors, including the i.MX 8 applications processors and S32N super-integration processors, which will enable Honeywell Anthem to deliver faster data processing for real-time artificial intelligence (AI)-driven insights. This seeks to enhance safety and optimize performance both in flight and on the ground. 

Septentrio Set to Release Compact GNSS Modules


Septentrio has introduced the mosaic-G5 series, a new range of GNSS receiver modules tailored

for robotics and other applications requiring compact components.

These modules represent a significant advancement in size and power efficiency, offering a 60% reduction in size and 40% lower power consumption compared to the mosaic-X5 receiver while maintaining high performance standards. This improvement enables reliable, high-accuracy positioning for devices

where minimal size, weight and power are critical, such as commercial UAVs, compact industrial robots and high-performance handheld devices.

The mosaic-G5 series expands Septentrio's existing mosaic portfolio, known for its all-band GNSS technology and robust performance in accuracy, reliability and resistance to jamming and spoofing, according to the company. This broad product lineup allows users to select the most suitable module for their specific design requirements.

The mosaic-G5 modules will be gradually released throughout 2025. 



DEFENSE

Slingshot Aerospace Advances GPS Jamming Detection

The U.S. Space Force’s Space Systems Command has awarded a \$1.9 million contract to Slingshot Aerospace to enhance its GPS jamming and spoofing detection capabilities. This contract — Positioning, Navigation and Timing – Secure Electronic Navigation Threat Intelligence and Location (PNT-SENTINEL) — aims to improve the company’s existing technology by incorporating advanced artificial intelligence and predictive analytics.

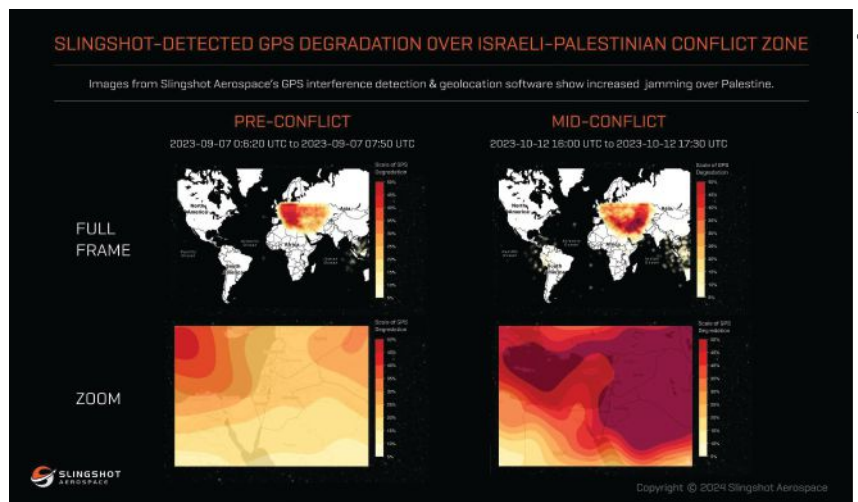
The PNT-SENTINEL program builds upon Slingshot’s previous work under the Data Exploitation and Enhanced Processing (DEEP) contract, awarded in October 2021. The technology developed through DEEP currently assists the U.S. Space Force in detecting GPS jamming and ground-based interference sources related to ongoing conflicts, potential future conflict zones and counterterrorism efforts.

Slingshot’s technology utilizes a mesh network of thousands of satellites to create a near-real-time picture of GPS jamming occurrences worldwide. This space-based approach offers a more comprehensive view of global jamming conditions compared to traditional ground-based detection systems.

As part of the contract, Slingshot will integrate its AI model, Agatha, into the PNT-SENTINEL system to enhance the technology’s ability to detect and differentiate between unintentional interference and deliberate jamming or spoofing attempts. The improved system also will implement pattern recognition algorithms to identify active jamming events and predict how situations may evolve.

The contract also includes provisions for expanding the system’s capabilities to monitor interference across multiple

GNSS sources, not just GPS. This multi-GNSS processing will allow for a more complete, real-time view of jamming activities by incorporating data from allied nations’ spacecraft. The PNT-SENTINEL system is designed to be interoperable with existing military systems, enabling near-real-time information dissemination to support rapid decision-making in national security operations. These enhancements aim to provide warfighters with a strategic advantage in GPS-contested environments.



Slingshot Aerospace

ANELLO Photonics Secures US Navy Contract

ANELLO Photonics has received a Phase I Small Business Innovation Research contract from the U.S. Navy. The six-month contract will allow ANELLO to demonstrate its optical gyroscope and sensor fusion technologies for navigation without relying on GPS.

Under the contract, the U.S. Navy will evaluate ANELLO’s integrated photonics technology and AI-based sensor fusion engine. These technologies aim to maintain accurate navigation

in challenging environments where GPS signals may be unavailable or compromised.

ANELLO Photonics’ technology can be used for construction, agriculture, transportation, robotics, unmanned vehicles and national security. The company’s focus on navigation solutions for GPS-challenged scenarios aligns with growing needs in both military and civilian domains for reliable positioning systems in diverse environments.



MACHINE CONTROL 

Bad Elf and GEODNET Launch 5-year RTK Service

Bad Elf and GEODNET have introduced a five-year RTK service for Bad Elf GPS receivers, designed to provide high-accuracy GPS positioning for professionals in surveying, agriculture, construction and geospatial data collection. The service offers real-time, centimeter-level accuracy, designed to improve the precision of GPS data for users.

The RTK service for Bad Elf GPS receivers offers enhanced accuracy, seamless integration and reliability. Users can achieve centimeter-level accuracy in real time, significantly improving the precision of their GPS data. The RTK service is designed for easy use with all Bad Elf GPS receivers, featuring a one-click activation process post-setup. Additionally, GEODNET's robust network ensures continuous and reliable service, even



in challenging environments, the company says.

GEODNET's network underpins the service, aiming to provide continuous and reliable performance across various environments. The company guarantees the availability of an RTK reference station within 40 km for subscribers in the United States and Europe, with potential expansion to other countries based on demand. 🌐

Topcon Expands Topnet Live Network Across US

Topcon Positioning Systems has expanded its Topnet Live reference station network by adding 200 new geodetic stations across the United States. This expansion enhances the availability of centimeter-level accuracy for industries

requiring precise positioning, such as engineering, surveying, construction and agriculture.

The upgraded network provides advanced network corrections that optimize operational workflows in various sectors. The enhanced infrastructure supports emerging technologies such as automated turf management, precision line marking, imaging systems and UAV operations for mapping and delivery.

This expansion builds upon previous efforts throughout 2024, resulting in a 30% increase in Topnet Live's total coverage in the United States. The network now offers comprehensive, network-modeled solutions that cater to a wide range of professional requirements across multiple market segments.

The Topnet Live network uses Networked Transport of RTCM via Internet Protocol to stream GNSS corrections data via the Internet for RTK positioning. This technology allows for centimeter-level accuracy by mitigating errors from factors such as ionospheric disturbances, satellite clock deviations and orbit inaccuracies. 🌐



SPACE & EARTH 

GMV Advances Galileo High Accuracy Service Data Generator

The European Union Agency for the Space Programme has selected GMV to develop a new version of the High Accuracy Data Generator (HADG) as part of Phase 2 of the Galileo High Accuracy Service (HAS) development.

This service offers free real-time precise positioning corrections to all Galileo system users. The first version of the HADG, also developed by GMV, is currently operational and provides users with the Initial Service (Phase 1) of the HAS.


The new contract spans up to 45 months and has a budget of up to €12 million. It covers the design, development, deployment, and support to commissioning, along with optional maintenance of an enhanced version



of the HADG. This updated version will integrate the functionalities necessary for providing the services outlined in Phase 2 (Full Service) of the HAS deployment.

The new version of the HAS data generator seeks to improve the performance level of Service Level 1 by deploying a new version of GMV's

magicPPP algorithms for precise corrections calculation and expanding the ground station network. This aims to provide global coverage and enhance the accuracy and availability of the SL1 service. Additionally, it will implement a new Service Level 2, a regional service available only in Europe that will transmit atmospheric corrections to reduce the convergence time required to achieve maximum accuracy at the user level.

Another key feature of the new HADG version is the implementation of a new functionality for the authentication of HAS corrections transmitted through the Galileo constellation, thereby increasing user security and confidence in the service. 


NASA and Italian Space Agency Demonstrate Lunar GNSS Payload

NASA and the Italian Space Agency are collaborating on the Lunar GNSS Receiver Experiment (LuGRE), which seeks to demonstrate the viability of providing positioning, navigation and timing capabilities on the moon using GPS and Galileo signals.

LuGRE's payload consists of a weak-signal GNSS receiver, a high-gain L-band patch antenna, a low-noise

amplifier and an RF filter. The receiver is designed to track GPS L1 C/A and L5 signals, as well as Galileo E1 and E5a signals. It will collect pseudorange, carrier phase and Doppler measurements; calculate onboard navigation solutions; and have the capability to record raw I/Q baseband samples for ground processing.

NASA's Space Communications and Navigation Program office funded and oversaw the experiment. It was selected as one of 10 research and technology demonstrations for lunar surface delivery by Firefly Aerospace, under NASA's Commercial Lunar Payload Services initiative.

LuGRE builds upon previous missions in the Space Service Volume, including experiments by AMSAT-OSCAR 40, GOES-R series satellites and the NASA Magnetospheric Multiscale mission. It aims to be one of the first demonstrations of GNSS signal reception and navigation in the lunar environment, potentially paving the way for operational use in future lunar missions. Upon completion, all LuGRE science data will be made available to the public for the benefit of the GNSS and space communities. 



NASA/Dave Ryan

SPACE & EARTH 

FrontierSI Releases LEO PNT Report

FrontierSI has released its Low-Earth Orbit (LEO) Positioning, Navigation and Timing (PNT) 2024 *State of the Market Report*. This report offers a comprehensive overview of the emerging LEO PNT market, showcasing its transformative potential in satellite navigation, the challenges it addresses and the key players shaping its evolution.

PNT services are integral to industries worldwide, from logistics and telecommunications to critical infrastructure. The rise of LEO satellites is set to revolutionize this space, overcoming limitations of traditional GNSS, such as vulnerability to interference and limited urban coverage, according to FrontierSI.

Key insights from the report, the first in a series of annual reports, include how LEO PNT addresses GNSS vulnerabilities, providing more reliable and precise

navigation solutions. Additionally, it addresses that the rise of commercial PNT players requires cooperation in areas such as interoperability, spectrum management and governance issues. The report is recommended for professionals and organizations deeply engaged in satellite navigation, including:

- Engineers, designers and project managers in the space and defense industries
- Autonomous systems manufacturers
- Policymakers and regulatory bodies responsible for satellite navigation and spectrum management
- Commercial stakeholders in telecommunications, transport and logistics
- Academics, researchers and analysts with an interest in satellite navigation technologies
- Investors analyzing the growth potential of LEO PNT solutions
- Providers of critical infrastructure reliant on precise timing synchronization

The LEO PNT *State of the Market Report* aims to provide stakeholders with the necessary insights to navigate this transformative period for PNT. 🌐



FrontierSI

CRPAs for PNT Removed from ITAR List

The Directorate of Defense Trade Controls has changed the regulatory status of Controlled Reception Pattern Antennas (CRPAs) for PNT. Starting September 2025, CRPAs will no longer be subject to the International

Traffic in Arms Regulations (ITAR). Instead, they will be reclassified under the less restrictive Export Administration Regulations (EAR) list, which is under the jurisdiction of the Department of Commerce.

The rule, in part, removes items from the U.S. Munitions List (USML) “that no longer warrant inclusion.” According to the rule, “certain anti-jam antennas no longer provide a critical military advantage, with increasing commercial utilization applicable to civil GPS resiliency.” By removing CRPAs for PNT, “the Department intends to facilitate civil global navigation system resiliency.”

The recent regulatory change is expected to significantly impact several industries, including airlines, autonomous vehicles, UAVs and critical infrastructure applications, which can benefit from the increased availability of CRPAs. Additionally, this change may open the U.S. market for CRPA manufacturing, potentially resulting in swift technological advancements and lower costs. 🌐



buradaki / Stock / Getty Images Plus / Getty Images



PREFACE

Professor Richard Langley and his 300 Innovation columns cannot be replaced, matched or continued. His columns have guided multiple generations through the pioneering decades of GPS, and then GNSS, development. Any attempt to follow in his footsteps would be inherently derivative. Yet, the overwhelming response to Richard's decades-long work indicates a continued desire in the GNSS community for thoughtful and thought-provoking GNSS and wider PNT R&D content. I, as a former doctoral student of Richard's (and, I happily can say, a good friend), have humbly agreed to lead a new column in an imperfect attempt to fill this information void going forward and add to Richard's enduring legacy. While the revolutionary days of GPS transforming the world and our daily lives are behind us, there remains much research activity, application and implication of technology development with GNSS at its core. So ends Innovation and begins Evolution.

As people's available time decreases, we are inundated with content — some of which is signal and much of which is mere noise, and we have more

varied interests. Evolution has been designed to communicate information at different levels and in several ways. The structure of each technical article will be as follows:

- Essence – a brief executive summary of the topic to entice the potential reader to invest their time (or not).
- Essentials – a clear and concise explanation of the technical problem(s) and developed solution tailored to all readers, from CEOs to students.
- Elements – technical details of the research methodology, results, analysis and discussion aimed at researchers and engineers.
- Evolutionary – conclusions offering insights into how future application of the research could improve our lives.

For those interested, future readings will be provided online. There will also be accompanying brief online video interviews with authors (other than myself).

It is our hope that readers will enjoy this new content.

— SUNIL BISNATH

THE EVOLUTION OF PRECISE POINT POSITIONING

BY SUNIL BISNATH

ESSENCE

Since the dawn of GPS, researchers have worked to improve the accuracy of estimated positioning, navigation and timing (PNT) from the receiver-derived pseudorange, carrier-phase and Doppler measurements. While the pseudorange-based accuracy of standard point positioning (SPP) at the level of 1s to 10s of meters sufficed for most users, carrier-phase-based relative positioning, real-time kinematic (RTK), network RTK (NRTK) and precise point positioning (PPP) measurement processing techniques were developed to provide decimeter-to-centimeter-level PNT under various constraints. Of these approaches, PPP — generally based on the state-

space reduction of measurement errors to a single GNSS receiver from a wide area calibration network — has evolved dramatically. Why should readers read this article, as PPP has been around for some two decades? Well, some communities may consider old performance specifications of conventional/classical PPP, a rather niche technology, for static use with post-processing of measurements, resulting in tens of minutes for solution convergence to the decimeter-level. However, there have been many performance advances, with more coming, affecting who uses the technology and how.

Figure 1 illustrates the timeline of PPP evolution, from 1) The development of the original technique in

- the late 1990s to reduce static GPS network measurement processing load.
- 2) The removal of GPS Selective Availability (SA), simplifying precise satellite clock prediction.
 - 3) The development of PPP-RTK, in which regional RTK-derived corrections are used to reduce position convergence time and increase accuracy.
 - 4) Successful isolation of PPP GPS dual-frequency carrier-phase ambiguities to increase accuracy.
 - 5) Full multi-constellation, multi-frequency (MCMF) processing to greatly reduce position convergence time.
 - 6) The introduction of GNSS constellation provider corrections. (Individual advances will be discussed in the *Elements* section.)

From initial scientific uses to becoming the commercial standard in remote areas or regions with limited GNSS terrestrial infrastructure, these research contributions are leading to ubiquitous open sky decimeter to centimeter-level positioning with a range of available corrections, increasing accuracy and reducing initial convergence for more applications.

ESSENTIALS

In the late 1990s, to improve positioning accuracy over SPP and avoid the heavy computational burden of network-adjusted relative positioning processing between many receivers, PPP algorithms (detailed in the *Elements* section) were formulated with undifferenced measurements between tracked satellites and a single receiver (Zumberge et al. 1997). Both pseudorange and carrier-phase measurements are utilized, with the former presenting many decimeter-level references and the latter ambiguous centimeter-level ranging. By filtering continuously tracked measurements over time, decimeter- to centimeter-level positioning is possible, as the state terms, including real-valued estimates of biased carrier-phase ambiguity terms — result in tens of minutes to hours of initial convergence time. This approach represents Hatch filtering in the position state rather than the observation domain. Key to PPP is the use of precise satellite orbit and clock estimates derived from a global reference network, which can receive measurements from an entire GNSS constellation. Additionally, to maximize performance, remaining error sources are modeled or estimated. While PPP was initially not as accurate as



FIGURE 1 Timeline of PPP evolution.

RTK and, more importantly, took tens of minutes to hours to attain solution convergence, the technique did not have the terrestrial infrastructure constraints of RTK or network RTK, which require reference receivers ~10 km to 15 km and ~75 km away, respectively. Once GPS Selective Availability was turned off in 2000, GPS satellite clock modeling became simpler and more accurate, and scientific and commercial PPP solutions quickly became the standard measurement processing technique for applications requiring decimeter-level accuracy in remote areas or places where it was not economically viable to install (an) RTK base station(s).

In the 2000s, two different approaches were developed to deal with the shortcomings of PPP: PPP-RTK and PPP-AR. In PPP-RTK, state space corrections from a regional NRTK solution are efficiently transmitted and applied as PPP corrections. As NRTK resolves carrier-phase ambiguities and estimates local atmospheric (ionospheric and tropospheric) refraction and reference station position all in a least-squares sense, PPP-RTK can produce centimeter-level positioning in seconds within a reference station network, where stations can be tens to hundreds of kilometers apart. In PPP-AR, the ionosphere-free linear combination of dual-frequency pseudorange and carrier-phase measurements is not employed; rather, the uncombined version, and the pseudorange and carrier-phase observation models, are extended to include and isolate satellite and receiver fractional carrier-phase biases, allowing PPP ambiguity resolution (AR) to integers with additional satellite code and phase biases from the network solution and between satellite single-differencing. Both approaches are having significant scientific and commercial success.

Unlike RTK, which has the benefit of significant additional calibration information from the reference station, PPP(-AR) must rely only on satellite-based corrections and the strength of the single-receiver observations. In recent years, additional GNSS constellation satellites and frequencies have been brought on-line in large numbers, and GNSS constellation-

provided PPP corrections have begun (Xu et al. 2021; Fernandez-Hernandez et al. 2022; Naciri et al. 2023). These developments have greatly increased estimation redundancy, making near-instantaneous PPP without regional reference stations possible (Naciri and Bisnath 2023). This evolution of PPP technology in terms of positional accuracy versus convergence time is illustrated in **Figure 2**. Therefore, it may be possible to a) dissolve the old GNSS duality of niche, professional-grade versus mass-market, low-cost hardware and software with low-cost hardware utilizing PPP (and RTK and PPP-RTK) software countermeasures to obtain precise PNT; and b) with PPP corrections from GNSS constellations, perhaps, as a reversion to SPP, to have PPP be the natural operational mode of precise GNSS PNT (Bisnath 2020).

ELEMENTS

Theoretical Development

The PPP measurement processing technique utilizes the GNSS pseudorange (code) and carrier-phase (phase) observables. For receiver r and satellite s , the respective code and phase measurements on frequency $f_i, i \in \{1, 2, \dots, n\}$ can be defined as:

$$\begin{cases} P_{r,i}^s = \rho_r^s + c(dt_r - dt^s) + \gamma_i I_1^s + M_r^s \cdot T_r + (b_{r,i} - b_i^s) + \epsilon_{P_i} \\ \Phi_{r,i}^s = \rho_r^s + c(dt_r - dt^s) - \gamma_i I_1^s + M_r^s \cdot T_r + \lambda_i (N_i^s + B_{r,i} - B_i^s) + \epsilon_{\Phi_i} \end{cases}$$

where $P_{r,i}^s$ and $\Phi_{r,i}^s$: pseudorange and carrier-phase measurements, respectively, in meters; ρ_r^s : geometric range between receiver and satellite; c : vacuum speed of light; dt_r and dt^s : receiver and satellite clock offset from GPS Time, respectively; $\gamma_i = f_1^2 / f_i^2$: ratio of frequencies applied to first frequency ionospheric delay I_1^s to recover ionospheric delay at frequency i ; T_r : zenith troposphere wet delay; M_r^s :

mapping function to map to satellite-receiver line-of-sight troposphere delay; $\lambda_i = c/f_i$: signal's wavelength; N_i^s : integer ambiguity on frequency i ; $b_{r,i}$ and b_i^s : receiver and satellite pseudorange hardware biases, respectively; $B_{r,i}$ and B_i^s : receiver and satellite phase biases, respectively; and ϵ_{P_i} and ϵ_{Φ_i} : residual unmodeled errors such as multipath and noise in code and phase measurements, respectively.

In order to eliminate ionospheric refraction, the original PPP solution forms the ionosphere-free (IF) linear combination of the dual-frequency GPS code and phase measurements:

$$\begin{cases} P_{r,IF}^s = \frac{f_1^2 P_{r,1}^s - f_2^2 P_{r,2}^s}{f_1^2 - f_2^2} \\ \Phi_{r,IF}^s = \frac{f_1^2 \Phi_{r,1}^s - f_2^2 \Phi_{r,2}^s}{f_1^2 - f_2^2} \end{cases}$$

From this combined form, the IF float PPP equations are (Kouba and Héroux 2001):

$$\begin{cases} P_{r,IF}^s = \tilde{\rho}_r^s + c(\tilde{dt}_r - dt^s) + M_r^s \cdot T_r + \epsilon_{P_{r,IF}} \\ \Phi_{r,IF}^s = \tilde{\rho}_r^s + c(\tilde{dt}_r - dt^s) + M_r^s \cdot T_r + \lambda_{IF} N_{IF}^s + \epsilon_{\Phi_{r,IF}} \end{cases}$$

where the terms with tildes are biased by other terms from the starting observation equations, but allow for enough redundancy for user position, receiver clock offset, a zenith tropospheric term and real-valued, biased phase ambiguity terms to be estimated. In a sequential least-squares or Kalman filter optimal estimation process, positional accuracy depends on the quality of the satellite orbit and clock corrections, along with applying additional error modeling (including satellite and receiver antenna phase center offset and variation, solid Earth tides, ocean loading and phase wind-up), and, most importantly, the quantity, geometrical distribution and quality of the code

and phase measurements. The state is initialized with m-level pseudorange measurements and slowly converges to the centimeter-level over tens of minutes to hours as the real-valued, biased phase ambiguity estimates reach steady state. This original or classic PPP solution, characterized by slow convergence to a fixed ambiguity-like positioning solution, may be what some in the community still think of as PPP.

PPP-RTK was developed as a means to remove these

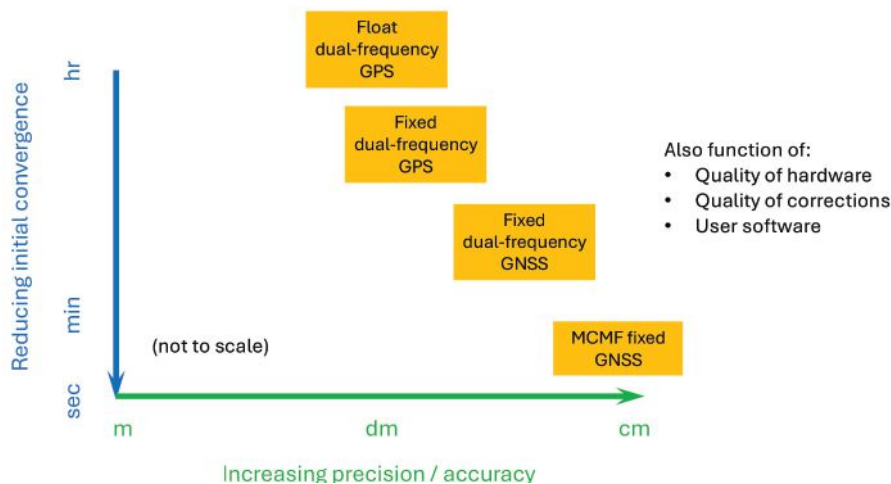


FIGURE 2 PPP and PPP-AR technology evolution in terms of accuracy versus convergence time.

shortcomings of classical, float PPP by supplying PPP-like error state corrections from a regional RTK network to allow near-instantaneous carrier-phase ambiguity resolution AR, (AR), solving both PPP's convergence and accuracy problems (Wübbena et al. 2005). Significant operational improvements include increased spacing between (N)RTK reference stations, so less GNSS terrestrial infrastructure is required, and significant reduction in data transmissions from observation space representation (OSR) to state-space representation (SSR). By providing regional atmospheric corrections and ambiguity fixing, RTK-like performance is achieved but with larger CORS spacing. This approach has found commercial success in economically sustainable regions.

In parallel, active research continued in PPP-AR, given its desirable characteristic of not requiring regional reference stations. Multiple solutions were developed (e.g., Collins et al. 2008; Ge et al. 2008; Laurichesse et al. 2009), each of which reformulated the PPP observation equations to isolate the phase ambiguities, while overcoming datum defects in the estimation process. For example, the decoupled clock model (DCM) (Collins et al. 2008) isolates the phase ambiguities and directly estimates them as integers. The DCM does not make any assumptions regarding receiver biases and uses separate terms for code and phase clocks due to the imprecision in their synchronization — hence the model's name. Satellite code and phase biases are required, along with satellite orbit and clock corrections. Then, standard AR methods, such as LAMBDA, can be applied. In the DCM, the fundamental code and phase equations are altered to:

$$\begin{cases} P_{r,i}^s = \rho_r^s + c(dt_r - dt^s) + \gamma_1 I_1^s + M_r^s \cdot T_r + (b_{r,i} - b_i^s) & + \epsilon_{P_i} \\ \Phi_{r,i}^s = \rho_r^s + c(\delta t_r - dt^s) - \gamma_1 I_1^s + M_r^s \cdot T_r + \lambda_i(N_i^s + B_{r,i} - B_i^s) & + \epsilon_{\Phi_i} \end{cases}$$

where dt_r and δt_r are the receiver code and phase clocks, respectively. The receiver pseudorange bias $b_{r,i}$ is parameterized in such a way that it is grouped into the receiver pseudorange clock forming $\overline{dt_r}$ and ionospheric delay forming I_i^s . These terms are derived to be:

$$\begin{cases} \overline{cdt_r} = cdt_r + \frac{f_1^2}{f_1^2 - f_2^2} b_{r,1} - \frac{f_2^2}{f_1^2 - f_2^2} b_{r,2} \\ I_1^s = I_1^s - \frac{f_2^2}{f_1^2 - f_2^2} (b_{r,1} - b_{r,2}) \end{cases}$$

Through substitution, the DCM dual-frequency observation equations become:

$$\begin{cases} P_{r,1}^s = \rho_r^s + c(\overline{dt_r} - dt^s) + \gamma_1 \overline{I_1^s} + M_r^s \cdot T_r - b_1^s & + \epsilon_{P_1} \\ P_{r,2}^s = \rho_r^s + c(\overline{dt_r} - dt^s) + \gamma_2 \overline{I_1^s} + M_r^s \cdot T_r - b_2^s & + \epsilon_{P_2} \\ \Phi_{r,1}^s = \rho_r^s + c(\delta t_r - dt^s) - \gamma_1 \overline{I_1^s} + M_r^s \cdot T_r + \lambda_1(N_1^s + B_{r,1} - B_1^s) - \frac{f_2^2}{f_1^2 - f_2^2} (b_{r,1} - b_{r,2}) & + \epsilon_{\Phi_1} \\ \Phi_{r,2}^s = \rho_r^s + c(\delta t_r - dt^s) - \gamma_2 \overline{I_1^s} + M_r^s \cdot T_r + \lambda_2(N_2^s + B_{r,2} - B_2^s) - \frac{f_1^2}{f_1^2 - f_2^2} (b_{r,1} - b_{r,2}) & + \epsilon_{\Phi_2} \end{cases}$$

In decoupling the receiver clocks, the carrier-phase

measurements lose their datum. To remove the estimation singularities, one satellite is selected as the reference satellite, its ambiguities are fixed to arbitrary integer values and used for between-satellite single-differencing. $N_i^{ref} = N_i^{ref} + \delta N_i^{ref}$, where N_i^{ref} are the arbitrarily set integer ambiguities on frequency i and δN_i^{ref} are the differences between the actual integer ambiguities and the arbitrarily set ones. Carrier-phase cycle slips must be detected and changes to the reference satellite accounted for. While initial solution convergence is still a characteristic of uncombined, dual-frequency PPP-AR, the uncombined model solved the problem of brief data outages (solution re-convergence), as the slant ionosphere estimates are used as a bridging parameter between small data gaps.

The dual-frequency model can be expanded to, e.g., quad-frequencies for multi-constellation, multi-frequency (MCMF) PPP-AR. Accounting for the use of a reference satellite per constellation, accounting for any spatial and temporal reference system differences between constellations, and additional inter-frequency pseudorange biases (IFBs) the up to quad-frequency DCM formulation can be derived as:

$$\begin{cases} P_{r,1}^s = \rho_r^s + c(\overline{dt_r} - dt^s) + \gamma_1 \overline{I_1^s} + M_r^s \cdot T_r - b_1^s & + \epsilon_{P_1} \\ P_{r,2}^s = \rho_r^s + c(\overline{dt_r} - dt^s) + \gamma_2 \overline{I_1^s} + M_r^s \cdot T_r - b_2^s & + \epsilon_{P_2} \\ P_{r,3}^s = \rho_r^s + c(\overline{dt_r} - dt^s) + \gamma_3 \overline{I_1^s} + M_r^s \cdot T_r - b_3^s + IFB_{r,3} & + \epsilon_{P_3} \\ P_{r,4}^s = \rho_r^s + c(\overline{dt_r} - dt^s) + \gamma_4 \overline{I_1^s} + M_r^s \cdot T_r - b_4^s + IFB_{r,4} & + \epsilon_{P_4} \\ \Phi_{r,1}^s = \rho_r^s + c(\delta t_r - dt^s) - \gamma_1 \overline{I_1^s} + M_r^s \cdot T_r + \lambda_1(N_1^s - B_1^s) & + \epsilon_{\Phi_1} \\ \Phi_{r,2}^s = \rho_r^s + c(\delta t_r - dt^s) - \gamma_2 \overline{I_1^s} + M_r^s \cdot T_r + \lambda_2(N_2^s - B_2^s) + \delta t_{12} + \epsilon_{\Phi_2} \\ \Phi_{r,3}^s = \rho_r^s + c(\delta t_r - dt^s) - \gamma_3 \overline{I_1^s} + M_r^s \cdot T_r + \lambda_3(N_3^s - B_3^s) + \delta t_{13} + \epsilon_{\Phi_3} \\ \Phi_{r,4}^s = \rho_r^s + c(\delta t_r - dt^s) - \gamma_4 \overline{I_1^s} + M_r^s \cdot T_r + \lambda_4(N_4^s - B_4^s) + \delta t_{14} + \epsilon_{\Phi_4} \end{cases}$$

with:

$$\begin{cases} \overline{cdt_r} = cdt_r + \frac{f_1^2}{f_1^2 - f_2^2} b_{r,1} - \frac{f_2^2}{f_1^2 - f_2^2} b_{r,2} \\ c\delta t_r = c\delta t_r + \lambda_1(\delta N_1^{ref} + B_{r,1}) - \frac{f_2^2}{f_1^2 - f_2^2} (b_{r,1} - b_{r,2}) \\ \overline{I_1^s} = I_1^s - \frac{f_2^2}{f_1^2 - f_2^2} (b_{r,1} - b_{r,2}) \\ \delta t_{12} = \lambda_2(\delta N_2^{ref} + B_{r,2}) - \lambda_1(\delta N_1^{ref} + B_{r,1}) - (b_{r,1} - b_{r,2}) \\ \delta t_{13} = \lambda_3(\delta N_3^{ref} + B_{r,3}) - \lambda_1(\delta N_1^{ref} + B_{r,1}) + \frac{f_2^2 - f_3^2}{f_1^2 - f_2^2} (b_{r,1} - b_{r,2}) \\ \delta t_{14} = \lambda_4(\delta N_4^{ref} + B_{r,4}) - \lambda_1(\delta N_1^{ref} + B_{r,1}) + \frac{f_2^2 - f_4^2}{f_1^2 - f_2^2} (b_{r,1} - b_{r,2}) \\ IFB_{r,3} = \frac{f_3^2 - f_2^2}{f_1^2 - f_2^2} b_{r,1} - \frac{f_3^2 - f_2^2}{f_1^2 - f_2^2} b_{r,2} + b_{r,3} \\ IFB_{r,4} = \frac{f_4^2 - f_1^2}{f_1^2 - f_2^2} b_{r,1} - \frac{f_4^2 - f_2^2}{f_1^2 - f_2^2} b_{r,2} + b_{r,4} \\ \overline{N_1^s} = N_1^s - \delta N_1^{ref} \\ \overline{N_2^s} = N_2^s - \delta N_2^{ref} \\ \overline{N_3^s} = N_3^s - \delta N_3^{ref} \\ \overline{N_4^s} = N_4^s - \delta N_4^{ref} \end{cases}$$

There is therefore the need for accurate and consistent MCMF satellite orbit, clock, code bias and phase bias

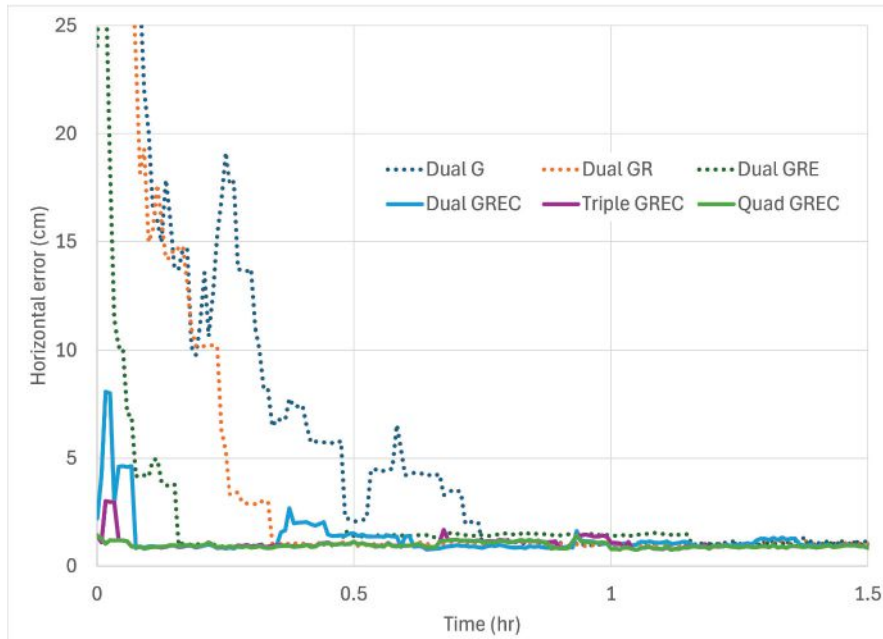


FIGURE 3 PPP-AR horizontal positioning error for various combinations of GNSS constellations and number of frequencies showing average initial convergence for IGS stations CUSV (Thailand), KIR8 (Sweden) and RABT (Morocco) on day of year 128 in 2024. Results presented are the average of 24 hours of data, reset every three hours.

corrections. Some constellation-based corrections, e.g., from QZSS, BDS and Galileo, are appearing.

Results and Analysis

How has PPP positioning solution convergence and accuracy evolved? The above model is now used to illustrate the performance of MCMF PPP-AR with up to four frequencies. The quad-frequency model has been implemented in the York-PPP client engine developed at York University. For performance illustration purposes, Centre national d'études spatiales (CNES) MCMF correction products are used for consistency and one day (day of year 128 in 2024) of high-quality MCMF

GNSS observations are used from each International GNSS Service (IGS) stations CUSV in Bangkok, Thailand, KIR8 in Kiruna, Sweden, and RABT in Rabat, Morocco. Note that data from other days and other comparable stations produce similar positioning results. Simulated real-time, sequential least-squares, kinematic processing was performed for the following observation scenarios: 1) dual-frequency GPS (dual G); 2) dual-frequency GPS and GLONASS (float), with no ambiguity fixing of the frequency-division, multiple access GLONASS signals (dual GR); 3) dual-frequency GPS, GLONASS and Galileo (dual GRE); 4) dual-frequency GPS, GLONASS (float), Galileo and BeiDou (dual GREC); 5) up to triple-frequency GPS, dual-frequency GLONASS (float), triple-frequency Galileo and triple-frequency BeiDou (triple GREC); and 6) up to triple-frequency GPS, dual-frequency GLONASS (float), quadruple-frequency Galileo and quadruple-frequency BeiDou (quad GREC). Operational effects, such as correction latency, are not considered. **Figure 3** demonstrates MCMF PPP-AR horizontal error initial solution convergence for these scenarios, averaged from each 24-hour dataset, reset every three hours across the three global stations.

The dashed time series in figure show the benefits of adding constellations in the PPP-AR processing. From

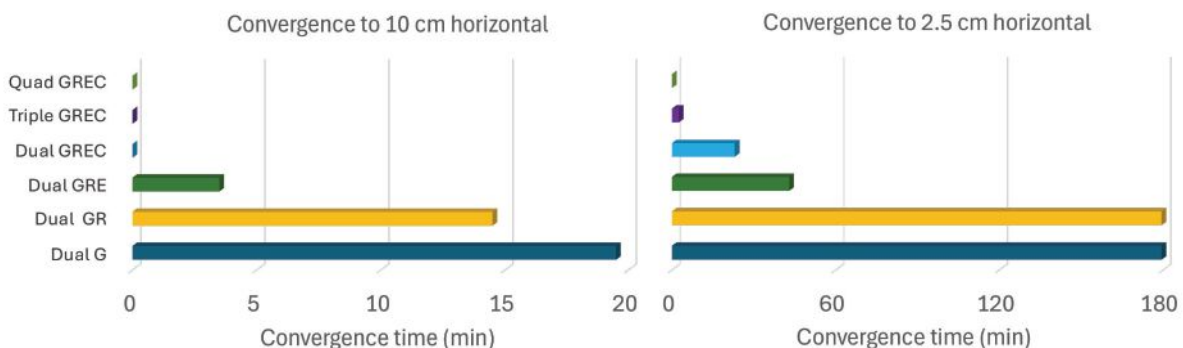


FIGURE 4 PPP-AR horizontal positioning convergence times for various combinations of GNSS constellations and number of frequencies to 10 cm and 2.5 cm for data used in Figure 3.

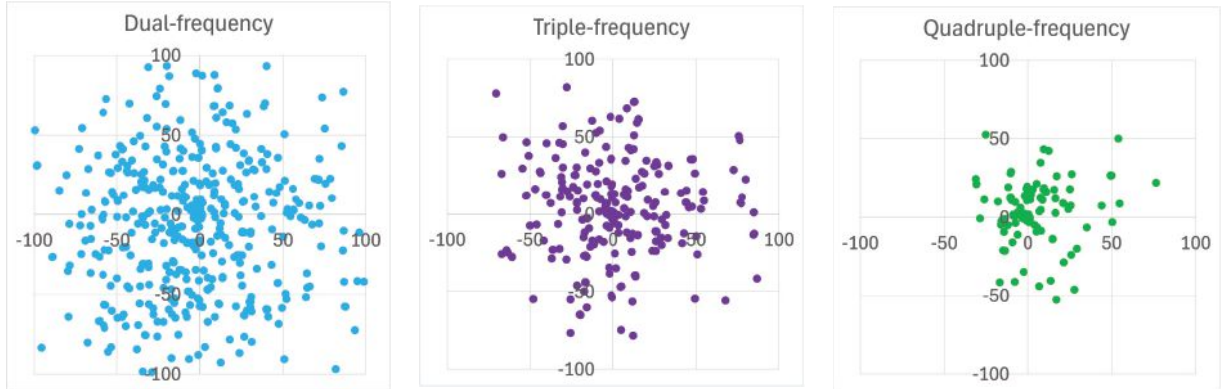


FIGURE 5 MCMF PPP-AR horizontal positioning error for dual-frequency GNSS (left), up to triple-frequency GNSS (center) and up to quadruple-frequency GNSS (right) for IGS stations CUSV (Thailand), KIR8 (Sweden) and RABT (Morocco) on day-of-year 128 in 2024. Results are epoch-by-epoch solutions in the north and east directions in centimeters with 8,640 position estimates in each scenario.

the average of the dual-frequency GPS solutions, the addition of each constellation reduces convergence time by approximately one-half. Then, by adding additional frequencies, convergence time is further reduced to basically instantaneous convergence using available measurements on up to four frequencies from all four GNSS constellations. These results bode well for GNSS data collection in sky-obstructed areas or with lower-quality hardware. **Figure 4** provides the convergence times for the average solutions from each processing scenario to reach and sustain below 10 cm and 2.5 cm horizontal error, respectively. These are typical specifications for numerous static and kinematic applications. Four constellation, dual-frequency data are required to attain 10 cm horizontal positioning error or better near-instantaneously. However, to achieve the 2.5 cm convergence definition, at least triple-frequency data are necessary. The post-10 cm convergence horizontal solution accuracy, as defined by rms error, is 9 cm for dual-frequency GPS and 1 cm for each of the GREC processing scenarios. The post-2.5 cm convergence horizontal solution accuracy, as defined by rms error is 17 cm for dual-frequency GPS and 4 cm for

each of the GREC processing scenarios.

What if a more robust PPP solution is considered that also further analyzes the introduction of additional frequencies? The same three-station, one-day dataset can be processed in an epoch-by-epoch mode, where all filter states are reset. Therefore, there is no filtering with no assumptions about system dynamics. In this case, using a 30-second sampling rate, results in 8,640 position estimate “snapshots” — a robust process of estimation that can be useful for, e.g., clearly defining integrity for safety-of-life applications. The MCMF PPP-AR results for 1) dual-frequency GPS, GLONASS (float), Galileo and BeiDou (dual GREC); 2) up to triple-frequency GPS, dual-frequency GLONASS (float), triple-frequency Galileo and triple-frequency BeiDou (triple GREC); and 3) up to triple-frequency GPS, dual-frequency GLONASS (float), quadruple-frequency Galileo and quadruple-frequency BeiDou (quad GREC). **Figure 5** illustrates the epoch-by-epoch horizontal positioning performance (in cm) for these three scenarios using planimetric subplots. Most position estimates for each scenario are near each subplot center. Adding measurements from the additional

frequencies from the dual-frequency base to up to three frequencies and then up to four frequencies for the same four constellations greatly improves horizontal positioning precision and greatly reduces the quantity and magnitude of positioning outliers.

Table 1 provides the epoch-by-epoch MCMF GNSS PPP-AR horizontal and vertical 68th (1-sigma), 95th (2-sigma) and 99th (3-sigma) percentile positioning error statistics for the same dataset. At the 68th percentile, all scenarios produce centimeter-level horizontal and sub-decimeter-level vertical positioning. However, at the 95th percentile, only triple- and quad-

(units: cm)	GREC Scenario	68th percentile	95th percentile	99th percentile
Horizontal	Dual	1.1	13.6	81.4
	up to Triple	1.1	2.3	46.3
	up to Quad	1.1	2.1	10.3
Vertical	Dual	7.7	30.0	202.0
	up to Triple	7.0	17.5	114.5
	up to Quad	6.8	14.2	44.3

TABLE 1 MCMF PPP-AR positioning error for 68th, 95th and 99th percentiles (in cm) for data used in Figure 5.

Scenario	Dual G	Dual GE	Dual GREC	Triple GREC	Quad GREC
Average redundancy	34	62	121	154	183

TABLE 2 Average estimation redundancy for data used in Figure 5.

frequency processing can produce centimeter-level positioning in the horizontal component and near decimeter-level positioning in the vertical. To assess extreme position estimate outliers, the 99th percentile statistics show that dm-level horizontal positioning can be maintained with quad-frequency processing.

The MCMF PPP-AR filtered results indicate that near-instantaneous, cm-level PPP is achievable with quality geodetic observations. The epoch-by-epoch, unfiltered results imply that robust, centimeter-level PNT is achievable. **Table 2** provides the average redundancy in the epoch-by-epoch processing, where the redundancy is the difference between the number of measurements used and the estimation states. This measure provides insight to how the increase in the number of measurements, while not increasing the number of satellites or the dilution of precision, significantly improves PNT estimation performance for PPP-AR — as this is a measurement-driven technique. The average redundancy increases from 34 to 62 when expanding from dual-frequency GPS to dual-frequency GPS + Galileo and to 121 when using dual-frequency measurements from all constellations. Additionally, increasing processing to include up to triple-frequency measurements and quad-frequency measurements grows this metric to 154 and 183, respectively. The estimation process then becomes more robust against measurement errors and biases. It has more measurement strength to estimate all state parameters, including slant ionosphere refraction terms and integer ambiguities, allowing for improved position estimation precision.

EVOLUTIONARY

MCMF PPP-AR performance continues to improve. Positioning performance for quality geodetic measurements can produce horizontal centimeter-level positioning performance nearly instantaneously. Robust performance can be obtained with epoch-by-epoch processing, resulting in centimeter-level and few-centimeter-level horizontal and vertical positioning at the 95th percentile level using up to quadruple frequency measurements. Also, inclusion of additional measurements from additional frequencies greatly improves estimation redundancy, thereby improving state estimation.

Future research developments, testing and implementation include: adding measurements from available fifth frequencies; investigating less reliance on noisy and multipath-prone pseudorange measurements; expanding robust near-instantaneous PPP in urban environments; further defining/characterizing PPP integrity and safety integrity levels; having PPP be an independent or complimentary solution to/with (N)RTK for precise PNT; minimize requirements for atmospheric corrections; further use of PPP in mass-market hardware; and further integration of PPP as part of sensor suite solutions (e.g., automotive, smartphone, UAV, robotics, etc.) for resilient PNT.

Finally, what is the usefulness of the research in our lives? PPP measurement processing for GNSS is the scientific and industry standard for many user applications. There continues to be growing commercial adoption of this evolving technology, including expanded use in traditional (N)RTK precise applications, mass-market applications using low-cost hardware, and safety-of-life applications, including automotive, other passenger vessels, smartphones, robotics, UAVs and for aids to pedestrians. 🌐

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ADVERTISER	PAGE(S)
CAST NAVIGATION	7
GEODNET	INSIDE FRONT COVER
GPS NETWORKING	15
NOVATEL	BACK COVER
SAFRAN TRUSTED 4D	8,9
SBG SYSTEMS	13



AUTONOMOUS VESSEL COMPLETES SEA TRIALS IN NORWAY

The REACH REMOTE 1, an uncrewed surface vessel developed by Reach Subsea in partnership with Kongsberg Maritime and Massterly, has been officially delivered after extensive sea trials overseen by Det Norske Veritas and the Norwegian Maritime Authority. This 24 m vessel is equipped with advanced hull-mounted survey sensors and a Work Class Electric ROV, designed to enhance subsea operations by improving efficiency, safety and environmental sustainability.



CAR TRACKING LEADS TO SUCCESSFUL ARREST

The Pinole, California, Police Department utilized the StarChase GPS-based tracking system to safely apprehend suspects in a stolen vehicle. Instead of engaging in a dangerous high-speed chase, officers launched a GPS-enabled tracker that stuck to the vehicle, offering real-time location tracking. The Pinhole Police Department told *The Richmond Standard*, "This operation highlights how technology and collaboration keep our community safe — by reducing the dangers of high-speed pursuits while ensuring accountability and swift action."

ESA IN SEARCH OF VERY LOW-EARTH ORBIT TECHNOLOGIES

The European Space Agency (ESA) is seeking innovative space application ideas for very low-Earth orbit (VLEO), an orbital region between 100 km and 450 km. This initiative aims to explore new frontiers in space technology by soliciting creative solutions from researchers and innovators. ESA said VLEO presents several advantages, including reduced launch costs, enhanced Earth observation capabilities and a more harmless radiation environment. ESA is particularly interested in proposals addressing technological challenges specific to this orbital regime, such as atmospheric drag mitigation, advanced propulsion techniques and specialized satellite designs.



3D MAPPING OF NEW ZEALAND COASTLINE

New Zealand has launched a coastal mapping project to help communities understand and mitigate climate change impacts. Led by Toitū Te Whenua Land Information New Zealand, the initiative will use lidar technology to create detailed 3D maps of up to 40% of the country's coastline throughout three years. The \$30.2 million project involves mapping 4,780 square km of coastal and seafloor terrain using specially equipped planes with high-resolution scanning equipment. Two suppliers, Woolpert NZ and NV5 Geospatial, will conduct the mapping across the North and South Islands, beginning in regions such as the Bay of Plenty and Invercargill.



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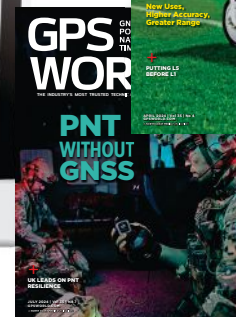
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