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SIMULATORS STRENGTHEN RECEIVER RESILIENCE



THE SPATIAL
AI REVOLUTION

EVOLUTION

SEPTEMBER 2025 | Vol 36 | No 7
GPSWORLD.COM

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GEODNET

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RTK allows for centimeter-level GPS accuracy, with convergence times of under 15 seconds.

Benefits of using GEODNET



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Centimeter level accuracy

Supports ALL signals from GPS, Galileo, BeiDou, and GLONASS

Easy NTRIP Connection

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GEODNET currently is partnered with:



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BY WILLIAM TEWELOW



Krisada Teplakmanont / E+/Getty Images

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BroadSim Wavefront 2.0 is the evolution of Safran Federal Systems' BroadSim Wavefront CRPA test system, designed to advance NavWar simulation. (Credit: Safran Federal Systems)

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Capitol Hill Event Spotlights Urgent Need for GPS Backup Systems

BY DIANE RINALDO
CONSULTANT

GPS is the invisible backbone of modern life, supporting America's national and economic security in ways both recognized and overlooked. While other countries have developed competing systems, GPS remains far ahead of its rivals. Yet that dominance is also a vulnerability. GPS is a single point of failure, and the U.S. lacks complementary positioning, navigation and timing (PNT) solutions. A successful disruption could cost the U.S. economy \$1.6 billion per day and impact everything from first responders to our energy grids.

As threats to GPS reliability mount, policymakers and industry leaders gathered on Capitol Hill to underscore the

urgent need for backup systems to protect America's PNT infrastructure.

Last month, I hosted an event on Capitol Hill called: "The Race to GPS Resiliency: What the US Can Do Today to Strengthen National Security." It brought together senior officials from the Department of Defense (DOD), the Federal Communications Commission (FCC), Congress and industry to make the case for a layered approach to PNT resiliency. These experts examined the technical vulnerabilities of GPS, the increasing frequency of jamming and spoofing incidents, and the policy measures required to expedite the deployment of complementary technologies. 🌐

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

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Published monthly



Shining a Spotlight on PNT, GNSS and More

A glimpse into the future of positioning, navigation and timing (PNT) is coming this month, courtesy of ION GNSS+.

The Institute of Navigation's (ION's) largest technical meeting is an annual event that takes place this year in Baltimore, Maryland, September 8-12.

Over the years, the conference broadened its focus to applications and added a "+" to its name to incorporate all the PNT technology that aids GNSS in location. If you're a longtime reader of *GPS World* magazine, you know we made the same move years ago, too, adding PNT to our stated remit.

International leaders in GNSS and related PNT fields gather at ION GNSS+ to present new research, introduce new technologies, discuss current policy, share new applications, demonstrate products and exchange ideas.

Exhibitors will showcase the latest GNSS technology, products and services. Meanwhile experts will share hundreds of research papers in presentations and panels. This year,

topic highlights include low-Earth orbit satellites for PNT, alternative and resilient navigation in GNSS-denied environments, autonomous systems and applications, and lunar navigation. You can see the full technical program at ion.org/gnss/program.cfm.

At ION GNSS+ 2024, 1,037 registered attendees and 45 paid exhibitors descended on Baltimore. ION said 433 papers were accepted and 285 were submitted for proceedings. Expect more of the same this year.

We're heading to ION GNSS+ this year, and we're excited to meet up with our readers, contributors and sponsor companies. We're also eager to learn more about the latest PNT developments, which we plan to share in print and online in the coming months. 🌐

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Ramberg / E+ / Getty Images

BKZS: Türkiye's Regional GNSS System Takes Shape

BY GEORGE PAPADAKIS, CIVIL AND STRUCTURAL ENGINEER

Türkiye is laying the groundwork for its own satellite navigation system, the Bölgesel Konumlama ve Zamanlama Sistemi (BKZS), or Regional Positioning and Timing System. As a key pillar of Türkiye's 2030 Industry and Technology Strategy, BKZS reflects the country's ambition to gain strategic autonomy in satellite-based positioning, navigation and timing (PNT), moving away from dependence on foreign systems such as GPS.

BKZS was established as one of the 10 flagship goals of Türkiye's National Space Program, introduced in 2021. It directly addresses growing national security concerns: In times of geopolitical conflict, GNSS signals can be jammed or disabled — leaving nations vulnerable if reliant on foreign

services. President Erdoğan's 2030 roadmap emphasizes preparing for "a new era of challenges," where technological independence is seen as vital to national sovereignty.

At the core of BKZS development is innovative timing technology.

Military users stand to gain the most immediate benefits, with access to secure, independent timing and positioning data.

The TUBITAK National Metrology Institute has designed Türkiye's first domestically produced rubidium-based atomic clock for use in positioning satellites. Developed in collaboration with the Turkish Space Agency, the prototype is undergoing qualification testing. Considering that atomic clocks are among the most expensive and sensitive components of a GNSS system, their in-house development not only reduces reliance on foreign suppliers but also delivers significant cost savings and strengthens national expertise. The strategic plan involves an initial technology demonstration phase using a 6U CubeSat, a miniaturized satellite based on the CubeSat standard. This satellite — currently in production — will test the atomic clock in orbit and gather critical performance data, helping to validate system components and gain operational experience ahead of full deployment.

BKZS is being designed as a regional system focused on Türkiye and its surrounding geography. Preliminary architecture envisions an eight-satellite constellation with an estimated cost of \$2.8 billion. While this figure underscores the program's scale, it also reflects the strategic priority attached to securing sovereign PNT capabilities. Military users stand to gain the most immediate benefits, with access to secure, independent timing and positioning data. However, the system also is intended for broad civilian use, including smart transportation systems, precision agriculture, emergency response and disaster management.

Read the full article at gpsworld.com/bkzs-turkeys-regional-gnss-system-takes-shape/ 🌐

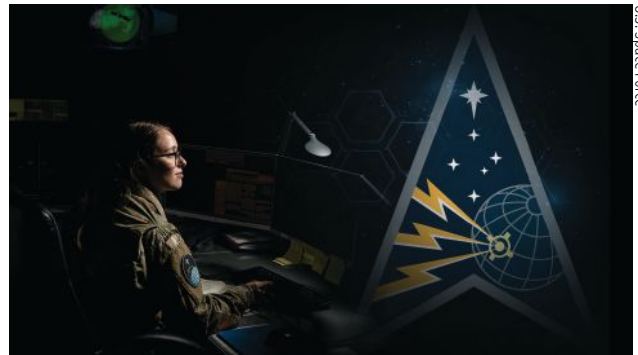
OCX Nears Full Operational Integration

The U.S. Space Force's Space Operations Command has accepted a modernized operating system for GPS, designed to maintain the resiliency of the constellation and enhance PNT services to meet evolving user demands.

The GPS Next Generation Operational Control System (OCX) upgrade is part of a broader set of Space Systems Command acquisition programs designed to deliver a range of modernized capabilities across the GPS III enterprise. In addition to OCX, these programs include the GPS III/IIIF satellite vehicles and Military GPS User Equipment.

The modernization effort is expected to improve signal access in electronically contested environments, increase the system's ability to detect failures, enhance position and time transfer accuracy, and strengthen the integrity and uninterrupted availability of the M-code.

"One of our missions is to deliver sustained, reliable GPS capabilities to America's warfighters, our allies, and civilian users," said Cordell DeLaPena, program executive officer for military communications and PNT at Space Systems Command. "The current enterprise modernization efforts underway give users confidence that GPS will continue to provide worldwide premier PNT service."



US Space Force

Mission Delta 31, in partnership with Space Systems Command, developed a systematic process involving transition exercises, rehearsals and constellation transfer trials to verify the system's integrity and capability prior to full transfer, according to Col. Stephen Hobbs, commander of Mission Delta 31. Hobbs added that risk reduction activities are underway to demonstrate OCX's ability to integrate with existing, on-orbit GPS satellites.

Raytheon initiated the delivery of OCX to the U.S. government with the submission of the Department of Defense Form 250 on July 1, 2025. Following acceptance, Mission Delta 31 will continue integrated systems testing, operational readiness exercises and preparations for the eventual transfer of the GPS constellation to the new system. Hobbs said testing and transition events will continue until the system is ready to transfer to operations, which is expected in late 2025. 🌐

Xona Space Systems Advances LEO Navigation with Pulsar-0 Satellite Testing

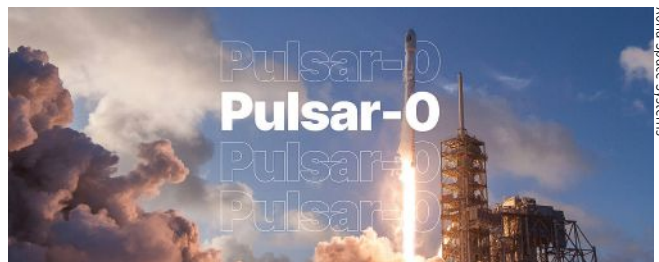
Xona Space Systems' Pulsar-0 satellite, the company's first production-class asset for a commercial navigation constellation, is now operational and undergoing in-orbit testing. Launched in March 2024 on SpaceX's Transporter-10 mission, Pulsar-0 is designed to assess the performance of Xona's Pulsar architecture, which aims to provide high-accuracy, resilient PNT services from low-Earth orbit (LEO).

According to Xona, Pulsar-0 is transmitting LEO-based PNT signals using a payload built to support signal authentication and resilience against interference, capabilities that have

become more important as concerns about vulnerabilities in traditional GNSS systems increase.

The system's encrypted and authenticated signals are designed to mitigate risks from jamming and spoofing, delivering stronger and more reliable service in environments where legacy GPS may be degraded.

Xona's Pulsar constellation is being developed as a commercial complement to GNSS, offering



Xona Space Systems

centimeter-level accuracy and greater resistance to interference through modernized signal design and LEO deployment. The company reports that its initial signal waveforms already are being used by select government and commercial partners for prototyping and validation. 🌐

1. TRIPLE-BAND MODULE

FOR HIGH-PRECISION APPLICATIONS IN GROUND AND AIR ROBOTICS

The ZED-F20P is a L1/L2/L5 triple-band GNSS module. It provides OEMs deploying fleets of ground robots, drone light shows, and other dynamic autonomous platforms with centimeter-level RTK and precise-point positioning (PPP)-real-time kinematics (RTK) positioning, fast convergence times, and integrated security features. The ZED-F20P delivers deterministic, centimeter-level and PPP-RTK accuracy tailored to the needs of lightweight and dynamic platforms. Its end-to-end silicon-to-firmware architecture supports 25-Hz update rates, robust security features and low power consumption in a streamlined design. These capabilities combine to deliver industrial-grade reliability and enable smooth scaling from proof-of-concept to high-volume deployment without increasing system cost, power consumption, or integration complexity.

u-blox, u-blox.com



2. MEMS ACCELEROMETER

FOR MEASUREMENT WHILE DRILLING IN THE ENERGY SECTOR

The Tronics AXO315T0 is a high-temperature MEMS accelerometer designed for measurement while drilling (MWD) applications. It features a ± 14 g input range and a digital interface. It uses TDK's closed-loop architecture, which delivers advanced

vibration rectification and resistance to operational shocks. The device maintains a bias residual error of 0.8 mg across its operating temperature range of -30°C to $+150^{\circ}\text{C}$, enabling precise and continuous inclination measurements for directional drilling tools exposed to high temperatures. To meet the demanding reliability requirements of complex drilling



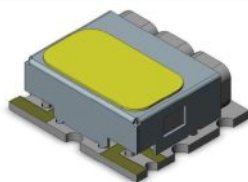
operations in harsh environments, the AXO315T0 offers a typical bias drift of less than 1 mg without recalibration after 1,000 hours at high temperature, providing a digital, low size, weight and power (SWaP) alternative to traditional quartz accelerometers. This advancement supports a new generation of measurement-while-drilling tools capable of long-term operation at elevated temperatures without compromising performance.

TDK Tronics, www.tdk.com

3. CERAMIC FILTER

SUPPORTS JAM RESISTANCE IN GNSS RECEIVERS

High-Q ceramic bandpass filters present a technical opportunity to build jamming-resistant GNSS receivers for mission-critical applications. Bandpass filters play a critical role in mitigating GNSS jamming by isolating legitimate satellite signals from interference. These filters are designed to allow frequencies within the GNSS operational bands (GPS L1/



L2, Galileo E1/E5) while attenuating out-of-band noise and intentional jamming signals. With their low cost and compact form factor, surface acoustic wave (SAW) filters are a natural fit for GNSS receivers, but they struggle in high-interference conditions due to limited out-of-band rejection and broader skirts. While SAW filters continue to meet performance requirements for consumer devices and systems, high-Q ceramic filters offer a robust upgrade for mission-critical applications needing mechanical and thermal stability, predictable tuning characteristics, and long-term reliability.

Knowles, knowlescapacitors.com

4. RTK BOARD

ADD-ON ACHIEVES SUB-METER ACCURACY



GNSS RTK 4 Click is a compact add-on board that provides high-precision GNSS positioning with RTK. The board features the LG290P, a quad-band GNSS module from Quectel capable of receiving signals from GPS, GLONASS, Galileo, BeiDou, QZSS and NavIC while using SBAS for enhanced accuracy. Applications include autonomous navigation, UAVs, intelligent robotics, surveying, and precision agriculture. GNSS RTK 4 Click supports multi-mode RTK algorithms with fast convergence times and high accuracy, as well as interference detection and integrity monitoring, ensuring sub-meter

positioning in demanding environments. It features UART and L2C interfaces, a USB Type-C port for standalone configuration, and a backup battery option for continuous operation. GNSS RTK 4 Click also features the ClickID function, which enables automatic identification by the host system, simplifying use.

Mikroe, mikroe.com

5. INERTIAL MEASUREMENT UNIT

HIGH ACCURACY AND STABILITY FOR DEMANDING CONDITIONS

The Xsens Avior is a lightweight, OEM form factor inertial measurement unit (IMU) with a compact 36.8 x 40mm footprint that offers enhanced performance in a wide variety of industrial and commercial applications. It is suitable for products manufactured in high volume thanks to its vertical 10x2-pin socket connector for simple board mounting, and its tolerance of any mounting orientation in all three axes. The product eases design integration, with UART, CAN, SPI and I2C interfaces on board and support for RS232 and RS422 via the product's development kit or an external transceiver. Heading accuracy is 1° RMS and roll and pitch accuracy is 0.2° RMS. In-run bias stability is 8°/hr in the gyroscope and $15\mu\text{g}$ in the accelerometer. Weighing 35.2g, the Xsens Avior is enclosed in a robust aluminum housing and has a rating of IP51 and an operating temperature range of -40°C to $+85^{\circ}\text{C}$. Applications include drones, 3D mapping and marine remotely operated vehicles.

Xsens, xsens.com





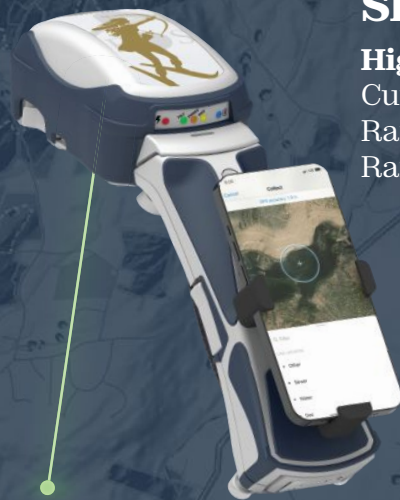
The Skadi Series™

High-Accuracy GNSS Receivers for Any Device or App

Skadi Tilt Compensation™

No more bubbling up!

Increase your productivity,
by reducing your time on each point.



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High Accuracy meets high portability

Cutting-edge sensors put an Invisible
Range Pole™ and an Extensible Virtual
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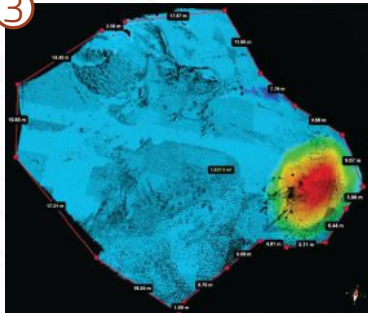
①



②



③



④



1. GEOSPATIAL SYSTEM

CENTIMETER-LEVEL ACCURACY FOR SLAM MOBILE MAPPING

Integration of the RTK-capable Trimble DA2 GNSS system with the Nexys autonomous mapping platform brings centimeter-level geospatial accuracy to SLAM-based mobile 3D mapping. Users can pair Exyn Nexys' lidar-based SLAM mapping with high-precision RTK corrections, allowing teams to georeference and anchor point clouds in the field without relying on ground control points or post-processing workflows. The result is faster, safer and more accurate decision-making for industries including mining, construction and critical infrastructure inspection. Intelligently combining RTK and SLAM delivers highly accurate and robust point clouds — even in challenging environments. When paired with the real-time colorization, users gain an added layer of visual context, enabling photorealistic mapping and the extraction of immersive georeferenced 360° imagery for enhanced situational awareness and analysis.

Exyn, exyn.com; Trimble, trimble.com

2. HYDROGRAPHIC USV

UNMANNED SURFACE VEHICLE FOR INLAND AND NEARSHORE WATERS

The HydroBoat 1200MB USV system for 3D hydrographic surveying integrates SatLab's autonomous vessel platform with the HydroBeam M2 multibeam echosounder in a portable unit. It can assist small teams with geospatial reconnaissance and hydrographic assessments. The HydroBoat 1200MB is fully integrated, combining navigation, sonar data acquisition, real-time visualization and data management. It supports a seamless workflow, from survey planning through to the delivery of final results. The integrated inertial navigation system delivers roll, pitch and yaw measurements without requiring field calibration. Real-time data visualization allows users to view high-resolution 3D point clouds, bathymetric profiles and sidescan imagery across multiple devices for immediate quality control and decision-making in the field. The USV can be used for river and reservoir surveys, bank mapping, structural inspections, sediment transport monitoring and infrastructure assessment.

SatLab, satlab.com

3. LASER SCANNER

HANDHELD FOR INDOOR AND OUTDOOR MAPPING

The SinoGNSS LS600 laser scanner is a handheld 3D scanning device designed for professional use in both indoor and outdoor environments. It integrates lidar, GNSS, an IMU and dual-camera systems for detailed, colorized point clouds and precise positioning data production. The LS600 includes advanced SLAM algorithms that work with a built-in RTK GNSS module. This combination allows the scanner to achieve centimeter-level accuracy, even in challenging environments. Dual 16 MP wide-angle cameras capture vivid, multi-angle color data merged with lidar data through visual-aided SLAM. Flash Point Cloud Technology enables real-time visualization of point cloud data immediately after scanning.

ComNav, comnav.com

4. DATA-PROCESSING

CLOUD PLATFORM FOR 3D DATA PROCESSING, ANALYSIS

CoCloud is a cloud-native platform developed for 3D data processing, management and collaborative analysis. It is designed to handle multi-source 3D data and supports streamlined workflows from data acquisition to deliverable creation, eliminating the need for local hardware investment. CoCloud incorporates an advanced photogrammetry engine capable of efficiently processing data from sources such as aerial imagery and lidar scans. The platform produces digital orthophotos, point clouds and OSGB models with a high level of precision suitable for professional applications. The platform offers tools for online data visualization, sharing and real-time collaboration on tasks such as volume calculations and point cloud editing. Its interface is designed to be intuitive and user-friendly, so users can perform complex 3D data operations without requiring extensive specialized training. CoCloud supports a range of data formats and includes features for dataset and timeline management.

CHC Navigation, CHCNAV.com

TEST RELENTLESSLY DEPLOY DECISIVELY OWN THE MISSION



Next-Gen NAVWAR Simulation with BroadSim Genesis

Massive Signal Capacity

BroadSim Genesis supports generation of up to 2000 signals, enabling advanced multi-constellation simulations across MEO, LEO, and alternative PNT sources—all in a single test environment.

Resiliency and NAVWAR Readiness

Designed to meet modern NAVWAR demands, BroadSim Genesis supports multi-antenna and multi-vehicle configurations, M-Code, and robust integrated jamming and spoofing capabilities to test against the most sophisticated signal threats.

Operator-Friendly Design

An intuitive UI, integrated front panel with SMA connectors, extractable drives, and onboard timing card make BroadSim Genesis easy to use, secure, and field-ready.

Be the first to receive details about our simulator upgrade program - coming soon!

sales@safranfs.com



JOIN THE WAITLIST



GNSS SOLUTIONS



Q+A with GEODNET Mike Horton

What is your most proven GNSS solution?

GEODNET's most proven GNSS solution is its global RTK network, which consists of more than 18,500 GNSS base stations that deliver real-time centimeter-level corrections. The network has been recognized by U.S. Congress and adopted by major institutions, including the U.S. Department of Agriculture, for its precision and accessibility.

What are the solution's key specifications?

The network supports GPS, GLONASS, Galileo and BeiDou, providing multi-band RTK corrections via NTRIP in RTCM 3.x MSM format with 1 Hz updates and typical latency of less than 1 second. Rover accuracy can reach 1 cm plus 1 ppm, depending on baseline distance.

What are the solution's key features and benefits?

Our decentralized model delivers enterprise-grade accuracy at a fraction of the cost, offering dense coverage, reliable uptime and token rewards for hosts. We offer a price match guarantee to make high-precision GNSS more accessible for professionals. If we can't beat your current RTK plan, we'll give you three months of GEODNET service for free.

Mike Horton, Project Creator
GEODNET



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GNSS SOLUTIONS



Q+A with NovAtel Suren Shanmugam

What is your most proven GNSS solution?

SPAN (Synchronous Position, Attitude and Navigation) technology is Hexagon | NovAtel's proprietary sensor fusion solution that optimally combines GNSS and inertial positioning to deliver best-in-class robust, accurate and reliable positioning, attitude, and navigation information, even in challenging environments where GNSS signals alone may be unreliable or even blocked.

What are the solution's key specifications?

SPAN GNSS+INS technology is available as a compact single enclosure, as in NovAtel's CPT7 and PwrPak7D-E1/E2, and it supports external inertial systems.

Our flagship CPT7 product is a

compact, dual-antenna GNSS/INS enclosure that uses a tactical-grade inertial measurement unit (IMU). It supports external wheel sensor input and precise time protocol (PTP) and features internal storage and standard communication protocols such as Ethernet, USB, and RS-232 for ease of integration.

Additionally, customers can leverage NovAtel's GRIT (GNSS Resilience and Integrity Technology) to manage unwanted interference signals and achieve centimetre-level positioning globally with TerraStar Correction Services without the need for a cellular modem or local base station.

What are the solution's key features and benefits?

SPAN's unique design deeply couples the multi-constellation and multi-frequency GNSS observations with high-rate inertial updates, ensuring maximum solution availability and continuity even in challenging operating environments.

SPAN technology is designed to operate with external IMUs from entry-

level to mid- and high-performance ones, providing customers with flexibility in terms of cost, performance, and compliance.

NovAtel's dual-antenna enclosures further enhance the SPAN solution with rapid and accurate IMU initialization and reduced drift, improving the overall fused solution.

These features and benefits are critical for unmanned systems, mobile mapping, aerial survey, automotive, and defense applications.

Suren Shanmugam, Senior Product Manager, GNSS Enclosures, SPAN and Software



The flagship GNSS+INS dual-antenna enclosure CPT7 from Hexagon | NovAtel.



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Calgary, Alberta, Canada
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communications@novatel.com
Web:
www.novatel.com

GNSS SOLUTIONS



Q+A with Safran Navigation & Timing Guillaume Obry

What is your most advanced GNSS solution?

Without a doubt, that would be Skylight. It's one of Safran's most advanced and flight-proven GNSS solutions to date in terms of performance and resiliency. We designed it with resilience, compactness and integrity in mind. It's a multi-constellation GNSS receiver, delivering outstanding navigation performance across a wide range of airborne military platforms, from fast jets and helicopters to UAVs.

Skylight underwent rigorous flight trials on a combat aircraft, and the results were impressive in terms of availability, integrity and performance. Our solution already has been selected by two major aerospace manufacturers, including Airbus Helicopters, which has integrated Skylight into its H225M platform. In today's threat environment, where PNT resilience is not an option, Skylight delivers agility, precision and robustness, even in the harshest environments.

What are the solution's key specifications?

Skylight is truly built for the battlefield. It's the first GNSS receiver to be flight-tested with compatibility for Galileo Public Regulated Service, which provides encrypted, spoofing-resistant signals. This is a critical game-changer for operations in contested airspace.

What are the solution's key features and benefits?

- First, Skylight embeds a comprehensive Interference Detection & Monitoring (IDM) algorithm. This IDM suite offers a comprehensive array of GPS/GNSS spoofing and jamming monitoring and detection.
- Skylight also is compatible with both encrypted Galileo PRS and M-code, which ensures it can operate seamlessly alongside U.S. and allied military systems.
- It includes a certified civil GPS channel, which means it also can operate in civil airspace without the need for a separate civil GPS receiver. That saves weight and cost, especially important for integrators working with tight platform constraints.
- Skylight also is fully compatible with our SkyNaute inertial navigation system. When integrated together, they offer enhanced reliability and resilience, especially critical in GNSS-denied or contested environments.

- Finally, we also offer an atomic clock upgrade option for missions that demand ultra-precise timing. That adds another layer of performance and resilience, especially for time-sensitive operations.

Skylight is the first flight-proven GNSS receiver designed for military use, providing armed forces with a strategic advantage. As threats to GNSS technology grow increasingly sophisticated, staying ahead is essential. With its compact design, operational flexibility, and future-ready architecture, Skylight is ideally suited for modern and future defense programs.

Guillaume Obry, GNSS Product Manager



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GNSS SOLUTIONS



Q+A with Safran Federal Systems Jaemin Powell

What is your most proven GNSS solution?

BroadSim, the flagship GNSS simulator from Safran Federal Systems, is our most proven solution — trusted across government, defense and commercial sectors. It sets the benchmark for high-dynamics, NAVWAR-ready simulation with real-time flexibility and unmatched signal fidelity. Building on this legacy, BroadSim Genesis represents the next generation of GNSS simulation. This advanced system supports more than 2,000 signals, including approved M-code (AES, MNSA, SDS) and Y-code generation, with integrated jamming and spoofing capabilities — all housed within a compact 4U chassis.

What are the solution's key specifications?

Key specifications include six RF outputs covering L1, L2, L5 and L6 frequencies, enabling complex and realistic multi-frequency test scenarios. Powered by the Skydel Engine, BroadSim Genesis operates at a consistent 1000 Hz, delivering true all-in-view signal generation across all current GNSS and LEO PNT constellations. With ultra-low latency down to 10 ms and zero effective latency, it is ideally suited for hardware-in-the-loop (HIL), real-time navigation, and dynamic threat simulation.

What are the solution's key features and benefits?

The solution's software-defined architecture ensures rapid innovation and adaptability, keeping pace with emerging threats and evolving test requirements. BroadSim Genesis combines robust performance, flexible signal modeling, and mission-focused features to meet the most demanding simulation needs — making it the definitive tool for PNT assurance, NAVWAR testing and next-generation receiver validation. We recently launched a program so simulation users can upgrade their legacy systems and easily convert scenarios.

Jaemin Powell, Senior Product Manager
- NAVWAR & Simulation



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GNSS SOLUTIONS



Q+A with Quectel Florian Bousquet

What is your most proven GNSS solution?

Quectel's LG290P, LG580P and LG680P are our flagship quad-band, multi-constellation GNSS modules, trusted by global customers in precision agriculture, robotics and autonomous systems for their field-proven centimeter-level positioning.

What are the solution's key specifications?

All three modules feature 1040 tracking channels and support concurrent reception of GPS, GLONASS, Galileo, BeiDou, QZSS and NavIC across L1, L2, L5 and E6/L6 bands. They deliver centimeter-accuracy RTK positioning and offer update rates up to 20Hz. The LG580P also supports dual-antenna GNSS heading for advanced orientation capabilities.

What are the solution's key features and benefits?

The modules achieve ultra-fast, five-second RTK convergence time using innovative algorithms specifically engineered for harsh environments, maintaining reliable centimeter-level positioning under dense canopy or in urban canyons. Advanced RTK features include long-baseline support and 10-minute correction outage tolerance, significantly reducing infrastructure dependency. For global operations without ground infrastructure, upcoming precise point positioning support from Galileo E6 or BeiDou B2b will enable standalone decimeter-level accuracy, positioning these modules as the ideal solution for next-generation autonomy.

Florian Bousquet, Senior GNSS Sales Manager



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The Spatial AI Revolution

Headlong into the Age of Intelligence

BY WILLIAM TEWELOW

The intriguing paradox about the information age is that it relies on semiconductor chips, which are fundamentally made from sand (silicon dioxide) — the most tangible and seemingly infinite resource on Earth. Yet, in 2023, the global digital storage capacity reached 110 zettabytes (110 followed by 21 zeros), which is a staggering figure; in fact, it is 15,000 times more than the number of grains of sand on Earth — and it's doubling every three years. The information age is suffering from excess information. Data is consuming the universe.

The velocity and quantity of information are overloading the ability to process it. This causes data-driven decision-making systems to fail. The limiting factor is human cognitive capacity to select, prepare and process the data, plus the ability to analyze it for meaningful insights.

It is reminiscent of the early days of the Corona satellites of the TALENT KEYHOLE (KH) mission series that began in the 1950s during the height of the Cold War.

Understanding activities behind the Iron Curtain was critical for national security. The KH satellites were expensive to launch and had short life spans. They used rolls of wet film dropped from space and captured by specialized aircraft with hooks to catch the canisters in mid-air. The low-resolution images (3 m to 5 m per pixel) were processed manually in darkrooms. Teams of 100 specialists, using razor knives and scotch tape, meticulously pieced together image strips into



PRESIDENT EISENHOWER awards Capt. Mitchell, USAF, C-119 pilot, the Distinguished Flying Cross for the first ever capture of a film cartridge dropped from space, in a photo circa 1960.

massive mosaics spanning several square meters. Working around the clock, assembling the full image would take up to five days, with subsequent analysis requiring another week. In total, from catching the film canister to delivering a final intelligence report, it took 17 days — a testament to imagery intelligence in the industrial era, characterized by massive operations demanding significant time and manpower, but it

“We live in a world where there is more and more information, and less and less meaning.”

— Jean Baudrillard,
“Simulacra and Simulation,” 1994

was too expensive and unsustainable.

In 1976, the technological landscape shifted dramatically with the launch of the KH-11 satellite, which could transmit 15 cm resolution images digitally to ground stations and was capable of distinguishing objects as small as a dinner plate. The satellite dramatically compressed intelligence-gathering timelines. Processing and analysis time decreased from 17 days to mere hours. The first digital image was shown to President Carter. That first image is believed to be of ongoing tensions in the Middle East, but it symbolized more than the triumph of technology; it represented a fundamental shift marking the end of the industrial era and ushered in the information age.

Advancements in imagery were paralleled by developments in mapping, driven by the need for accurate spatial referencing. Various

cia.gov/resources/csi/static/corona.pdf

technologies throughout the 1970s offered partial solutions, but a solution did not happen until 1981 when Esri introduced Arc/INFO, a breakthrough geographic information systems (GIS) software that could operate on minicomputers instead of huge mainframes. That formed the basis of modern spatial analysis and visualization technologies; coming together with digital imagery is what allowed the information age to overtake the industrial era.

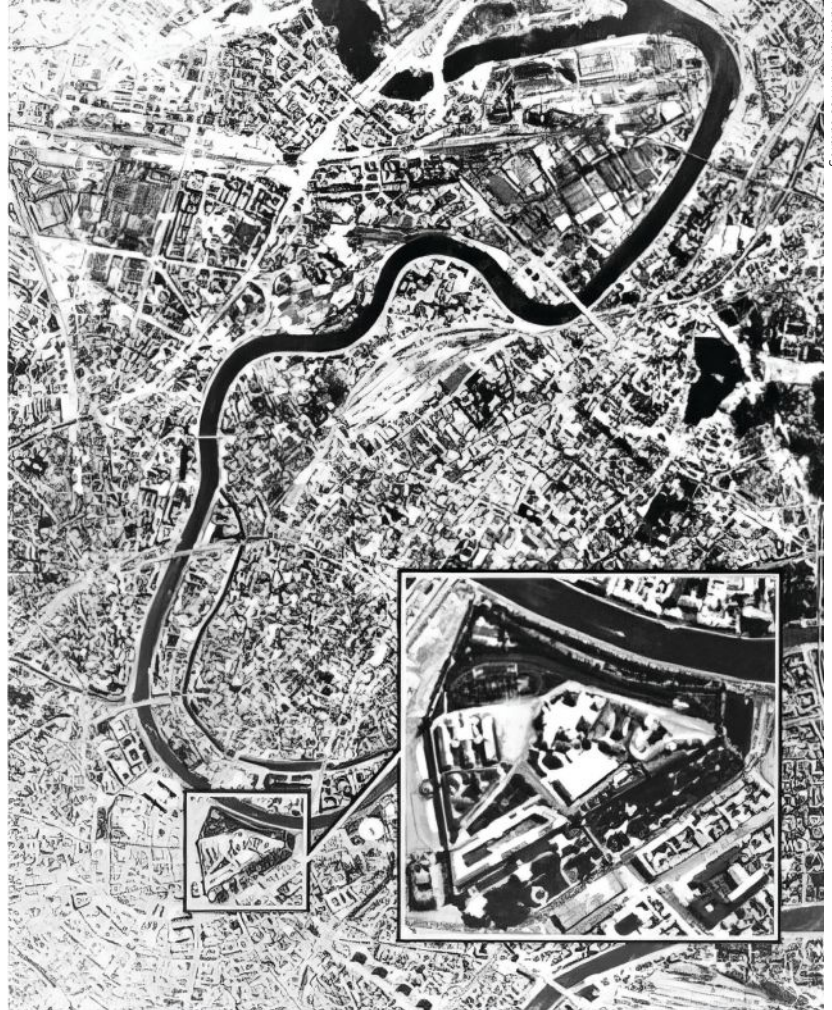
In 2025, a similar technological transformation currently is underway. As the amount of information overwhelms existing systems, artificial intelligence (AI) is emerging as the solution. The information age is transforming into the intelligence age, where big processing meets big data. Advanced algorithms, machine learning and large language models (LLM) can swiftly and efficiently handle vast amounts of information. So, with data being the new oil, AI is the refinery.

The Esri Federal GIS Conference in February could have been promoted as the “Dawn of GeoAI” conference. The term Geo AI is a subset of Spatial AI, and it is in its infancy. Esri is incorporating AI into many of its applications. Companies at the expo were teasing Spatial AI solutions in their products and services.

What is Spatial AI?

When the transformative power of AI is combined with spatial information systems, magic happens. Value is created that did not exist before.

Spatial intelligence is the ability to think, visualize and understand in three dimensions. It is one of the primary types of intelligence. Currently, Spatial AI is capable of interacting with analysts using natural language to build models and perform tasks. Similar to so much else happening with AI, its capabilities are increasing rapidly.



A CORONA SATELLITE image of Moscow captured May 28, 1970, as part of the **TALENT KEYHOLE** reconnaissance mission series.

With iterative learning, the AI repeats a task millions of times on various training data to perfect its abilities, running through different scenarios multiple times with different datasets while completing multiple tasks. The AI quickly learns and can eventually surpass humans. This makes AI a super tool.

Combine that capability with AI's ability to access and infer an entire compendium of knowledge on a subject. The AI is able to ingest text, images, audio and video in minutes, and then reason and understand them all within the context of the parameters provided. Through its

own AI agents, it will automatically run functions to garner insights, and then communicate those results through data visualizations, text, audio and natural speech. Spatial AI is an evolved form of AI able to understand data in the context of space and time within the body of knowledge it can access. It will monitor everything in real time to identify anomalies and hidden patterns and provide deep insights. It doesn't just solve the information overload dilemma for data-driven decision-making, but it enhances it far beyond expectations.



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- > Successive
- Angle-of-Arrival
- > Collaborative GEO



The Coming World of AI Assistants

The future is already here. Reality is approaching science fiction at warp speed. A person living 100 years ago would only be able to understand the world of today as magic; and likewise, the world 20 years from now will appear magic to us.

Interfacing with a Spatial AI system is similar to the multi-dimensional world we already exist within. Flat screens, keyboard and mouse will be secondary tools behind natural language and natural gestures and immersive experiential environments. The Spatial AI-enabled world will blur the lines between what is virtual and what is real. Jobs, businesses and the economy already are transitioning. The most well capitalized businesses are investing in this new technology.

One of the industries at the forefront is healthcare. Imagine you are a neurosurgeon. Your patient has a glioblastoma identified by the MRI/CT scans uploaded into the Spatial AI Medical Assistant called SAIMA (pronounced Sāmā; when speaking with the system, you call it “Sammi”). The MRI/CT scans show a 3D model of the patient’s brain, highlighting the glioblastoma in red. Placing the integrated augmented reality (AR) glasses on, you can zoom in on the glioblastoma to see the extent of the growth and view it from any angle. This helps formulate a surgery plan.

The patient’s medical records are in SAIMA along with the corpus of knowledge about glioblastomas. SAIMA is regularly updated with the latest algorithms and models. After reviewing the preliminary data, you have SAIMA run the spatial analytics and all the applied functions on the data. It takes approximately 35 minutes to complete. During that time, you review the SAIMA updates and go to lunch. You receive a text message from SAIMA after it completes its processing, letting you know it is



Krisada Teekulnanont / E+ / Getty Images

finished without encountering any issues. SAIMA works with a system called VisAR, which is a precision surgical navigation system. After returning to your office, you put on the VisAR glasses to begin the review. Sammi begins by showing you the glioblastoma and pointing out it is a large, heterogeneous mass located in the frontal lobe and appears to be 4 cm to 5 cm in diameter, in an irregular shape with nodular and cystic components. As it goes through the review, it zooms in and rotates the 3D image, highlighting the exact area being talked about. You interrupt Sammi during this review and ask if the patient has been experiencing motor function issues since the tumor is in the frontal lobe, and you continue to probe further in a natural conversational tone as you delve deeper into the analysis. The conversation between you and Sammi is recorded and added to the file.

The review with Sammi takes several hours, during which a high-confidence surgery plan is developed that you will present to the multidisciplinary tumor board, who will further query SAIMA. This thorough process ensures the best

results and further trains SAIMA about glioblastomas, which will be used for a post-surgery debrief and for insurance purposes. Following a successful board meeting, SAIMA proceeds to reserve the operating room, schedule the patient, and create a detailed surgery plan with specific duties and exact times for each member of the surgical team. This plan is then disseminated to all members of the surgical team and preoperative staff. A detailed surgical procedure file is generated, which serves as a navigation file, similar to Waze or Google Maps, providing step-by-step instructions to guide the surgery. This file will be loaded into ROSA (Robotized Surgical Assistant), a high-precision robotic surgeon.

On the day of the surgery, you wear special Bluetooth gloves that are synced with the SAIMA/VisAR glasses and ROSA. In real-time, magnified between 15x and 40x, you observe ROSA surgically removing the cancerous tissue. Overseeing the process, you see a tumor that has spread beyond the original CT/MRI scan and zoom-in on the tumor, and you take control of ROSA to manually remove the tissue. The

surgical system uses a “differential engine” concept to scale down the surgeon’s movements to match the magnification level of the procedure, allowing for precise and delicate tissue removal. This means that the surgeon’s natural movements are reduced to a smaller, more precise scale, enabling accurate and intricate procedures. For example, a 1 cm movement by the surgeon might be translated into a 0.1 mm movement of the robotic arm, allowing for high-precision work. The system is dependent upon a high-level of spatial intelligence to make those calculations in real-time.

Afterward, you return the surgery back to the automated control of ROSA to follow the surgical procedure file plan. Throughout the fully immersive procedure, you speak with Sammi in a calm, natural language and responsive manner.

The patient, a married middle-aged father of two, not only survives but thrives because of the accurate analysis of SAIMA and the precision of ROSA, with you overseeing the entire process. The Spatial AI-based surgical system allows you to do what you wanted to do as a neurosurgeon and save people’s lives.

Nothing is Permanent Except Change

Breakthrough innovations, such as the internet, have changed the world. Spatial AI is going to do the same. These technologically driven schisms are huge opportunities. One can only speculate how it will alter the future. Once a technology takes hold, and it becomes obvious there is no going back, its adoption will accelerate, and in those moments, careers make exponential leaps. Those in front of it will make substantial gains. Position yourself accordingly. Learn about Spatial AI and Geo AI. Carve out your own specialty, such as Spatial AI/AR (augmented reality), Spatial AI/VR (virtual reality), Spatial AI/XR (mixed reality), and Spatial AI/FMV (full motion video). The future is yours to imagine. 🌐

WILLIAM TEWELOW is a designated Geographic Information Systems Professional. He has a master’s degree in Organizational Leadership with a focus on Performance Management, a bachelor’s degree in Intelligence Studies focused on geospatial intelligence, and an undergraduate degree in Geographic Information Technologies.



William retired from the Federal Aviation Administration in 2025 after 16 years in various roles supporting geospatial information for aviation operations in the national airspace. He is a graduate of the management fellowship Program for Emerging Leaders where he served on special assignment to the Department of Transportation, leading a national strategic geospatial initiative under the authority of the White House Open Data Partnership.

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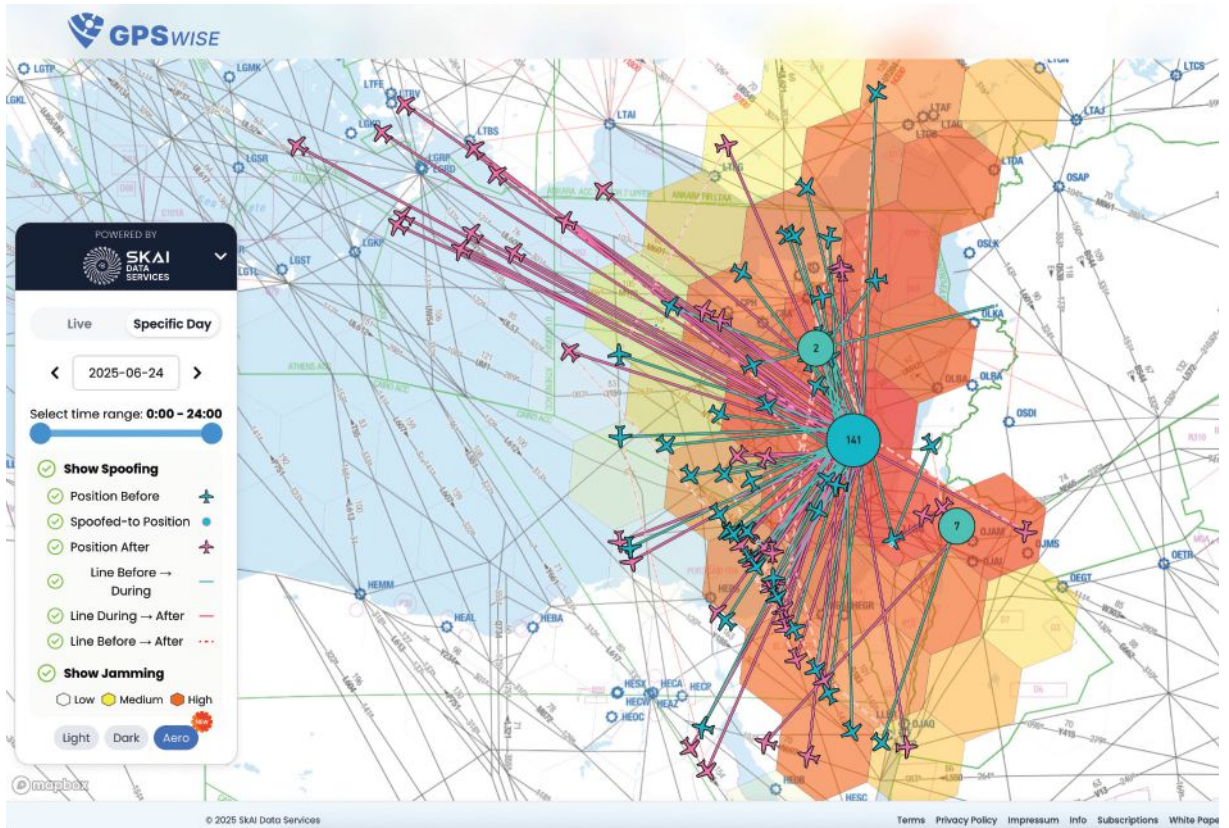


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SKAI DATA SERVICES' GPS Spoofing and Jamming Tracker Map uses live ADS-B data from the OpenSky Network to display potentially spoofed aircraft and recent GPS jamming activity in real time.

TESTING GNSS RECEIVERS AGAINST JAMMING AND SPOOFING ATTACKS

— MARKUS IRSIGLER, SEBASTIAN KEHL-WAAS, CARSTEN STÖBER, JÜRGEN DAMPF, ROHDE & SCHWARZ GMBH & CO. KG

GNSS jamming and spoofing pose a significant threat to global security, as satellite-based navigation and timing systems are utilized in various application fields, including critical infrastructure, transportation, military operations and communication networks. These intentional interferences disrupt signals or deceive GNSS receivers, leading to navigation errors, loss of situational awareness and potential safety hazards.

Local, low-power jamming is often used to deliberately prevent GNSS-capable devices from recording positions and being tracked. Such jamming devices, known as

personal privacy devices (PPDs), typically are used to prevent fleet monitoring, concealing personal travel, or evading toll systems. Although mostly illegal, PPDs are fairly widespread and can pose a significant threat to GNSS availability, at least on a local scale.

On the other hand, large-scale incidents are frequently observed. Regional jamming often occurs in conflict zones to protect military assets or disrupt enemy operations. Jamming also has been reported near critical infrastructure. Spoofing typically is less frequent than jamming, but it poses a more concerning integrity threat when incorrect PVT data is used for navigation. Well-documented events include the (in)famous 2017 incident



affecting ships in the Black Sea, where a spoofed GNSS signal led vessels to report incorrect positions. Jamming and spoofing also play an important role in the Ukraine conflict, where it is used to disrupt enemy drones, guided munitions and navigation. Such events clearly highlight the vulnerability of GNSS-dependent systems and the need for robust mitigation techniques and strategies.

Against this background, testing how GNSS devices react to such threats has become more and more important, especially if they feature dedicated jamming detection and mitigation techniques. In such cases, the main test objective is to verify that these detection and mitigation techniques work as expected and that the GNSS receiver reacts properly and as expected in response to such attacks.

Categorization of GNSS Threats

The most critical and common GNSS threats originate from interference signals that occur in the vicinity of a receiver. Unlike system-inherent threats that originate from GNSS satellites or atmospheric conditions, these

threats can be termed as “man-made.”

Jamming can be divided into two types of attacks. **Brute-force jamming** aims at completely blocking GNSS reception for a receiver by deliberately emitting interference signals like CW interferers, broadband noise or frequency sweeps with very high-power levels. As a result, the carrier-to-noise values will drop below the receiver’s acquisition and/or tracking threshold, and GNSS signals cannot be processed anymore. In contrast to such a simple jamming attack, where the attacker needs to have only basic knowledge about the GNSS signals (e.g., center frequencies and signal bandwidths), **systematic jamming** is a much more sophisticated attack, which can be further divided into:

- **Intelligent or smart jamming.** The objective is to jam only a specific part of the navigation message (e.g., the ephemeris data section), so the navigation message never can be fully decoded and the receiver never will be able to perform a position fix. All other parts of the navigation message remain unaffected, allowing signal tracking to continue for the receiver.

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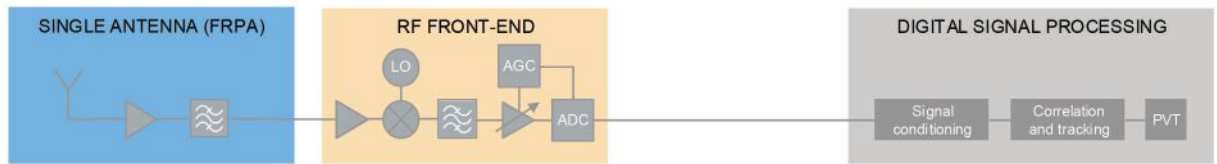
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FIGURE 1 Basic architecture of a FRPA receiver.

Smart jamming is much more complicated to implement for an attacker as the jammer must only be active during specific time intervals; this requires that the jammer is somehow synchronized with GNSS/Coordinated Universal Time. Moreover, the attack requires knowledge of the navigation message structure and what information the receiver needs to compute a position. Nevertheless, if done correctly, the attack is rather difficult to detect.

- **Matched spectrum jamming.** The objective is to generate a GNSS-like jammer signal with the same spectral characteristics as the real GNSS signals but without any valuable navigation information (i.e., the navigation message is missing). Matched-spectrum jamming is not straightforward, and to be effective, an attacker must replicate the GNSS signals for multiple visible satellites simultaneously, considering signal characteristics such as pseudo-random noise codes and, ideally, their correct Doppler shifts.

In contrast to jamming, GNSS deception techniques aim to force the receiver to compute an incorrect PVT solution, compromising the integrity of GNSS-based navigation. The two basic methods are:

- **Meaconing.** This rather simple approach is based on rebroadcasting a delayed version of live GNSS signals. This can be realized by using a commercial GNSS repeater. Alternatively, previously recorded actual GNSS signals can be replayed.

- **Spoofing.** This includes generation and broadcast of forged GNSS signals. This is typically done using a GNSS simulator, but specialized, modified GNSS receivers combined with a transmitting unit can also be used. The simulated signals need to be self-consistent, i.e., a GNSS receiver must be able to compute a PVT solution based on the simulated constellation. Spoofing attacks can be rather simple, e.g., broadcasting high power signals that represent a different location than those of the receiver under attack. The aim is to force the receiver into a reacquisition process, tracking and processing only the fake GNSS signals.

Additionally, the PVT performance of a GNSS receiver can also be degraded by objects in the vicinity of a GNSS user, causing **signal obstruction** and reflections from buildings,

trees, or the ground. **Multipath** can cause significant ranging and positioning errors. Multipath effects can hardly be avoided and must be seen as a permanent threat to GNSS signal quality.

Finally, other existing signals and services can interfere with GNSS, either because there is a frequency overlap (in-band interference) or harmonics from other signals fall into the GNSS bands (out-of-band interference). The effect of this type of interference on GNSS receiver performance can be analyzed by performing **coexistence** tests.

RX-Internal Detection and Mitigation Methods

Some of the threats discussed above can be detected and/or mitigated by the GNSS receiver. The capability of a GNSS receiver to detect and apply countermeasures to threats such as multipath, jamming or spoofing depends on the receiver's availability of specific features and basic architecture. **Figure 1** shows the basic building blocks of a typical GNSS receiver with a single, fixed reception pattern antenna (FRPA).

The three basic building blocks are the antenna, the RF front-end and the digital signal processing section. The antenna is responsible for receiving the weak GNSS signals and successive amplifying and band-limiting. It typically features a low noise amplifier (LNA) and a band-pass filter. The signals are then fed to the receiver front-end where the signals are amplified, down-converted to an intermediate frequency and converted to the digital domain. Part of this process is the automatic gain control (AGC) loop; the AGC acts as a variable amplifier, adjusting the power of the incoming signal and keep it constant over time. The sampled and quantized stream of IQ data is then fed to the digital signal processing section, where signal conditioning, acquisition and tracking, and PVT solution computations take place.

In contrast, some receivers use an adaptive antenna array, also referred to as controlled reception pattern antenna (CRPA). The idea is to weigh the signals received by each element according to dedicated optimization criteria. Typical optimization criteria are to minimize the signal's output power towards a dedicated direction ("null-steering"), or to maximize the signal to interference



or signal to noise ratio (“beamforming”). The underlying receiver architecture is more complex as signal weighting mechanisms must be added to the signal processing chain. These can be integrated before the digital processing block (“pre-correlation”) or implemented as an additional processing step between the correlation and tracking stages in the digital signal processing section (“post-correlation”). Both approaches are very effective in mitigating jamming and spoofing attacks, as they can either form a null in the direction of a strong jammer/spoofers or form beams toward the wanted signals from GNSS satellites, thereby de-weighting unwanted signals from certain directions of arrival (DOA).

Testing: Methods, Setups and Challenges

The test methods, strategies and setups used depend on the architecture of the GNSS receiver being tested, the receiver features that need to be evaluated and the specific testing objectives.

A first categorization can be made by examining the origin of the GNSS signals being used for testing. The signals may come from real GNSS satellites and

be used instantly and on-site (live GNSS testing) or recorded, stored and played back in the lab (record/replay). Alternatively, testing can be done entirely in a lab environment using GNSS simulators. In comparison to using real GNSS signals — either via live testing or the record/replay approach — using GNSS simulators in a lab environment offers significant benefits.

Simulation vs. Live GNSS testing. One major drawback of using live signals is that the system conditions are often unknown at a given point in time, and — most importantly — they change over time. The locations of the satellites — and thus the geometric conditions — change as the satellites move along their orbits. Errors, such as atmospheric effects, are also time- and location-dependent. One of the most unpredictable error influences is multipath. The magnitude of multipath errors depends on a variety of different parameters, including the number of reflections, the distance between the reflection points and the antenna or the strength of the reflected signal. The latter is determined by the material properties of the reflecting surface. Both the geometric conditions and the material properties of the reflectors change or may change

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over time; the geometric conditions due to the permanent motion of the satellites and the reflector properties due to meteorological influences like rain, dew, or snow.

As a result, when using live signals, one must expect that the conditions change unpredictably and will never be the same for two distinct points in time. It is therefore very unlikely that two successive test runs can be performed under identical conditions. Repeatable testing, which is one of the most important test requirements, is impossible when using live GNSS signals.

Well-defined and controlled simulation conditions can only be ensured by using a GNSS simulator. A simulator typically offers fully customizable and repeatable scenarios (i.e., one and the same test scenario) that can be repeated as often as needed, producing the same signals with the same characteristics. Moreover, a simulator is often a more cost-effective and efficient solution, whereas using live signals would be time-consuming, complex, expensive or even impractical.

The following discussion of typical test setups therefore focuses on the use of signal generators for GNSS testing. In terms of test scenarios, the focus will be on jamming, spoofing and coexistence testing.

Basic simulator setups. The basic approach for testing against GNSS threats is to combine a “clean” reference GNSS simulation scenario with interfering signals and add the combined signals to the device under test (DUT). This can be implemented using two separate signal generators or an integrated solution that combines GNSS simulation and threat signal generation in a single instrument. Based on the architecture of the integrated solution (1 RF output vs. multiple RF outputs), GNSS and interfering signals are already combined internally, or GNSS and interfering signals can be fed to different RF outputs and combined with an external combiner before fed to the DUT.

Conducted testing vs. OTA testing. The basic setups

introduced above only work if the receiver has dedicated and accessible input connectors to feed the antenna signal to the receiver’s front end. This is sometimes not the case, so that conducted testing is not possible and over-the-air (OTA) tests must be considered. A classic example of such DUTs are mobile phones, where no antenna connector is available, at least not without dismantling the device.

Testing such devices against interfering signals is still possible by using a shield box. The shield box has an RF input to feed in the combined GNSS and interfering signals. The signals are then retransmitted into the inside of the box and the DUT uses its integrated antenna to receive and process the signals coming from the GNSS simulator.

An alternative setup is to use a shield box with two RF inputs. In this case, the wanted signals and the interfering signals are not combined externally but are fed to the shield box via separate RF input connectors and transmitted to the GNSS DUT via separate transmit antennas.

Additional aspects and challenges must be considered when performing OTA tests using mobile phones as a GNSS DUT. This includes conducting a proper cold start, removing all preexisting navigation-related information from its memory, and disabling any other sensors that may contribute to computing the phone’s position. This typically is not a concern for most standalone GNSS receivers that feature dedicated cold start procedures and usually have no other positioning sensors on board. On the other hand, initiating a real cold start for GNSS modules in mobile phones can be tricky. Just rebooting the phone does not necessarily work, and the availability of dedicated settings also depends on the phone’s operating system (e.g., iOS vs. Android).

Another challenge during OTA testing of mobile phones is how to assess and analyze the impact of any interfering signals on signal acquisition, tracking and positioning. This requires detailed analysis and monitoring features on the mobile phone, which typically are not a standard feature of the phone’s operating system. Specialized GNSS monitoring and data apps can be used instead.

Testing with live signals. GNSS tests also may be performed by a GNSS simulator in combination with live GNSS signals using existing field infrastructure such as GNSS receivers installed at mobile base stations. A typical use case is to add one or several jamming/spoofing signals, or even an entire (stronger) “spoofing constellation” to an existing “live GNSS constellation” and test how the GNSS receiver reacts to such an attack.

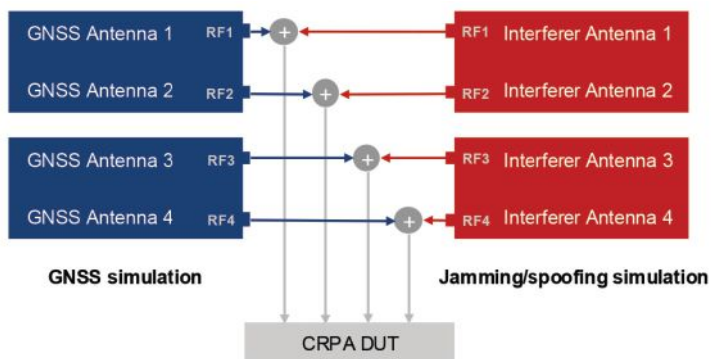


FIGURE 2 A possible setup for testing a 4-channel CRPA receiver against jamming or spoofing attacks.



CRPA testing. For testing GNSS receivers with multiple antenna inputs, particularly CRPA systems, several RF sources/paths need to be combined and synchronized. **Figure 2** shows a possible setup for testing a 4-channel CRPA receiver against jamming or spoofing attacks. It is based on the 2-path signal generator architecture and consists of two signal generators for generating GNSS signals for each antenna (left part of the setup) and two signal generators for generating the jammer/spoofing signals (right part of the setup).

USERS CAN TEST against GNSS threats using the R&S(R)SMW200A.

This approach may be a good alternative to simulating everything with a GNSS simulator, as much more GNSS channels and RF paths are required with a simulator-internal approach. There also are some challenges associated with this test method, e.g., the signal generators, which need to be operated in a field environment. Moreover, for more sophisticated spoofing attacks, a prerequisite is the capability to time-synchronize the GNSS simulation with the live GNSS constellation.

GNSS and interfering signals are combined per antenna element and fed to the RF inputs of the CRPA receiver under test.

For CRPA testing, it must be ensured that the phase relations between the GNSS signals and the interfering signals represent the actual geometrical conditions and, above all, remain consistent throughout the simulation. To achieve this, a common local oscillator signal needs to be used for generating the GNSS and interferer signals

Smart Positioning For Connected Vehicles

Automotive Grade Standard Precision GNSS Positioning Chips and Modules For Cockpit Navigation Application



Automotive Grade High Precision GNSS Positioning Modules For Intelligent Driving Application



- ▶ Automotive-grade products comply with AEC-Q100/104
- ▶ Production process conforms to IATF16949



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in all signal paths.

To correctly simulate the directions of the satellite signals and the interference signals, the test system must be calibrated at the RF interface to the DUT with respect to amplitude, phase and propagation time. This means that the amplitude, phase and propagation time differences between the individual RF paths, resulting for example from cables or RF components, must be compensated.

Rohde & Schwarz Solution

Rohde & Schwarz GNSS test solutions address requirements for testing GNSS receivers against threats, offering options from basic single-channel waveform generation to advanced multi-frequency, multi-constellation simulators with two RF outputs, hundreds of channels and internal threat simulation, including non-GNSS signals for jamming and coexistence tests. The R&S(R) SMW200A vector signal generator can be equipped with a wide range of GNSS features and options. It can generate simple interference signals, such as noise or CW interferers, using an optional noise generator, and supports standard communication signals, including LTE, for coexistence testing. Users also can create custom interferer signals with MATLAB or Python and replay them on the instrument. The R&S(R)Pulse Sequencer software enables both standard and complex jamming scenarios, accounting for factors such as moving interference sources, moving GNSS receivers and antenna patterns. The software can calculate the correct amplitude, phase, and propagation times based on signal characteristics and system configuration. 🌐

Note: For a longer version of this article and sidebars, see [gpsworld.com/simulators-strengthen-receiver-resilience](https://www.gpsworld.com/simulators-strengthen-receiver-resilience).

Opening New Doors for Research in GNSS

The Minerva Program by Safran Electronics & Defense

In universities across the world, theory lays the foundation, but in the field, realism builds true expertise.

For students studying GNSS engineering, textbooks and simulations alone are no longer enough. Tomorrow's engineers need to use the same applications and work with the same complex environments that professionals face in the real world. This means using tools that generate actual RF signals, not just software abstractions — tools that recreate urban canyons, interference, jamming, spoofing and satellite dynamics with precision.

Safran has established the Minerva Academic Partnership Program, an initiative that brings its Skydel GNSS Simulation Engine to qualified educational institutions worldwide.

A Modern, Software-Defined Approach to GNSS Simulation

At the heart of this initiative is the Skydel simulation engine, a software-defined GNSS simulator. Built to leverage commercially available off-the-shelf (COTS) hardware, Skydel eliminates the need for proprietary hardware. It delivers the full spectrum of satellite constellations — as well as LEO ones — and frequency bands. By integrating Skydel in their projects, researchers now have the tools to pursue ambitious ideas with confidence, such as:

- Designing and testing custom signals or constellations not yet in existence
- Simulating real-world scenarios that can include both environmental and man-made interference
- Integrating and testing additional sensors and platforms through open-source plug-ins and hardware-in-the-loop setups

- Conducting rigorous resiliency testing against jamming and spoofing in a controlled, repeatable environment without real-world risk
- Building their own simulator with existing hardware components around Skydel

Empowering the Next Generation of PNT Innovators

Through the Minerva program, Safran provides full-feature Skydel licenses for faculty and student use, creating an environment where learning and innovation thrive. This initiative not only eliminates the barrier to entry but also fosters collaboration between academia and industry — fueling a new wave of GNSS advancements.

A Global Initiative

Today, Minerva includes more than 80 member institutions and boasts a growing portfolio of peer-reviewed publications and conference presentations.

“This momentum highlights the real-world impact of the program and its role in driving local research excellence and fostering a vibrant, collaborative international GNSS community,” said Pierre-Marie Leveel, program director of PNT simulation at Safran Electronics & Defense. “Safran Electronics & Defense’s Minerva program is more than just a software — it’s a mission to democratize GNSS simulation and nurture the next generation of PNT researchers. As innovation becomes more critical to national sovereignty, transportation, and space exploration, empowering students and researchers has never been more vital.” 🌐



Elevating GNSS Simulation

With Safran Electronics & Defense

The evolution of Safran Electronics & Defense's GNSS simulators — across both software and hardware — has been shaped by the growing demands of users and the broader market.

“The demand for multi-vehicle and multi-antenna scenarios has never been higher, and the same can be said for interference simulation,” said Pierre-Marie Laveel, program director of PNT Simulation at Safran Electronics & Defense.

To address these challenges, Safran's GSG-7 and GSG-8 Gen2 simulators are engineered to handle a range of applications, from basic to advanced GNSS jamming and spoofing resiliency testing.

A single GSG-8 Gen2 simulator from Safran E&D can generate more than 2,000 signals without the need for additional hardware. This capability is essential when modeling legacy signals, multipath effects, jamming and spoofing scenarios, or even LEO-constellations.

“The market is also demanding realism,” Laveel said.

All Safran simulators are powered by the Skydel Simulation Engine, which is updated quarterly. Each release introduces new features, signals, and enhancements, enabling more authentic simulations and offering the flexibility to create virtually any GNSS testing scenario.

Staying Ahead of Market Changes and Signal Threats

The recent increase in signal interference threats has driven the demand for enhanced PNT resilience, leading to the broader use of both conducted and over-the-air testing. The anticipated deregulation of CRPA technology also is expected to open the door for civilian markets to perform testing.

The ability to safeguard GNSS networks from jamming and spoofing attacks has never been more vital. Achieving this level of resilience calls for a GNSS simulator that can generate dedicated RF signals for evaluating the effectiveness of CRPA architectures.

Safran's GSG-Wavefront, featuring a shared LO design, stands out as a field-proven, off-the-shelf solution for CRPA receiver testing. It has a customizable platform that offers upgradable options powered by Skydel — the company's GNSS simulation engine.

In recent years, Safran has seen its fastest growth in the New Space market. Safran's simulators are used for satellite navigation, LEO constellations and rocket launch and landing systems.

“Additional challenges can arise when developing new



Safran Electronics & Defense

UNIVERSITY OF AUBURN students testing GNSS resiliency of their autonomous race cars using Safran's Skydel simulation software.

signals or constellations, such as the newest LEO ones, said Laveel. “Our close partnerships with both Xona Space Systems and TrustPoint have allowed us to overcome these challenges.”

One of these challenges is ensuring compatibility and coherence with a range of GNSS receivers. Laveel shared that Safran E&D is in a unique position, as it also designs and manufactures its own receivers, such as the newly released Skylight.

Safran simulators support all legacy signals, including GPS, Galileo, BeiDou, GLONASS, NavIC, QZSS and SBAS, across all bands and security features such as M-code, PRS and Galileo OSNMA. The systems also offer compatibility with emerging LEO constellations, including Xona's PULSAR X1 and X5, as well as TrustPoint. Custom signals and custom constellation features offer users the flexibility to create entirely new signals and satellite constellations, or to modify existing configurations.

“It is de rigueur these days for companies to claim or incorporate AI into their solutions. In addition to using AI for tropospheric modeling based on real-world data, Safran Electronics & Defense has also taken a different approach to using AI in GNSS simulation,” Laveel said.

He added that the company's upcoming demonstration at ION GNSS+ 2025 will reveal Skydel AI, a new tool designed to make scenario creation and parameter setting as simple as writing an email. “The amount of people who can now easily test their prototypes, products or systems will dramatically increase as the steep curve to learn GNSS simulation is flattened.” 🌐



PNT Testing for Contested Environments

With Spirent Federal

PNT has become ubiquitous, touching nearly every sector from defense to autonomy, and is evolving fast in both scope and complexity. Ongoing conflicts in Eastern Europe and the Middle East have underscored how critical — and vulnerable — positioning and timing are, driving new test requirements focused on navigation warfare (NavWar) threats such as jamming and spoofing. In defense applications, contested environments have become the norm, not the exception.

Hypersonic missiles present unique testing challenges related to evaluating real-time high dynamics and large quantities of jammers and spoofers. The proliferation of autonomous vehicles ratchets up the SWaP-C and performance demands for the PNT technology they depend on.

As autonomy becomes reality across land, sea and air, PNT sits at the core of system safety and function — making robust, realistic test capability more important than ever.

The Future of PNT

The company stays close to its customers, many of whom are defining the future of PNT.

To meet rapidly evolving threats and faster testing cycles, Spirent prioritizes flexibility using its high-performance software-defined radio technology. It offers rapid-response simulation that evolves with threat intel. Spirent's test tools allow users to inject custom threat models, emulate dynamic environments and test with realism.

Spirent has seen a rapid uptake in space — particularly LEO and lunar — domains. As alternative PNT gains traction, new players and missions need proven simulation tools. Spirent is also seeing increased adoption in mission-critical applications deploying CRPAs, requiring high-performance testing and threat modeling.

The Rise of Complementary PNT

Unlike other wireless domains, PNT testing is not tightly standardized, meaning Spirent's tools must deliver both flexibility and accuracy across diverse needs.

The complexity of PNT technology and associated threat vectors is scaling to levels never seen before. In addition to making sure its test solutions match this sophistication, Spirent prioritizes simplifying the configuration of these test scenarios.

The ecosystem is growing more complex, making interoperability and strategic partnerships increasingly



Spirent Federal

NEW SPIRENT PNT XE simulator testing a drone's resilience against spoofing in the field.

essential. Spirent maintains a large portfolio of supported PNT signals, including all open signals from GPS, Galileo, GLONASS, BeiDou, QZSS, IRNSS and SBAS, in addition to early access signals such as Xona's LEO-PNT. Users can also work with pre-ICD waveforms through Spirent's Flex capability.

The company is working toward advancing anti-jamming antenna technology by supporting testing of high-element CRPA arrays and modeling emerging NavWar threats. While many of Spirent's CRPA test systems are utilized in conducted (cabled) lab-based test beds, some customers use Spirent's patented radiated anechoic chamber test setups to ensure antenna performance is accounted for.

Simulation in a Smaller Form Factor

PNT Xe, Spirent's newest release, brings Spirent's simulation architecture into a smaller, more accessible form factor and supports field testing for spoofing resilience. Live-sky GNSS signals are synchronized with spoofed signals from PNT Xe, allowing the receiver under test to experience both simultaneously.

PNT Xe is ideal for agile development environments, allowing teams to test code changes with precision and speed. Suitable for authorized users of GPS M-code, PNT Xe eliminates the reliance on secure labs by supporting unclassified military signal testing using GPS AES M-code.

PNT Xe represents a shift — making advanced GNSS testing accessible at scale without compromising fidelity, consistency or integration quality. 🌐

BY ROB VANBRUNT, CEO, SPIRENT FEDERAL SYSTEMS AND JAN ACKERMANN DIRECTOR, PRODUCT MANAGEMENT, SPIRENT COMMUNICATIONS



Tackling NavWar and PNT Threats

With Safran Federal Systems

GNSS simulation has evolved well beyond accuracy testing. It now covers full-spectrum NavWar and PNT validation. Today's simulators are expected to generate real-time GNSS, LEO signals, inertial measurement units (IMU), alternative navigation sources, jamming and spoofing — all from a single system.

“The number of signals continues to grow with the rise of multi-PNT sources and advanced threat capabilities,” said Jaemin Powell, senior product manager, NavWar & Simulation at Safran Federal Systems. “Our customers are preparing for GPS-denied operations, validating NavWar responses and ensuring resiliency in contested domains.”

Powell noted that Safran Federal developed BroadSim Genesis to enable simultaneous streaming of

L1, L2, L5 and L6 GNSS and LEO signals with integrated jamming and spoofing — all within a compact 4U platform.

The company's strategy is built on a software-defined architecture, allowing for rapid adoption to evolving threats and mission requirements, Powell said. Safran Federal collaborates closely with government stakeholders and defense primes to stay up-to-date with new requirements and incorporate real-world threat vectors, such as spoofing and jamming. The BroadSim platform supports software upgrades for every feature, from adding constellations and LEO signals to enabling hardware-in-the-loop (HIL) support or integrating additional PNT resources.

While defense and aerospace continue to serve as core markets,

rising demand also is coming from space companies, LEO-PNT developers, and advanced electronic warfare laboratories now relying on Safran simulators.

“These users value the scalability, fidelity and flexibility of our simulation solutions, especially in environments with high dynamics,” Powell said. “They are looking beyond traditional GNSS, and we address that need with a simplified, all-in-one platform.”

Large-Scale Simulation

“Large-scale simulation is technically demanding,” Powell added. “Generating thousands of signals across multiple bands with ultra-low latency and 1000 Hz update rates pushes both hardware and software boundaries.”

Maintaining the intuitive Skydel interface while adapting to evolving NavWar requirements remains a top priority for the company. For example, Safran Federal introduced real-time automated calibration for BroadSim Wavefront, which executes before every scenario. This allows users to power up and immediately begin testing, eliminating recalibration and setup delays.

“Simulation is more than just signal generation. It is about enabling operational confidence,” Powell said.

“Our platform gives users the ability to stress test systems, visualize behavior in real time and adapt quickly without relying on range time or live sky testing. . . We are enabling teams to meet their toughest NavWar and PNT challenges with confidence and flexibility. If you have demanding requirements, we are ready to deliver a solution that is intuitive, capable and built for the future.” 🌐



Safran Federal Systems

BROADSIM WAVEFRONT now features real-time automated calibration, allowing users to power up their simulator and immediately begin testing, eliminating recalibration and setup delays.

Calian GNSS



Calian is a leading developer, manufacturer and provider of high-performance smart GNSS, GNSS and Iridium antennas and accessories. Calian is known for its Accutenna, Helical, Verostar, VeraPhase and TruPrecision lines of antennas.

TruPrecision Smart Antennas

TruPrecision smart GNSS antennas combine Calian's high performance GNSS multi-band/multi-constellation antennas with state-of-the-art GNSS multi-band/multi-constellation receivers, built-in inertial management units and L-band or terrestrial network GNSS correction/augmentation services to deliver 3 cm to 6 cm positional accuracy after a 40-second convergence period.

GNSS Timing and Navigation

Accutenna antennas are suited for precise timing, positioning and navigation applications. The general-purpose Accutenna is available in several housed and embedded form factors. Other key features include multi-constellation and multi-signal support, eXtended Filtering (XF), and strong multipath mitigation.

Unmanned Aerial Vehicles

Calian's range of patented multi-constellation and multiband precision housed and embedded helical GNSS antennas are designed for UAVs, where low weight, low power consumption and small size are absolute requirements. A key feature of the helical antenna is that it does not require a ground plane to perform optimally. XF filtering is also available in the helical line.

Land and Geodetic Survey Applications

Land and geodetic survey applications demand precise and accurate antennas. Calian's VeroStar supports a 2 mm phase-center variation (PCV) and is small and light, making it ideal for real-time kinematic (RTK) and precise point positioning (PPP) rover applications. The VeraPhase and VeraChoke antennas are ideal for reference station (CORS and IGS) antennas as they support 1 mm and 0.5 mm PCV, respectively.

GNSS Accessories

Calian provides a wide range of smart-power GNSS signal splitters and in-line amplifiers. The smart-power splitters feature a failover feature — if one attached GNSS receiver fails, the next attached receiver will automatically power the splitter and attached GNSS antenna. Antenna installation brackets and cables are also available.

Antenna Installation and Customization Support

Installing a GNSS antenna in a radome or on a surface requires a deep understanding of how GNSS signals behave in the presence of other components (electronics, PCBs, metal surfaces). To ensure customers achieve optimum performance from their antenna, Calian provides installation and customization support. The antenna element, cable type, length and connector type can also be tailored to specific needs.

Calian's resilient GNSS antennas are designed to deliver robust positioning in

the presence of intentional and accidental jamming. Calian's GNSS antennas support two anti-jam technologies: Fixed Reception Pattern Antenna (FRPA) and Controlled Reception Pattern Antenna (CRPA). Both technologies employ advanced nullforming to mitigate GNSS jamming. Whether deployed in defense, transportation, or autonomous systems, Calian's anti-jam antennas provide reliable GNSS signal reception under adverse jamming conditions.

Confidence. Engineered.

Calian GNSS

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CORPORATE PROFILE

CAST Navigation

For more than 40 years, CAST Navigation LLC has earned a reputation for excellence with commercial, defense, and military clients by delivering performant, reliable GNSS/INS simulator solutions.

Our focus on doing one thing exceptionally well lets clients generate precise, accurate, and repeatable results, whether developing new navigation technologies or testing nav systems during integration.



Simulate Anywhere on Earth

CAST Navigation simulators can model GNSS conditions anywhere on Earth in the air, sea, land, and space domains. An intuitive graphical interface lets users configure the vehicle under test to create high-fidelity simulations of the most extreme conditions, from jamming in hostile territory to highly dynamic 6-DOF vehicle motion.

CAST Navigation Simulator Capabilities

CAST Navigation combines its four core capabilities — Inertial, GNSS, Jamming, and CRPA — into solutions optimized for each client's requirements. Modularity allows the solution to evolve as those needs change.

CAST Inertial simulators provide high-rate inertial data for testing EGI and GNSS/INS navigation systems. Clients can configure the simulator to model specific navigation units' output performance characteristics and drift rates.

CAST GNSS produces precise, repeatable GNSS RF wavefronts for each antenna element. These wavefronts simultaneously simulate multiple constellation types, each with as many as 16 satellites in view.

CAST Jammer adds natural, urban, and adversarial interference for antenna testing, verification, and integration. Test profiles can specify source position and trajectory, output power level, and other properties to simulate increasingly complex GNSS environments accurately.

CAST CRPA generates a complete set of GNSS RF wavefronts for each phased array antenna element. These wavefronts simultaneously simulate multiple constellation types, each with as many as sixteen satellites in view. CAST Navigation's proprietary synchronization technology combines GNSS and interference wavefronts in a composite signal that reflects real-life phase differences in signal reception.

CAST Commitment

CAST Navigation's singular focus is on delivering robust GNSS/INS simulation solutions that exceed clients' expectations through unrivaled accuracy, precision, and repeatability. Its focus extends beyond technology to set the standard in service and support. This is why, for over 40 years, CAST Navigation has become the trusted industry leader in GNSS/INS simulation.



Images: CAST Navigation

CAST

NAVIGATION

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OEM 

Quantum Magnetometer Could Solve GNSS-Denied Navigation Problems

Fraunhofer IAF presented the latest version of its compact, integrated quantum magnetometer. The diamond-based system is characterized by its robustness, high integration density and measurement sensitivity. With its easy calibration, high sensitivity of a few picotesla and high dynamic range, it offers new measurement possibilities in applications that require precise measurement with minimal interference, such as navigation.

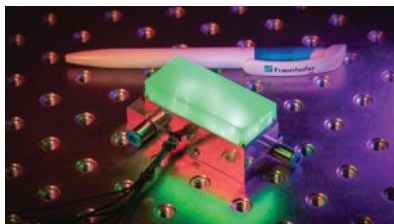
The highly integrated vector magnetometer is based on nitrogen vacancies in diamond and provides access to the smallest magnetic fields.

The unique properties of the NV center in the diamond lattice, which is arranged along the four crystal axes, enable all vector components of the magnetic field to be detected with a single sensor chip using <100> diamond. This reduces the calibration effort and opens up new possibilities for various applications.

Increased Sensitivity

Researchers at Fraunhofer IAF have reduced the size of the integrated quantum magnetometer by a factor of 30 in one year. The sensor head now has a compact size comparable to conventional optically pumped gas-cell magnetometers with high sensitivity in the picotesla range. The diamond-based system also has high robustness and wide measuring range, which allows flexibility in a variety of measurement scenarios with extremely low calibration requirements.

Optional water cooling ensures robust and reliable measurement of magnetic



Fraunhofer IAF

The compact quantum magnetometer is based on nitrogen vacancies in diamond.

fields even under difficult operating conditions. The wafer sizes of the ultra-pure diamond are to be further developed next year from the current two inches to industrially scalable four-inch wafers.

Safe Navigation without GPS

Despite their high precision and coverage, today's navigation systems are often prone to interference and are not available everywhere. Alternative navigation methods are therefore gaining in importance. The Earth's magnetic field is a promising basis for this, as it exhibits regional differences that can be used as an invisible map for autonomous navigation, especially in areas where GPS signals are disrupted or difficult to receive.

Fraunhofer IAF's quantum sensor makes it possible to create comprehensive magnetic field maps and provide reliable navigation based on them. The vector magnetometer offers an autonomous, interference-free method for global positioning and navigation. It complements satellite-based navigation and works without satellite signals, for example underwater, in canyons, underground, in buildings, or in tunnels. 🌐

DOD's DIU Issues Quantum Contracts

Honeywell has been selected by the U.S. Department of Defense's (DOD) Defense Innovation Unit (DIU) to participate in the Transition of Quantum Sensing (TQS) program, aiming accelerate adoption of quantum sensors for near-term alternative positioning, navigation and timing (PNT) and intelligence, surveillance and reconnaissance (ISR) applications for the U.S. Joint Forces Command.

Honeywell will support the TQS program under two DOD contracts: CRUISE (Compact Rubidium Unit for Inertial Sensing and Estimation) and QUEST (Quantum Enabled Sensor Technologies for MagNav).

The CRUISE program will focus on developing quantum sensor-based inertial measurement units (IMUs) as a standalone navigation solution without relying on traditional GNSS, susceptible to jamming and spoofing. Honeywell will support the development of this quantum-sensor-based technology, which will enable the measurement of acceleration and orientation from an IMU mounted to a vehicle to calculate changes in position and velocity.

The QUEST program aims to advance the performance of magnetic anomaly-aided navigation (MagNav), a GNSS-independent navigation technique that uses quantum magnetometers to leverage measurements of the Earth's magnetic field as a navigation signal.

The DOD aims to improve these quantum magnetometers and demonstrate their utility in GNSS-denied flight. 🌐

OEM

Maritime Gyro Compasses Provide Independence from GNSS

With real-world disruptions increasingly affecting shipping and aviation safety, Kongsberg Discovery's motion gyro compasses (MGCs) deliver an alternative for reliability, accuracy and resilience in contested environments, according to the company.

Although traditional gyrocompasses are immune to GNSS signal-based attacks by design, many modern navigation systems incorporate GNSS data to enhance positioning accuracy. For maritime operators, having an autonomous and reliable source of

heading and positioning data ensures safety and maintains operational continuity in contested or signal-denied environments.

Kongsberg's MGCs use high-grade strap-down inertial sensors that detect the Earth's rotation without needing external input. This allows them to determine true north and maintain precise heading without relying on GNSS. Unlike traditional mechanical gyros, Kongsberg's MGCs can estimate latitude internally. This ensures consistent accuracy from equatorial regions to the poles.



Kongsberg

The system also supports Doppler-based seabed and water-column tracking to determine vessel velocity, eliminating the need for satellite-derived speed data. 🌐

DEFENSE

Australian Navy Trials Validate Quantum Solution for GPS Denial at Sea

Q-CTRL has completed a major field trial with Australian Defence on board the Royal Australian Navy's Multi-role Aviation Training Vessel (MATV), the MV Sycamore. The results of the trial demonstrated advancements in software-ruggedized quantum sensing for navigation.

In the trials, Q-CTRL field deployed a quantum dual gravimeter, which measures tiny variations in Earth's gravity as part of a next-generation quantum-assured positioning, navigation, and timing (PNT) system operable when GPS is unavailable or untrusted.

This first trial saw over 144 hours of continuous operation and successful

data collection with no human intervention during real maritime operations.

"Quantum sensors provide a near-term opportunity to achieve transformational defense capabilities, but previous deployments in the field have struggled to deliver defense-relevant performance," said Q-CTRL CEO and founder Michael J. Biercuk. "Operating on a real moving vehicle is just not the same as conducting a science experiment; at Q-CTRL, we've taken a different approach to getting quantum sensors out of the lab, focusing on software as the critical enabler of performance in the real world."

Earlier this year, Q-CTRL announced successful airborne field trials



Q-CTRL

Developed and fielded in 14 months, the dual gravimeter was installed in a "strapdown" configuration in the space of a single server rack in a communications room onboard MV Sycamore. The sensor consumed only 180W of power – about 10 times less than a household toaster.

of a new generation of quantum-magnetic navigation solutions, Ironstone Opal, validated for the first time to outperform comparable conventional alternatives in challenging real-world settings by 50 times. 🌐

DEFENSE

HBK Shrinks Tactical-Grade Navigation into 15g

MicroStrain by HBK has launched the 3DM-CV7-GNSS/INS, an ultra-compact, tactical-grade inertial navigation system (INS) designed for seamless integration into space-constrained platforms.

Combining advanced inertial technology with tightly coupled, onboard dual-frequency GNSS receivers, the 3DM-CV7-GNSS/INS delivers the precision and reliability needed for navigation and localization in dynamic environments, particularly those where GNSS signals may be weak, intermittent, or denied altogether.

From autonomous robotics to drones and unmanned ground vehicles, this



HBK MicroStrain

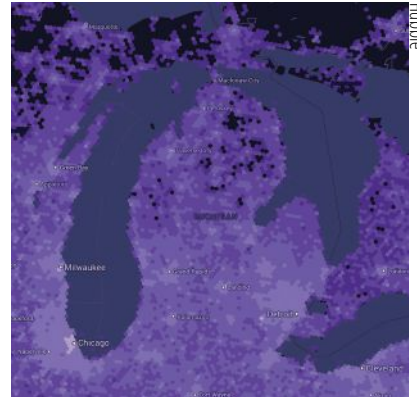
new solution helps engineers overcome one of the toughest challenges in modern navigation: achieving consistent, high-quality data in challenging conditions.

Weighing 15.6 grams and measuring 38x30x10mm, the 3DM-CV7-GNSS/INS offers tactical-grade performance without size, weight, or cost trade-offs. Its user-friendly functionality, adaptive extended Kalman filter, and full industrial temperature calibration deliver robust and reliable data acquisition across a wide range of real-world scenarios.

Engineers benefit from the sensor's compatibility with open-source platforms such as PX4 and ROS, which enables faster development cycles and easier integration into existing architectures. 🌐

MOBILE

Hubble Launches Global Bluetooth Tracking Network



Hubble

The new Hubble BLE Finding Network is a Bluetooth Low Energy (BLE) network built for enterprise use. Hubble, based in Seattle, is a satellite startup enabling Bluetooth devices to connect directly to space.

While consumer platforms like Apple's Find My and Google's Find My Device brought BLE discovery to personal devices, Hubble now brings that same reach and simplicity to businesses, offering real-time visibility and full data ownership on a global scale.

"Consumer networks proved what's possible, but businesses were left out," said Alex Haro, co-founder of Hubble. "We're giving them a powerful alternative with global visibility, zero infrastructure and full ownership of their data."

The Hubble BLE Finding Network leverages nearly 100 million passive scanners across gateways, smartphones and partner infrastructure, powered by low-cost BLE chips already embedded in billions of devices. This extensive network covers homes, cities, transit systems and industrial sites, enabling comprehensive global asset tracking for enterprises. 🌐

SandboxAQ and Acubed Advance Magnetic Navigation

SandboxAQ and Acubed, the Silicon Valley innovation center for Airbus, have released real-world test results from a five-month, nationwide project designed to test the accuracy of AQNav.

AQNav is an artificial intelligence-driven magnetic navigation (MagNav) system. It uses advanced quantum magnetometers to read Earth's crustal magnetic anomalies, then employs large quantitative models (LQMs) to filter out electromagnetic interference and precisely determine an aircraft's position without relying on satellite signals.

The results come from a nationwide initiative with Acubed's Flight Lab to test the navigational accuracy of AQNav. Meeting the aviation industry's

Required Navigation Performance (RNP) standards is necessary for deploying the system on military, commercial and civilian aircraft.

AQNav was tested under various operational scenarios and demonstrated advanced precision, according to SandboxAQ. The goal was to determine whether magnetic anomaly-aided navigation could broadly meet navigation requirements for commercial aircraft. AQNav's capabilities exceeded the accuracy required for en route travel between airports. 🌐

RNP Standard	Required Accuracy (meters)	% of Flight Time Met
RNP 0.3	550	64%
RNP 1	1,852	95%
RNP 2	3,704	100%



GNSS HIGH INTEGRITY FOR HIGH ACCURACY APPLICATIONS

State-of-the-Art, Challenges and Perspectives

BY ROBERTO CAPUA AND SUNIL BISNATH

ESSENCE

The transport sector is moving toward a large-scale autonomous driving implementation. A high accuracy and high integrity positioning system is a prerequisite for safe, autonomous navigation in this field. The rail sector, through international initiatives (e.g., U.S. Positive Train Control and European Rail Traffic Management System) has been developing, over the past decade, traffic control systems able to integrate usual technologies, such as odometers, with augmented GNSS — through RTK (real-time kinematic) or SBAS (satellite-based augmentation system) integration. In the automotive sector, GNSS is one of the sensors used to achieve autonomous navigation, as addressed within ISO 26262. In the maritime sector, the International Maritime Organisation (IMO) defined Resolution A.915(22) over two decades ago and recommends the use of GNSS for coastal navigation and automatic docking, while the MASS (Maritime Autonomous Surface Ships) concept is growing as an application. A harmonized standardization and certification framework is needed for advancing such applications.

For different GNSS receivers and systems to share measurements and corrections, a universal language, e.g., a standard containing data formats, transmission protocols, correction types, etc. is required. Through the auspices of the Radio Technical Commission for Maritime Services (RTCM), in 1983, stakeholders established RTCM Special Committee 104 for “Differential GPS” (later to be known as “Differential Global Navigation Satellite Systems (DGNSS)”). Version 1 developed standards for DGPS. Version 2 supported GPS and eventually GLONASS pseudorange information for primarily navigation applications. Since 2004, Version 3 (RTCM SC104, 2024) has expanded the format for modern RTK and network RTK use with more efficient data structures for more signals.

Integrity studies started from aviation sector standards, e.g., RTCA (2016). However, relevant models, targeted for enroute and approach phases of aeronautics applications, are not applicable to harsh, terrestrial, urban environments with high multipath, shadowing and interference effects. Recognizing the growing safety-critical nature of emerging user applications,

and the introduction of company or industry-specific specifications, in 2018, RTCM established Special Committee 134 (RTCM SC-134) “Integrity for GNSS-based High Accuracy Applications” to define a standard for the implementation of integrity monitoring services to high accuracy applications. Message types allow users to calculate their integrity (i.e., safety) performance in real-time and implement their own Fault Detection and Exclusion algorithms. To support many technologies, many applications and be scalable, the standard uses a “multi-modal,” “multi-service” and “technology agnostic” approach. SC-134 efficiently builds on the SC-104 standard. The full SC-134 standard is expected to be delivered in late 2025. This column analyzes the state of the art and future perspectives of GNSS high integrity for high accuracy technologies and relevant standardization framework for emerging applications navigation needs.

ESSENTIALS

Integrity Monitoring (IM) Systems

A classification of high-accuracy GNSS IM systems, based on current systems and integrity monitoring development trends, is given in TABLE 1.

ELEMENTS

High Accuracy Augmentation

High accuracy positioning and relevant integrity monitoring functions must start from a generalized pseudorange (C) and carrier-phase (Φ) measurement definition, containing the terms involved in any kind of GNSS augmentation approach (differenced or undifferenced):

$$\begin{aligned} C_i^j &= \rho^j + c(dt - dT^j) + d\rho^j + d_{ion}^j + d_{trop}^j + b_{Cl} - B_{Cl}^j + \varepsilon_p \\ \Phi_i^j &= \rho^j + c(dt - dT^j) + d\rho^j - d_{ion}^j + d_{trop}^j + b_{L1} - B_{L1}^j + \lambda_i N_i^j + \lambda_i W + \varepsilon_\phi \end{aligned} \quad (1)$$

where

$\rho^j = \sqrt{(x^j - x)^2 + (y^j - y)^2 + (z^j - z)^2}$ is the geometric distance between the receiver and satellite j , i is the frequency identifier, dt and dT^j are the receiver and satellite clock offsets, $d\rho^j$ is the orbit error, $d_{ion}^j = \mu_i \bar{I}$ is the ionospheric error, where $\mu_i = f_i^2 / f_1^2$ and \bar{I} is the first order ionospheric delay, $d_{trop}^j = m^j \cdot T$ is the tropospheric error, where m^j is the tropospheric mapping function and T is the

TABLE 1 A classification of integrity monitoring systems

Integrity monitoring system type	Description
Standalone	Through a sufficient number of redundant measurements, the rover is able to determine satellite health status on the basis of fault detection or fault detection and exclusion algorithms without external augmentation through RAIM (Receiver Autonomous Integrity Monitoring).
Global Integrity	Integrity of GNSS satellites and constellation Signal In Space is based on a regional and global network of Reference Stations. This can be applicable to PPP Services. Satellite clock, orbit, code and phase biases integrity monitoring is part of this group. The integrity monitoring of the Reference Station and Augmentation infrastructure is also to be performed.
Local Integrity	Integrity monitoring stations are located near single reference stations (RSs), providing single station corrections. Integrity check is performed in signal domain (e.g., navigation data check, residual checks, etc.) or in position domain (analysis of the position error applying the corrections provided by RS). IALA (International Organisation for Marine Aids to Navigation) beacons and other systems provide pseudorange corrections. Carrier-phase corrections foreseen in IALA Guidelines, see Blanch et al. (2015). RSIM (RS and IM) standards are particularly concerned with this class of integrity monitoring system.
Network Integrity	In a Network providing DGNSS, wide-area or network RTK (real-time kinematic) services, RS measurements are collected at control station and relevant corrections (e.g., VRS (virtual RS), network RTK) broadcast and accessed by the rover through terrestrial or satellite means. Signal or position domain integrity can be performed through a parallel network of IM systems or through the analysis of reference station measurements. GBAS (ground-based augmentation system) and LAAS (local-area augmentation system), for aviation Precision Approach (currently working with pseudorange measurements only), and IALA beacons are examples of such systems. Within this class are also SBAS (space-based augmentation system) and relevant extended ARAIM (advanced RAIM) systems, where IM and message calculations are performed through the elaboration of raw data coming from a regional network of RSs. Concerning RTK positioning integrity, new systems are emerging, based on the definition of Protection Level for carrier-phase measurements (e.g., CRAIM). New techniques based on ARAIM SS (Solution Separation) and advanced Ambiguity Fixing Validation Test are also rising. Within this framework, the monitoring of Reference Station Integrity and Augmentation System for PPP-RTK services is included.
Advanced Integrity	Innovative new systems, based on the integration of existing ones (e.g., SBAS + GBAS + ARAIM + ...) or from external systems (e.g., auxiliary data from external sensors) for providing increased integrity levels and serving highly demanding applications. This class is the most challenging, as new messages must be developed. Upcoming applications requiring higher levels of integrity (e.g., autonomous driving) fall within this class.

residual zenith tropospheric delay, λ is the wavelength, N_i^j is the integer carrier phase ambiguity for satellite j and frequency i , $b_{Lp}, b_{Ci}, B_{Li}^j, B_{Cj}^i$ are the receiver i and j satellite biases, respectively, and W is the windup effect, affecting carrier-phase measurements. High-accuracy systems can be grouped as per **Table 2**.

Integrity concepts and development

In the aviation sector, the principle of Integrity Monitoring is based on the definition of Misleading Information (MI). An MI occurs when the true navigation error exceeds an appropriate Alert Limit. A Hazardous Misleading Information (HMI) is said to happen for a given operation when the true navigation error exceeds the Alert Limit, and no timely warning is provided. The TTA (Time to Alert) is usually expressed in terms of probability of providing HMIs during a predefined time interval (e.g., 150 s for the Aviation Precision Approach, or based on a predefined metric as Tolerable Hazard Rate, expressed per hour. In the rail sector, Integrity requirements are expressed in terms of THR (Tolerable Hazard Rate), i.e., the tolerable rate of HMI events per hour.

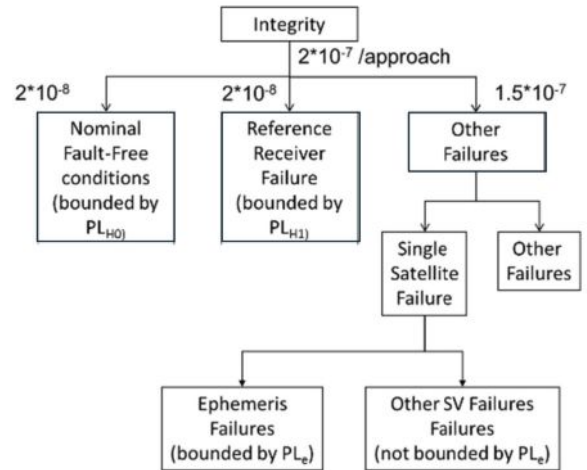


FIGURE 1 General Integrity Fault-Tree example

A classical representation of Integrity performances is the Stanford Plot, shown in **Figure 2**. The x-axis represents the Position Error (m), while the y-axis represents the Protection Level calculated by the user. A Hazardous Misleading Information (HMI) event occurs if the Position Error is greater than the Alert Limit, but the Protection Level is less than the AL. The Protection Level is usually determined by the user receiver as in the following (e.g., in case of H_0 nominal Fault-Free conditions):

TABLE 2 A high accuracy GNSS classification

Solution	Advantages	Disadvantages
SBAS	Medium accuracy (1 m)	Pseudorange only (current version)
Open Satellite Services (e.g., Galileo HAS)	High accuracy (20 cm)	Integrity of the Broadcast data, Ionosphere and troposphere error needing dense Reference Station Networks for lower convergence time services
DGNSS	Higher reference station spacing	Low accuracy (1 m), based on pseudoranges only
RTK/NRTK	High accuracy, short convergence / fixing time	Dense RS networks, receiver obsolescence, maintenance costs Dependent on mobile communication systems availability and quality of service
PPP	Sparse RS networks, global parameter broadcasting	Long convergence time to 10 cm accuracy
PPP-AR	Lower convergence time, higher accuracy with respect to PPP	Still some convergence time
PPP-RTK	Fast convergence time High accuracy, sparser RS network with respect to NRTK, performance depending on RS density	Reliant on local reference stations for precise STEC (slant total electron content) and ZTD (zenith tropospheric delay) estimation Dependent on mobile communication systems availability and quality of service
Cooperative or Peer PPP-RTK	High accuracy and fast convergence time	Not relying on dense permanent reference station networks for local ionospheric and tropospheric errors estimation User receiver to receiver short range communication for precise STEC and ZTD sharing

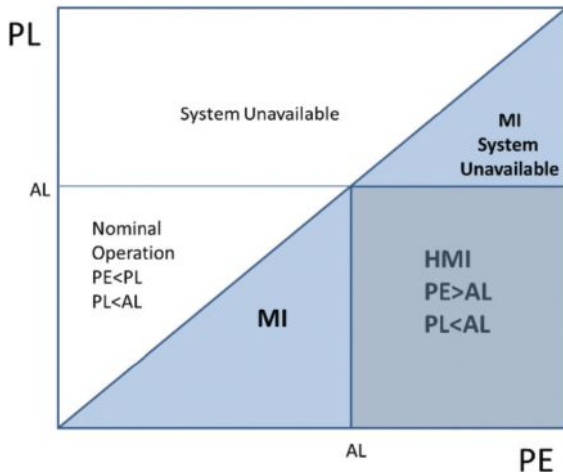


FIGURE 2 Stanford integrity plot

$$PL_{H0} = K_{H0} \sigma_{PE} \quad (2)$$

Where the K factor is dependent on the target Probability of HMI and σ_{PE} is the pseudorange standard deviation. A similar expression holds for the PL in the H_1 case.

The probability of an HMI event is the probability that the Position Error exceeds the given PL and no timely alert is provided. Assuming, for instance in the Fault Free case, that the estimation error is overbounded by a zero-mean normal distribution, the following holds:

$$P_{HMI} < P_{rMD} = Pr(PE > PL) = \text{erfc} \left(\frac{PL}{\sqrt{2}\sigma_{PE}} \right) \quad (3)$$

From **Figure 3**, the probability of HMI is bounded by the probability of Missed Detection belonging to the tails

of the probability distribution. Therefore, it can also be argued that PL bounds PE with a probability of $1 - Pr_{MD}$.

Inverting Equation (3) with respect to PL, given the target Integrity Risk (i.e., the probability of Missed Detection), and using Equation (2), the K factor can be determined as $K = \sqrt{2} \text{erfc}^{-1}(P_{MD})$ and fixed a priori, e.g., (Neri et al. (2015)), allowing the user to calculate the PL in real-time through Equation (2), once a support for σ_{PE} is provided. This feature is what the Augmentation systems perform.

In the SBAS case, the following values are provided for Precision Approach:

Vertical Protection: $K_{VPA} = \text{normal cdf}^{-1}(1 - 10^{-7}/2) = 5.33$

Lateral Protection: $K_{HPA} = \text{normal cdf}^{-1}(1 - 10^{-9}/2) = 6.08$

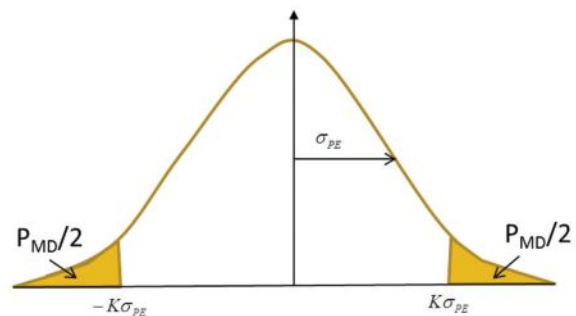


FIGURE 3 Determination of K, assuming a normal distribution of position residuals

For emerging Augmentation Systems (e.g., PPP-RTK), the challenges for integrity are increasing, due to the presence of different error estimation factors and the need for a robust Ambiguity Fixing Validation method.

Generalized ARAIM and Protection Level Definition

A generalization of ARAIM and Protection Level definitions, including carrier-phase ambiguity resolution, can be the basis for a harmonized Integrity Monitoring Framework for future implementations.

A generalization of the Integrity Risk, as analyzed within RTCM SC134 (Capua et al., 2024; RTCM SC134, 2025; Khanafseh and Pervan, 2010) is defined as:

$$IR = IR(H_0) + IR(H_f) + IR(H_{fn}) \quad (4)$$

where:

$IR(H_0)$ Is the Integrity Risk in fault-free conditions

$IR(H_f) = \sum_i^N IR(H_{fi})$ Is the Integrity Risk under defined Fault Conditions

$IR(H_{NM})$ Is the Integrity Risk in non-modeled conditions Including the Ambiguity conditions implies defining Correct Fixes and Incorrect Fixes conditions:

$$IR(H_0) = IR_{CF}P_{CF} + IR_{IF}P_{IF} = IR_{CF}P_{CF} + \sum_{j=1}^J IR(IF_j)P(IF_j) \quad (5)$$

P_{CF} is the probability of the correct fixing of ambiguities

P_{IF} is the probability of incorrect fixing of ambiguities

A generalized ARAIM definition can, therefore, be defined and Protection Levels defined through the inversion of the following upper bound equation for the Integrity Risk:

$$IR \leq 2Q\left(\frac{XPL - b_0}{\sigma_0}\right) + \sum_{j=1}^s Q\left(\frac{XPL - K_j \sigma_{aj} - b_j}{\sigma_j}\right) P_{A_j} + \sum_{i=1}^h Q\left(\frac{XPL - K_i \sigma_{ai} - b_i}{\sigma_i}\right) P_{H_i} + P_{NM} \quad (6)$$

where:

X is the dimension of the monitoring (e.g., Horizontal or Vertical)

Q is the complement to one of the cumulative distribution functions of the standard normal Gaussian distribution b_0 e σ_0 are biases and standard deviations for the H_0 case σ_{aj} is the standard deviation of the difference between the solution before and after exclusion

b_j e σ_j are the Fault case parameters (incorrect fixes or H_f) P_{A_j} P_{H_i} e P_{NM} are the probabilities of Fault under the hypothesis of incorrect Ambiguity Fixes, H_i fault Case, and Not Modeled case, respectively.

The Protection Level can be calculated by the user through the inversion of the above generalized equation. The probability of Faults and overbounding parameters can be calculated by Augmentation Service Providers and sent to the user.

The user can calculate the solution based on Solution Separation or Non-Solution Separation techniques. In the first case, parallel modeled fault cases are calculated, and the PL derived from the maximum of the single PLs:

$$PL = \max(PL_{-H_0}, PL_{H_{faul1}}, \dots, PL_{H_{faul,s}})$$

PPP-RTK Integrity Trends

PPP-RTK is assuming relevance for potential large-scale applications in road and autonomous driving applications. The elevated integrity and safety risks associated with these applications are emphasizing the need to develop robust and safe high-accuracy and high-integrity PPP-RTK solutions. PPP integrity monitoring is characterized by distinctive aspects with respect to other GNSS high-accuracy techniques. PPP involves several precise products and corrections estimations (e.g., satellite orbit, satellite clock, Earth observation parameters), therefore specific error and threats models must be developed. On the other hand, PPP-AR implies the estimation of further parameters (e.g., integer carrier phase ambiguities requiring pseudorange and carrier-phase satellite biases). PPP-RTK is based on the precise estimation of regional/local ionospheric and tropospheric errors by an augmentation provider. After the application of global network satellite ephemeris and clock corrections, code and phase biases, the application of ionospheric and tropospheric estimations as pseudo-observables at the user level leads to near-instantaneous convergence times as compared to PPP-AR.

At the user level, urban environments cause adverse multipath and non-line-of-sight effects. Carrier-phase multipath has a smaller impact than pseudorange multipath. The main impact of multipath is noisier real-valued estimates of carrier-phase ambiguities, requiring longer solution convergence time. This situation can have a greater impact on low-cost equipment, which may not be equipped with robust receiver multipath rejection suppression and low-grade antennas. AR solutions are also very sensitive to correct cycle slip detection. The impact of wrong ambiguity fixing must be carefully considered, introducing large errors into the PPP-AR solution. Time correlation must be properly considered in the user's Extended Kalman Filter, e.g., through modelling by state augmentation technique. Furthermore, single error estimation impact can be shared among different components (e.g., biases impacting on ionospheric estimation), depending on the PPP-AR model applied, e.g., uncalibrated phase delays, fractional-cycle biases, or decoupled clock model.

User Range Accuracy (URA) or residuals are currently used by some service providers for providing Quality Indicators. Some service providers perform PPP integrity monitoring based on a combination of significant indicators (Merino and Lainez, 2012). Figure 4 illustrates a representative Fault Tree for PPP-RTK integrity.

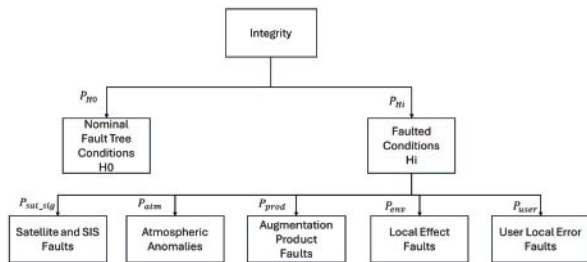


FIGURE 4 A representative Fault Tree for PPP-RTK Integrity

Different PPP-RTK Integrity Monitoring techniques have been studied in the literature. Traditional ARAIM approaches consider satellite and constellation faults only. ARAIM cannot monitor failure modes that are common to all satellites, such as incorrect receiver antenna phase center variations or zenith tropospheric delays. In the same way, faults in ionospheric estimations can affect several satellites simultaneously. The traditional ARAIM methods cannot handle multiple faults correctly, which have a high probability when carrier-phase measurements are used, especially for multiple GNSS constellations. Blanch et al. (2019) present a method based on multiple Kalman filters to reduce the computation of PPP integrity monitoring. Phelts et al. (2020) describe the application of an ARAIM algorithm to PPP for integrity monitoring. The application of Faults classification for the ARAIM implementation have been carried out in Zhang et al. (2023), demonstrating fast convergence and PPP-RTK PL improvements.

EVOLUTIONARY

Integrity Monitoring techniques are evolving, driven by the need for high accuracy and high integrity mass market applications in the field of transport (automotive, rail and maritime) and autonomous driving. Building on the original Integrity Monitoring standards for aviation, new models and integrity for GNSS high-accuracy applications are evolving, taking into account the characteristics and models of emerging applications (e.g., urban environments, characterized by a high level of multipath). Leveraging the heritage of RTCM SC104 standards for high accuracy applications, the RTCM SC134 “Integrity for GNSS-based High Accuracy Applications” committee is developing a standard for multi-modal applications and services, encompassing most relevant safety-critical applications (automotive, rail and maritime) and state-of-the-art augmentation techniques (RTK, NRTK, PPP-RTK, and open satellite correction services, such as Galileo HAS) (RTCM SC134, 2025).

A Generalized ARAIM SS separation model is applied, involving the transmission from a service provider of

overbounding parameters (e.g., standard deviation, biases and time correlation) as well as Probabilities of Fault of satellites, constellation and augmentation systems. Different models can be applied (user centric, mixed integrity, augmentation centric) to accommodate different Integrity Monitoring and FDE approaches at user level. Due to the harsh environments of emerging safety critical applications, a clear distinction between Global Effects, monitored by Service Providers (e.g., Signal In Space Faults and Augmentation System Faults) and Local Effects, monitored by the user receiver (e.g., multipath, interferences, etc.) must be applied.

Due to the multi-modal nature of transport, a harmonization of safety metrics and models is also needed, through liaison among standardization committees. As with universal adoption of standalone GPS then GNSS for a whole generation of users, it is anticipated that high integrity processes will allow for high accuracy GNSS to be central in large-scale, safety-of-life positioning solutions in the years to come. 🌐

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NETHERLANDS DEFENCE ADOPTS BATS

The Netherlands Ministry of Defence has procured eight V-BAT unmanned aircraft systems from Shield AI to enhance maritime intelligence, surveillance and reconnaissance operations for the Royal Netherlands Navy and Marine Corps. Officials highlighted the V-BAT acquisition as part of a broader effort to modernize the force. The navy's decision was informed in part by V-BAT's demonstrated success in Ukraine, where the platform is executing long-range, long-endurance ISR and targeting operations independently of GNSS.



RESEARCH EXPOSES RUSSIA AS JAMMING CULPRIT

Radio waves emanating from secretive facilities run by Russia's military have been identified as the culprit behind GNSS jamming in the Baltic Sea. Polish researchers collected information on jamming and spoofing incidents involving the Gdansk airport, shipping lanes, and the airspaces of Estonia and Finland. The interference has been recorded almost daily since Russia's full-scale invasion of Ukraine in February 2022. In March, eight European countries, including the Baltic states, Finland, Poland, France, the Netherlands and Ukraine, lodged a complaint with the UN about the practice.



QASCOM DELIVERS MOON TEST BED

Qascom SRL, Italy, has successfully delivered the final presentation of the NAVISP-EL2-081 – MOOD (Moon testbed) project, a multi-year effort to develop a GNSS simulation testbed for lunar, cislunar and space-based PNT applications. To create a Moon-capable testbed, Qascom upgraded its QA707 GNSS simulator with lunar-specific ranging strategies, support for multiple coordinate reference systems, custom signal transmitters and a 3D Viewer for real-time scenario visualization. It also integrates BeiDou B1C signal simulation and dual-frequency RF streaming capabilities.



SOUTHSPAN TAKES BIG STEP FORWARD

Lockheed Martin has completed the critical design review (CDR) of SouthPAN, the last major hurdle it needed to clear before testing can begin. Passing the CDR means all major risks have been identified and resolved, and its system interfaces were sufficiently mature. The \$1.18 billion project comprises two main facilities, the first in Uralla, New South Wales (pictured), and the second on the southern tip of the South Island. SouthPAN will serve both Australia and New Zealand, improving GNSS accuracy to as little as 10 cm. SouthPAN works by using several distributed ground stations to monitor GNSS signals and then compares each station's known location with position data from the satellites.



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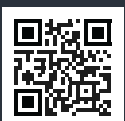
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