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'RECALCULATING' GPS

GPS IS THE GOLD STANDARD OF POSITIONING, NAVIGATION, AND TIMING—BUT WHAT HAPPENS WHEN IT ISN'T?

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ALTHOUGH GPS IS THE GOLD STANDARD OF POSITIONING, NAVIGATION, AND TIMING, IT'S NOT WITHOUT WEAKNESSES. GEOINT OFFERS ALTERNATIVE SOLUTIONS.

BY MATT ALDERTON

A LocataLite transmitter antenna broadcasts over a vast area of the White Sands Missile Range in New Mexico.

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GPS

Anyone who reads the Sunday comics has probably chuckled at the antics of red-bearded, big-bellied Hägar the Horrible. Part Viking, part "everyman," he spends his days pillaging and plundering, and his nights embroiled in quagmires that satirize both medieval and modern living. One time, for example, Hägar's wife, Helga, chastises him for "eating like a barbarian," then remembers that's exactly what he is.

Thanks to caricatures like Hägar, it's easy to stereotype Vikings as vulgar, brutish, and dim. However, Vikings were extremely astute—especially when it came to navigation. In a world without even compasses to guide them, Vikings traversed the Baltic Sea and Atlantic Ocean using nature as their only guide. By tracking the sun, moon, and stars, Vikings could determine whether they were traveling in the desired direction. And when the sky was overcast, they memorized landmarks and used migrating whales and birds as guides.

IMAGE COURTESY OF LOCATA

Although civilization's most trusted navigational aide remains the sky, humanity now trusts in satellites rather than the sun. In particular, the 30 satellites that constitute the United States Global Positioning System, otherwise known as GPS.

"GPS is a worldwide enabler that is depended on by billions of users," explained Col. Steve Whitney, director of the GPS Directorate within the Space and Missile Systems Center at U.S. Air Force Space Command, which manages and maintains the nation's GPS capabilities. "The constellation provides a minimum of four satellites in view from any given place on the surface of the Earth to deliver sub-meter positioning accuracy to military and civil users worldwide."

IT TOOK THE U.S. MILITARY MORE THAN 30 YEARS TO DEVELOP GPS

GPS provides more than positioning—it is essential for positioning, navigation, and timing, or PNT. Communities across the globe rely on PNT, according to Capt. Dana Goward (Ret.), the U.S. Coast Guard's former director of marine transportation systems. This speaks to PNT's remarkable influence, he said—but also to its increasing vulnerability, which stems from a reliance on GPS as the "be all, end all" of PNT systems.

"An extended GPS outage could quickly pose a near-existential threat for America," predicted Goward, who is also executive director and president of the Resilient Navigation and Timing Foundation and a member of the National Positioning, Navigation, and Timing Advisory Board. "PNT is really, really important, and we should have as many sources of it as we need and can use."

Thanks to the GEOINT Revolution, which is making location awareness as pervasive as it is powerful, worldwide efforts are underway to provide exactly that: more and better sources of PNT that will work in tandem with GPS to preserve the capabilities on which humanity has come to rely.

OVERNIGHT CHANGE, DECADES IN THE MAKING

Like many other technologies that emerged from the Space Race, the world can thank the Cold War for GPS. When the Soviet Union launched Sputnik in 1957, American scientists discovered the radio signals transmitted by the world's first satellite grew stronger as it approached their receivers and weaker as it passed. The scientists theorized that one could determine the location of a receiver by measuring its distance from satellites overhead, which could be calculated based on the speed at which the signals arrived.

So was born the premise for GPS. Receivers such as the ones found in smartphones and vehicle navigation systems "listen" for signals from the nearest GPS satellites, each of which includes a timestamp generated by an atomic clock on board the satellite and a celestial location uploaded by monitor stations tracking its position from the ground. Upon receiving the signals—signals from four different satellites are needed to deliver accurate positioning—receivers note the satellites' locations then calculate their relative distance from each by comparing the time at which the signals were sent and received. By plugging the distances into a basic geometric formula, receivers approximate their location on a map.

"Each GPS satellite is transmitting a time signal, and that's all it really is—a very precise, well synchronized time signal," Goward explained.

Although the concept of GPS seems simple, it took the U.S. military more than 30 years to develop it, starting in 1959, when the U.S. Navy built the first satellite navigation system to locate submarines, and culminating in 1995, when the first GPS constellation was declared fully operational.

"It's important to remember that GPS is a U.S. military program that was developed to provide positioning to units in theater," said Dr. John Janis, a senior systems engineer at Harris Corp., which supplies the navigation payload for all GPS satellites. "When [GPS] was first envisioned and developed, there was never any conception that it would

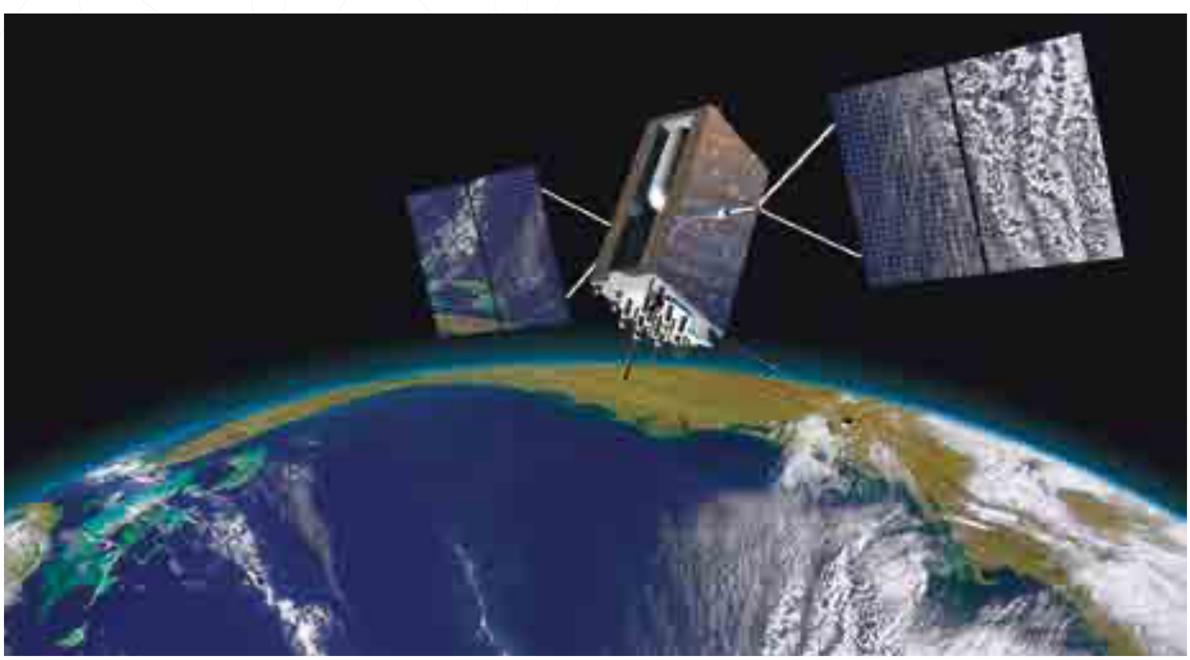

IMAGE COURTESY OF LOCKHEED MARTIN

MOST GPS satellites on orbit have surpassed operational design life, and users are demanding more advanced capabilities. To sustain and modernize the constellation, the U.S. Air Force is developing the next generation satellite system, GPS III.

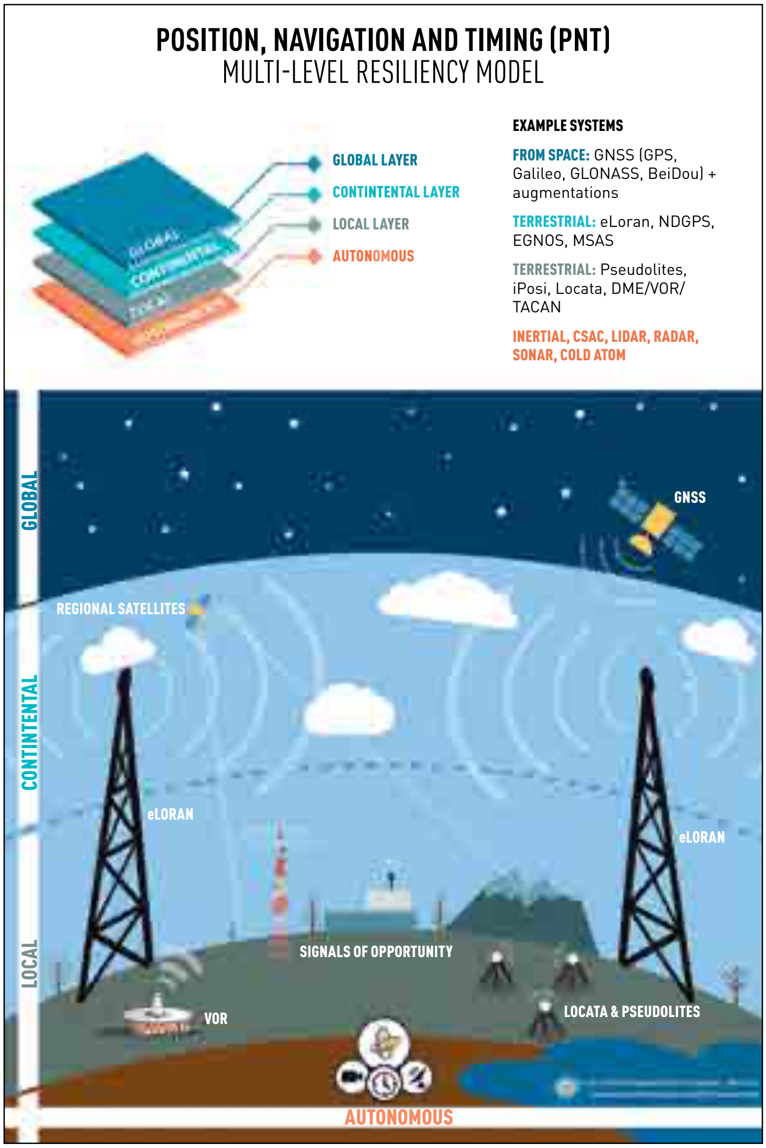

ILLUSTRATION COURTESY OF RESILIENT NAVIGATION & TIMING FOUNDATION

THE NAVIGATION and timing services provided by GPS are silent utilities upon which almost all technologies depend. The Resilient Navigation & Timing (RNT) Foundation supports a multi-layered architecture, a resilient ecosystem, of multiple, complementary sources for navigation and timing that have different failure modes. This resilient ecosystem will ensure users always have access to these essential services and help protect critical infrastructure.

become as integrated into every facet of our lives as it is today."

Presidents Ronald Reagan and Bill Clinton ensured that it did. When an errant airliner was shot down in Russian airspace in 1983, Reagan recognized the potential safety benefits for commercial aviation and issued an executive order allowing civilian use of GPS signals in advance of the system's completion. The military degraded those signals for national security purposes until 2000, when Clinton ordered the Department of Defense (DoD) to end the practice known as "Selective Availability."

"In plain English, we are unscrambling the GPS signal," said Dr. Neal Lane, Clinton's science advisor, during the 2000 press conference. "It's rare that someone can press a button and make something you own instantly more valuable, but that's exactly what's going to happen today. All the people who bought a GPS receiver for a boat or a car … are going to find that they're suddenly 10 times more accurate as of midnight tonight."

UNREALIZED UBIQUITY

When the U.S. turned off Selective Availability, the commercial sector began exploiting the new, more accurate GPS signals to develop everything from in-car navigation systems to "assisted GPS" technology integrating GPS into cellphones.

"Now, GPS is everywhere. It's a ubiquitous concept," said Dr. Mark Petovello, a professor of geomatics engineering at the University of Calgary, where he studies PNT as a member of the university's Position, Location, and Navigation (PLAN) research group. "It's become a critical component of our society—especially with mobile phones, which in many respects are walking positioning engines."

Petovello said his students illustrate the ubiquity of GPS. They use their cars' navigation systems to find the fastest route to school and work, and to find the nearest Starbucks on their way to class. They use wearable devices to calculate the distance of their morning run. They use their laptops to track textbooks ordered from Amazon. And they use their smartphones to request rides home from parties or find eligible dates in the dormitory next door.

All of that leverages GPS for positioning and navigation. What neither college students nor the general public realize, however, is they also rely on GPS for exquisite timing.

"Timing happens largely without us knowing it, but it's equally ubiquitous," Petovello said.

Timing begins with the nation's power grid, which leverages GPS timestamps on diagnostic data to prevent and resolve power outages using root cause analysis.

"GPS signals are used to synchronize power substations across the country to make sure the grid is functioning properly," Janis explained. "Each of these power stations has specialized receivers that require accuracy on the order of milliseconds, which they get from … GPS."

Cellphone networks also depend on GPS to operate cell towers, which are synchronized using precision time signals so phones can find available frequencies on which to conduct their calls without interference or overlap. The same principle applies to computer networks, including the internet, which uses synchronized timestamps to regulate the flow of information from one computer to another. Meanwhile, the Federal Aviation Administration (FAA) uses GPS to synchronize hazardous weather reporting, seismic researchers use it to monitor earthquake threats, and Hollywood studios employ it for the movie slates that help filmmakers synchronize on-screen audio and video.

Even the global financial system is powered by GPS.

"There are 250 million trades a second on the New York Stock Exchange," Goward said. "How are they sure they're buying and selling in the sequence in which orders are received? Well, all of that is time stamped using GPS."

IMMINENT INTERFERENCE

It's easy to imagine the consequences of a large-scale GPS failure. Unfortunately, the risk isn't merely imagined.

"The potential threats to the GPS constellation are vast and very real, ranging from physical attack [to] cyber-attack and signal interference or jamming," Whitney said.

Mother Nature is one of the most innocuous threats, but also one of the most probable. "In the last 10 years solar flares have caused several outages of GPS for 10 to 14 minutes," said Goward, noting the most recent outage occurred in 2014 and caused some ships to lose their way. "That's because during a solar flare the ionosphere is disturbed and GPS's very faint signals were unable to get through… If there was a solar flare large enough, it could fry our satellites and most of our ground electronics."

Collisions with manmade space debris or enemy attacks could also disable GPS satellites.

"The Chinese, North Koreans, and Russians all have the capability to launch weapons and interfere with satellites in space," Goward continued. "Of course, they depend on GPS almost as much as we do, so they'd be cutting off their noses to spite their faces. But the Department of Defense thinks it's a serious enough threat that it [plans to spend] $5 billion over the next five years to protect our national security space assets."

An attack on GPS satellites may never occur, but attacks on GPS signals aren't uncommon. In 2011, for instance, Iran spoofed—or faked—GPS signals to redirect and capture an American surveillance UAV from Afghanistan. A year later, North Korea successfully jammed GPS in South Korea, an attack strategy Russia is currently replicating in Ukraine.

"When a satellite is 12,000 miles away from a receiver and has limited power generation capabilities, as GPS does, it's very easy to disrupt that signal," Janis said.

Low signal strength makes GPS vulnerable for yet another reason—even when satellites and signals go unharmed, the system often cannot function in indoor, urban, or other environments that lack "line of sight" access to multiple satellites.

"The amount of power you get from a GPS satellite is roughly equivalent to the amount of light one of your eyes gets from a 100-watt light bulb about 1,500 kilometers away," Petovello said. "That amount of power is very small, yet you're trying to do quite a lot with it. As soon as you go into an urban canyon, underneath a tree, or inside a building, that power drops by another factor of 10, 100, 1,000, or more."

GPS: BROUGHT TO YOU BY GEOINT

Since its inception in 1963, GPS has been an asset of the U.S. Air Force, which manages and maintains the nation's GPS constellation from the Space and Missile Systems Center (SMC) at Los Angeles Air Force Base in El Segundo, Calif. GPS would not function, however, without GEOINT or the National Geospatial-Intelligence Agency (NGA).

"NGA does not design positioning and navigation systems, but we provide the geospatial data that allows them to work," explained NGA Senior Scientist for Geodesy and Geophysics Stephen Malys.

According to Malys, NGA traces its PNT roots to the mid '80s, when its predecessor, the Defense Mapping Agency, created World Geodetic System 1984 (WSG84), the standard Earth coordinate system that remains the foundational reference system on which GPS operates.

Some 30 years later, NGA remains a pivotal GPS actor.

"One of the most dramatic ways [NGA contributes] is by operating a global network of [terrestrial] monitoring stations that track GPS data 24 hours a day, seven days a week," continued Malys, who said monitor stations record where in the sky GPS satellites are and at what speed they're traveling while also facilitating synchronization of onboard atomic clocks—all of which are fundamental to the operation of GPS.

The U.S. has 17 GPS monitoring stations around the globe, 11 of which are operated by NGA and six of which are operated by the Air Force.

"Up until 2005, the Air Force had its own small network of five monitor stations," Malys explained. "With such a small network, there were a few gaps in coverage—a few hours on any given day when a satellite would not be in view of a ground station. We filled in those holes with our stations and made it possible for ground stations to more fully monitor what's going on with all our satellites at any given time."

More monitoring has led to improved accuracy, which bolsters NGA in its other role: that of a GPS consumer.

"We directly contribute to the GPS operation, but we're also a beneficiary of it," concluded Malys, who said military and commercial platforms collecting GEOINT typically rely on GPS for positioning. "GPS is the starting point for all geospatial data in the community ... We wouldn't have geospatial data at a global basis today without it."

PNT PINCH HITTERS

These gaps and vulnerabilities leave little doubt that the world needs more than one PNT system.

"It's important to have GPS backups," attested Petovello, who said efforts to augment GPS generally fall into one of two camps. "The first camp is looking at complete backups to the system in case GPS were to completely fail … The other camp is looking at systems that complement GPS in places where it doesn't work very reliably."

President George W. Bush led the first camp's charge in 2004 when he established the National Space-Based PNT Executive Committee (EXCOM) to oversee creation of a GPS backup. Led by the U.S. Departments of Transportation (DoT) and Homeland Security (DHS), the interagency committee in 2008 recommended the U.S. designate as its official "Plan B" a long-range marine navigation system known as eLoran.

The U.S. has been leveraging Loran technology—which uses land-based beacons to emit low-frequency radio signals to receivers for the purpose of positioning—since 1945, when the Navy deployed a Loran system to assist with marine navigation. The system's first iteration, Loran-A, included 72 Loran stations and as many as 75,000 receivers. Engineers continued to improve the technology to make it more effective, accurate, and affordable. The most successful version, Loran-C, was operational in the U.S. from 1957 until 2009, when the Obama Administration declared Loran technology obsolete and instructed the Coast Guard to dismantle the country's network of 24 Loran-C stations, which it did in 2011.

"Loran provides similar services to, but is very different in its physical characteristics from GPS," explained Goward, who noted that nine other nations still operate Loran systems, including Russia and China. "While GPS is in space, Loran is tower-based on Earth. While GPS has a very weak signal, Loran has a very powerful signal. While GPS transmits at a very high frequency, Loran transmits at a very low frequency."

Although Loran is still considered inferior to GPS for most applications, the eLoran system proposed by EXCOM—the "e" stands for "enhanced'— represents an improvement over Loran-C in several respects, according to Goward. For one, eLoran offers improved accuracy, availability, and stability for positioning. Secondly, it provides the same synchronized precision-timing capabilities as GPS; the system proposed by EXCOM would deliver GPS-like timing signals to receivers from 19 towers across the country, each with a range of approximately 1,000 miles and the ability to penetrate indoors, underground, and even underwater.

Although DoT and DHS said as recently as December 2015 that EXCOM remains committed to building an eLoran system, Nunzio Gambale doesn't believe that's the answer. Even the "enhanced" version is too expensive, too cumbersome, and not accurate enough, he said. Instead, his company, Australia-based Locata, has created a radio location system that mimics GPS on the ground. Rather than a space-based network of satellites, the system employs a terrestrial network of VHS-sized transceivers known as "LocataLites," which emit signals with centimeter-level location accuracy.

"GPS is a synchronous network of transmitters … our devices mesh to become a synchronous network of transmitters," explained Gambale, Locata's co-founder. "Functionally, they provide the same capability."

To maintain synchronous timing, GPS satellites rely on atomic clocks that synch with a master clock on the ground as they orbit overhead. Such clocks aren't just sophisticated—they're

PHOTO COURTESY OF NSRDEC

A GPS-GUIDED Joint Precision Air Drop System (JPADS) 2K parachute flies to its ground target. The U.S. Army is testing visually-aided navigation systems for JPADS use in GPS-denied environments such as canyons and cities.

expensive. To mimic GPS timing capability, LocataLites are outfitted with timing chips that synchronize with each other rather than an external time source. The result is a continuous feedback loop wherein each transceiver adjusts its outgoing signals to reflect the timing of its incoming signals. Although they're not as precise as GPS, the signals are equally synchronous and infinitely more affordable, which makes them ideal for backing up or complementing GPS at a local or regional level.

> **"Now, GPS is everywhere. It's a ubiquitous concept. It's become a critical component of our society—especially with mobile phones, which in many respects are walking positioning engines."**
>
> — Dr. Mark Petovello, professor of geomatics engineering at the University of Calgary

"Locata gives you everything about GPS except the 'G,'" explained Gambale, who likens GPS to Swiss cheese—Locata, he said, fills the holes. At Australia's Boddington Gold Mine, for example, LocataLites provide positioning in deep pits and against high walls where GPS signals are blocked. "Locata is to GPS what Wi-Fi is to the cellphone system. It's what you would invent if you wanted to have GPS for a business instead of GPS with a global military imperative."

Eventually, Gambale envisions a nationwide infrastructure of LocataLites.

"There are 1.8 million cellphone towers in America alone," he mused. "If you put a LocataLite on every one of those cellphone towers … you'd have a backup to GPS."

Another GPS backup concept uses localized sensors such as video. Draper Laboratory is betting on vision-aided navigation software called Lost Robot. Building on prior work in image-based absolute localization (IBAL), Lost Robot is being tested by the U.S. Army's Natick Soldier Research, Development, and Engineering Center (NSRDEC) for potential inclusion in the Army's Joint Precision Airdrop System (JPADS).

"IBAL uses a camera to correlate objects seen by the camera against preloaded images. By correlating what the camera sees with what was expected to be seen, and taking advantage of some ancillary sensors, an absolute navigation reference is produced," explained Chris Bessette, Draper's JPADS program manager. "Using very coarse initial navigation knowledge, along with observed and stored imagery, Lost Robot can determine its absolute position."

Lost Robot won't work on featureless terrain, like water or snow, but elsewhere the camera can register landmarks such as trees, rocks, and pavement, then surmise its positioning and navigation by comparing live visuals to pre-loaded maps and imagery.

It's a needed capability for a program such as JPADS, which uses GPS and steerable parachutes to airdrop equipment and supplies to soldiers in remote, adverse terrain where GPS is often jammed or inoperative.

"GPS is our primary navigation system, but we need redundancy to be able to handle certain environments that GPS may not be particularly well-suited for," said Gary Thibault, cargo air delivery team leader for product manager force sustainment systems at NSRDEC. "Vision-aided navigation is intriguing because it's something we as humans use every day."

SATELLITES' STAYING POWER

Along with vision-aided navigation, scientists are exploring inertial navigation systems that use motion sensors to determine positioning and orientation relative to a known starting point, as well as quantum compasses that could one day determine location by comparing the effects of gravity on cooled atoms with a gravitational map of the Earth. However, experts agree the most reliable PNT system remains a global navigation satellite system (GNSS) such as GPS.

"I don't see GNSS going away anytime soon," Petovello said. "There are other technologies out there—vision, inertial, and so on—that are quite good and maturing all the time, but … they provide relative instead of absolute position. For that reason, a GNSS component is still going to be very important."

Therefore, as policymakers and scientists debate the merits of eLoran, LocataLites, and vision-aided navigation, the U.S. Air Force is doubling down on GPS with a new constellation of GPS satellites known as GPS III, the first three of which are scheduled for launch in 2018.

"GPS is the world's global utility and our systems are the 'gold standard' for positioning, navigation, and timing services reaching over 4 billion users worldwide," Whitney said. "The Air Force is actively engaged in a modernization effort to provide better, more secure capability."

GPS III satellites will be more powerful, more secure, and have a longer life than previous iterations. According to Lockheed Martin, which is building the first eight GPS III satellites, the systems will transmit signals three times more accurate than current capabilities, provide military users up to eight times more effective anti-jamming capabilities, and have a 25 percent longer lifespan.

GPS III satellites will also host a new civil signal that will make them interoperable with international GNSS, which are poised to play a growing role in the PNT ecosystem.

"In the next decade, you'll see a proliferation of many different constellations, whereas until now it's really only been GPS that's been available," Janis said.

International constellations include Russia's Global Orbiting Navigation Satellite System (GLONASS), which was fully restored in 2011 following years of neglect; India's Indian Regional Navigation Satellite System (IRNSS), which completed its seven-satellite constellation in March; Europe's Galileo, which will begin offering initial services this year; China's BeiDou Navigation Satellite System, which is partially operational now and along with Galileo will be fully operational in 2020; and Japan's Quasi Zenith Satellite System (QZSS), which will be fully operational in 2018.

"GPS is a military system; governments in different countries want their own systems because they don't want the United States to have the power to shut off their navigation signals," Janis continued. "But there are advantages for the user, too."

Those advantages are apparent in commitments by the National Geospatial-Intelligence Agency (NGA), the Air Force, and others to support development of a universal GNSS receiver.

"There is an international effort to become interoperable with [other] systems," explained NGA Senior Scientist for Geodesy and Geophysics Stephen Malys. "It is another way to mitigate some of the concerns about vulnerability. Because if you have a GNSS receiver—as opposed to just a GPS receiver—that is receiving signals from all those systems, you're somewhat protected … If one system goes down, you still may have usable signals from the other systems."

Redundancy isn't the only benefit of international systems.

"As you add more satellites, you increase the availability of signals when you start going into places like urban canyons," Petovello said. "More importantly, your ability to compute a solution more accurately also improves."

A PNT-POWERED FUTURE

Near-term efforts to update GPS with new satellites and augment it with alternative constellations will go a long way toward preserving capabilities and addressing vulnerabilities. To fully secure a PNT-powered future, however, long-term challenges must be addressed.

The first step is naming a federal executive agent in charge of PNT, according to Gowan, pointing to a bill introduced by Congress last year—the National Positioning, Navigation, and Timing Resilience and Security Act of 2015—nominating DoD as that agent.

"Everybody agrees we need a complementary and backup system to GPS as part of the nation's PNT architecture, but it's nobody's job to get it done," Gowan said. "The senior leadership needs to recognize the problem and put one department in charge to lead the effort with other agencies and departments helping."

More fundamentally, the nation needs a new PNT workforce, according to Malys.

"In our community at large, GPS is taken for granted," Malys said. "People assume it's always going to be there. We do not have thousands of people here at NGA who work directly with GPS. We have a small cadre of people who are working with it closely, and not enough in my opinion."

Malys added, NGA is trying to raise PNT awareness with efforts such as "Time and Navigation," a PNT exhibit the agency introduced in 2013 at the Smithsonian Institution's National Air and Space Museum. "We're trying to motivate young people to develop an interest in PNT."

Malys remains confident the nation will solve its PNT problems, but traditional navigation artforms must not be forgotten: In 2015, the U.S. Naval Academy announced it was going the way of the Vikings by reinstating celestial navigation classes after axing them from its curriculum more than 15 years ago.

"It is a core competency of a mariner," U.S. Naval Academy Director of Professional Development Cmdr. Adan Cruz said in the Navy's announcement. "If we can navigate using celestial navigation, then we can always safely get from point A to point B."