A Day Without Space and a Call for Greater Positioning, Navigation, and Timing Resiliency in the United States

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At the same time, every day, all around the world, U.S. Navy Ships engage in a centuries-old ritual with an enduring and critical purpose.

"Good morning captain, the Officer of the Deck sends his (her) respects and wishes to inform you of the approaching hour of 12 noon. All reports [readiness of each department] are in hand. All chronometers have been wound and compared. Request permission to strike eight bells on time, sir."

The criticality of accurate time led to the installation of five chronometers in each ship, each independent of the others so that a single malfunction could be detected and addressed. This focus, not just on time but also on resiliency, with multiple complementary and backup reference sources, has been and continues to be essential to navigation. The importance of resilient time references continues to grow, as sensors, communications systems, tactical data, and weapon systems depend on highly precise time, now synchronized and shared across a distributed fighting force.

Our Nation has accomplished much in the last few years to address growing dependencies and threats to timely, accurate and available Positioning, Navigation, and Timing (PNT). It is important, though, to recognize that most of these efforts have centered around space-based alternatives to the Global Positioning System (GPS). We need a terrestrial complement and backup to GPS.

Potential adversaries understand well our National Security and Critical Infrastructure space-based dependencies and have planned contingency capabilities to attack space, should it create an asymmetric advantage. The best deterrent will be terrestrial PNT capabilities that can be supported in a cost-effective manner, with minimal changes to infrastructure and devices that rely on GPS today. Having a robust terrestrial complement that both improves PNT and supports backup, by design, is smart and can be achieved with minimal investment.

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In the longer term, we should make sure that 6G planning for the next decade supports and extends Positioning Reference Signals (PRS) and introduces robust and resilient PNT with layered and intentionally diverse failure modes as a fully included part of our network deployments. We should use the full range of spectrum and spectrum-based technologies (space and terrestrial) with multiple network node geometries to add layered diversity, using Primary, Alternate, Contingency and Emergency (PACE) concepts to make sure that lack of PNT does not disrupt otherwise sustainable missions and critical infrastructure operations.

Admiral Thad Allen, USCG (ret.), former Commandant of the Coast Guard, in his current capacity as the Chair of the Space-based PNT Advisory Board stated that *"America's continued over-reliance on GPS for PNT makes critical infrastructure and applications vulnerable to a variety of well documented accidental, natural, and malicious threats."* The board noted that *"There are significant reasons to be concerned. GPS is now lagging the capabilities found in other GNSSs – notably Galileo (European Union) and BeiDou (China). In the case of BeiDou, the system's enhanced resiliency and capability should be considered an element of 'soft power and an element of great power competition'"*. The Board, in their July 2024 report, *"concluded that our PNT capabilities have fallen behind those of other GNSSs, notably the European Union's Galileo and China's BeiDou. Efforts to date show a troubling shortfall in GPS's greater vulnerability to jamming and spoofing than systems featuring more robust signals."*[1]

Warning lights are 'blinking red.' After decades of U.S. worldwide leadership in PNT centered around GPS, we are on the cusp of losing this role due to lack of a coherent strategy to integrate multiple layers of PNT sources to address availability, accuracy, and resiliency objectives for the full range of mission and market dependencies on PNT.

Future U.S. PNT Call to Action

First, the U.S. should take immediate steps to address the PNT resiliency gap by establishing a designated set of frequencies that will support uplink and downlink reception of accurate PNT signaling to smart phones and IoT devices. This is urgent as the global market is changing fast. Getting this right in the U.S. market will be essential if we are to maintain leadership in global commercial PNT and address clear public safety risks.

Second, we should commit to robust, layered PNT resiliency as an integrated element of 6G and other future network systems. Critical infrastructure and consumer systems that need to work when disasters happen should not depend solely on space-based PNT being available.

Third, we need to address current PNT governance shortfalls. Current PNT oversight structures are fragmented, space-centric, and not chartered to holistically address the full scope of the nation's resilient PNT needs. There is a commonly used adage: "what got us here, won't get us there". The original governance structures evolved from the principally military origins of the GPS program and are not optimal for the balanced military and civilian use of PNT today. They do not have the scope required to analyze and deliver needed multi-faceted PNT resiliency. The robust commercial market that has built up around the strong GPS foundation is an example of this. Our commercial location services market is a national asset that deserves integrated, robust resiliency. We should have PNT oversight with authorities and expertise that support and enhance public and private elements of an integrated resilient PNT portfolio of complementary and backup capabilities.

It's time to approach PNT as a holistic set of capabilities where governance is built around the use and users of PNT signaling, and resources include a mix of government and commercial PNT capabilities. Admiral Allen is calling for *"a fresh look at our approach to PNT governance"* with development of *"a governance structure characterized by clearer authority and accountability"*. I agree with the findings of the Space-based PNT board: remove the blinders of 'space-based' from their remit, focus on PNT resiliency for current and future risk factors, and support this with legislation that clearly establishes the authorization and appropriations adequate to the task. The objective governance structure must reconcile the needs and contributions from multiple stakeholders that are not represented in the current policy deliberations. PNT Governance going forward, must bring innovation velocity with market follow through so that the U.S. can compete globally in an ever-evolving PNT market, while evolving appropriate risk mitigations to address the simultaneous, ever evolving threats to PNT and PNT dependent critical infrastructure.

To address these challenges, the U.S. must continue investing in its own PNT capabilities, including developing complementary and backup systems to GPS and strengthening cybersecurity measures. Furthermore, fostering international collaboration on PNT standards and interoperability will help mitigate the risks of fragmentation and ensure the continued availability of reliable PNT services for all.

These examples demonstrate the growing recognition of the need for diversified PNT capabilities. Space-based complements to GPS are coming online in the near term, but these are incomplete solutions. They share common failure modes that could invite attacks on space-based PNT. Developing terrestrial-based PNT will have a strong deterrence role and address everyday PNT gaps.

The current and growing PNT resiliency gap with the PRC will further expose our critical infrastructure to asymmetric attacks that while hurting all, will hurt the U.S. more. Growing space-based dependencies that are widely exploitable will be attractive targets for a growing number of nations and terrorist organizations.

The undeniable importance of PNT necessitates a proactive approach to securing this vital infrastructure.

The U.S. government, private sector, and academic institutions must collaborate to:

- **Continue Support for Space-based CPNT Development and Deployment:** Programs like Iridium PNT enhancements promise to significantly improve our response to GPS attacks. But these alone won't address the growing resilient PNT gap.
- **Commit to widely available and ultimately fully integrated Terrestrial PNT service:** Extend today's fragmented, inconsistent services to a nationwide, universally available system of systems that together provide complementary service while preserving diversity in failure modes for graceful degradation across the full spectrum of anticipated threats.
- **Promote Public Awareness and Strengthen PNT-related Cybersecurity Practices:** Increase both user and cybersecurity professional awareness of PNT vulnerabilities attack modalities, detection, and mitigation options. Risk-based assessments need to include PNT dependencies and likely threats to both terrestrial and space-based systems.
- **Foster International Cooperation:** Collaborate with U.S. allies and international partners to develop shared standards and best practices for PNT security. This strengthens global PNT resilience and reduces the potential for adversaries to exploit vulnerabilities.
- **Conduct Research and Development:** Support continuous research and development to enhance resilient PNT capabilities and stay ahead of evolving threats. This includes exploring emerging technologies like quantum-based positioning systems for increased robustness.

PNT Definitions

Positioning: accurately and precisely determining one's location and orientation to a given geographic standard. Where you are on the map … and now within a structure to include 3-dimensions.

Navigation: While positioning lets you know where you are, navigation helps you get to where you want to be. Navigation allows us to apply corrections to your course, orientation, and speed to reach the desired location (static or a moving target).

Timing: the acquisition and sustainment of accurate and precise time from a standard reference, such as Coordinated Universal Time (UTC). Timing has both absolute and relative applications. This is particularly important in communications and sensing as synchronization across various systems and devices must be maintained to correctly discern an encoded signal or observations from multiple sensors of the same event.

Complementary PNT: The Department of Defense (DOD) defines Complementary Positioning, Navigation, and Timing (CPNT) as systems and technologies that provide backup or alternative PNT services in the event of disruptions to primary systems like GPS. These complementary systems are designed to ensure the resilience and reliability of PNT capabilities, especially in scenarios where GPS signals might be unavailable, degraded, or manipulated. The U.S. Department of Transportation (DOT) has its own definition of CPNT. According to the DOT, CPNT systems are resilient PNT technologies that provide complementary services in the event of GPS disruption, denial, or manipulation. This definition aligns closely with the DOD's concept but is tailored to the needs of civilian transportation and infrastructure.

Terrestrial CPNT (TCPNT): Both DOD and DOT refer to complementary PNT signals that do not rely on space-based components as an essential element of a layered, defense in depth resilient PNT system-of-systems approach. To be most effective, TCPNT should not share the same failure modes as space-based PNT and should have intentionally diverse infrastructure that is survivable should adversaries choose to take steps to deny U.S. asymmetric space-based advantages.

National Security Dependencies on Accurate and Available PNT

The United States relies heavily on PNT services provided primarily by GPS. This dependence permeates every aspect of national security, public safety and social and economic engagement, impacting our ability for:

- **Positioning:** Provide first responders with the coordinates necessary for the successful dispatch of help in an emergency. On the battlefield, accurate location and tracking of military assets, including troops, vehicles, aircraft, and ships. Precise positioning is crucial for effective deployment, target acquisition, and battlefield awareness. Disrupted or manipulated positioning data could lead to mission failures, friendly-fire incidents, and compromised troop safety. Positioning

for military purposes must include x, y, and z axis information and tight calibration with the coordinate system (mapping) that orients our forces and their weapons to the physical world. Just as militaries have relied on accurate positions from GPS for decades, modern commercial supply chains, inventories and automation now depend on accurate position information. We also use position to target messaging, whether it's an emergency alert with warning information very specific to your current location or just-in-time advertising relevant to your local retail options.

- **Navigation:** Once 9-1-1 knows where you are, the response assets use navigation tools to get to where you are. Battlefield commanders rely on pinpoint accuracy for a variety of mission needs. GPS data is vital for air navigation, ship routing, and tactical maneuvers. Inaccurate or unavailable navigation information can result in logistical disruptions, missed targets, and collisions. Navigation needs include the rapidly growing population of Unattended Autonomous Systems as well as Remotely Piloted Vehicles. We all can relate to the potential danger and chaos of 'a day without GPS navigation,' as many of us no longer keep maps in the car, don't study our travel routes ahead of time, and are very accustomed to letting our GPS-based navigation tools provide us directions whose accuracy we take for granted. Self-driving vehicles are getting closer to reality, and navigation automation will only increase.
- **Timing:** The telecommunications that connect us to 9-1-1 require accurate timing shared between each node to route and discern the digital information that provides voice and other rich context about our emergency needs. Military units rely on synchronized timing for critical military operations and communications. Precise timing is essential for coordinated attacks, secure communication networks, and reliable detonation of weapons systems. Disruptions to timing signals could lead to communication breakdowns, mistimed operations, and compromised mission effectiveness. Spoofed timing can lead to catastrophic targeting mistakes. This area cannot be overstressed: We can only achieve the high-capacity, multimedia, multimode and secure communications we rely upon today, through the exacting synchronization of the digital representation of our signals. Every advance in communications throughput efficiency comes with a need for increased clock accuracy. Sensing, sensor fusion, datalinks, secure communications, electronic warfare, network operations, and command and control all depend on accurate timing. Our communities are increasingly reliant on systems-of-systems that exchange real-time information using protocols that depend on accurate, shared timing.

Examples:

- **Military GPS Receivers:** Soldiers rely on GPS receivers for individual and unit navigation, target location, and friendly-force tracking. Disrupted GPS signals could hinder troop movements, impede search and rescue operations, and leave soldiers vulnerable in combat situations.[2]
- **Precision-Guided Munitions:** Modern weaponry often utilizes GPS guidance for accurate targeting. Spoofed or jammed GPS signals could cause these weapons to malfunction, leading to civilian casualties and mission failures.[3]
- **Remotely Piloted Image and Video Intelligence, Surveillance, Reconnaissance and Targeting Communications:** Systems that support the communication of information between machines and the humans controlling the machines, require tight synchronization for the transmission channels that carry the links, and a second synchronization for the encryption protecting the data. We address the resiliency needs for end-to-end communications by including local clock sources, but over time, their accuracy drifts, and regular updates from a common timing source is critical. Attacks on time reference include spoofing, jamming, crypto-sync interruption and timing delay manipulation. Merely creating doubt in the accuracy of timing synchronization can create debilitating challenges for a highly connected force.

These examples highlight the critical role of PNT in national security. Disruptions to these services could have devastating consequences, jeopardizing military operations, endangering personnel, and potentially escalating conflicts. In a May 2021 report, GAO confirmed these findings and described some of the specific hurdles that have, and continue to keep DOD from developing solutions beyond specific, current mission needs:[4]

"DOD faces challenges in developing and integrating alternative PNT technologies. Officials from across DOD and experts told GAO that alternative PNT solutions are not prioritized within DOD. For example, there is no central program office responsible for developing the variety of alternative PNT technologies across DOD. DOD's continued reliance on GPS, despite known GPS vulnerabilities to disruption, presents a challenge for obtaining sufficient support to develop viable alternatives. DOD officials and experts also said challenges in establishing clear PNT performance requirements hinder technology development."

Growing Public Safety and Critical Infrastructure Dependencies on PNT

Beyond national security, PNT services underpin the smooth functioning of countless civilian activities. The Department of Homeland Security (DHS) identifies 11 critical industries that rely on precision timing, including communications, power distribution, finance, and information technology with 10 listed in the chart below.[5] Public Safety increasingly relies on digital communications needing accurate timing, emergency response is tied to accurate position information and automated navigation for route guidance. Our daily lives are increasingly reliant on accurate positioning, navigation, and timing data for:

- **Emergency Response:** First responders use PNT for communication, navigation, and location-based services during emergency situations. Disrupted PNT signals could hinder response efforts, delaying assistance and potentially endangering lives.
- **Financial Services:** Financial transactions rely on precise time synchronization to ensure accurate timestamps and prevent fraud. Tampering with PNT signals could disrupt financial markets and compromise financial security.
- **Transportation:** Autonomous vehicles, commercial air travel, and maritime navigation all depend on GPS for safe and efficient operation. Disruptions to PNT signals could lead to delays, cancellations, and safety hazards.
- **Other Critical Infrastructure:** The power grid, communication networks, and other critical infrastructure systems utilize PNT for synchronization and efficient operation. Disruptions to PNT could lead to cascading failures across vital infrastructure sectors.

Specific Examples:

- **Electrical Power:** The distribution of electricity requires accurate timing, shared commonly across wide areas spanning multiple states. The control plane synchronizes phase and coordinates constantly fluctuating demand and supply source relationships. The increased use of Distributed Energy Resources (DER) brings extremely useful efficiency and resiliency to the electric grid, but also expands the nodes for which accurate timing must be shared. An attack on shared timing used for DER control could be devastating for communities.
- **Transportation:** Ground, Maritime, and Air logistics, port operations, multi-modal transshipment and passenger travel rely on accurate navigation and transportation management that increasingly uses accurate, shared positioning, navigation, and timing to optimize flow. New and upgraded infrastructure often is sized for the

efficiencies that depend on widely available, accurate PNT. Loss of space-based PNT would bring chaos to transportation networks and logistics supply chains.

- **Financial Networks:** Modern markets rely upon automated exchanges. Market trades, generated by computer algorithms, are designed to respond automatically to real-time events as well as customer interactions. Shaving milliseconds off the round-trip between source data, financial brokers, and automated exchanges continues to drive the pursuit of lowest delay communication paths. Attacks on timing can greatly disrupt market operations, enable fraudulent activities, and impact access to accounts and consumer transactions in a cash-less society.
- **Converged Communications, Compute and Storage:** Modern networks rely on accurate and shared PNT for routing decisions, cloud operations, and encryption. As wireless networks bring the cloud to the edge of networks to support AI-enabled sensors and actuators, the dependency on PNT increases and crosses beyond the relative timing associated with single provider legacy communications.
- **Precision Agriculture:** Modern farming techniques utilize GPS-guided tractors and equipment for precise planting, harvesting, and resource management. Disrupted or maliciously compromised GPS signals could impact crop yields, disrupt agricultural operations, and threaten food security.[6]

  These examples illustrate the widespread reliance on PNT in civilian life. Disruptions to these services could have significant economic and societal consequences, causing widespread disruptions, endangering public safety, and jeopardizing national well-being.

Our Nation's experts in Risk Management (DHS NRMC) have called out the critical infrastructure dependencies on accurate PNT in the following chart:

EXAMPLES OF KNOWN PNT DEPENDENCIES[7]

Critical Infrastructure Sector	Areas Dependent on PNT (Not all inclusive)				
Chemical	Earth Drilling	Pipelines	Industrial Control Systems (ICS)	All Modes of Transportation	–
Communications	Wired/Wireless	Internet of Things	Health Care Monitoring	–	–
Critical Manufacturing and Defense Industrial Base	Supervisory Control and Data Acquisition (SCADA)	ICS	Monitoring	Workforce/ Asset Tracking	–
Dams	Power Generation	SCADA	Waterway Surveillance	–	–
Energy	Measurement	Monitoring	Control Systems	Automation	Protection
Financial Services	System Forensics	Regulatory Requirements	Time Stamping	–	–
Food and Agriculture	Food Sourcing	Food Control	Workforce/ Asset Tracking	Environmental Protection	Automation
Information Technology	Smart Devices	Cloud Operations	Incident Investigations	Boot/Runtime Security	–
Transportation	Aviation	Maritime	Pipelines	Rail	Roadway
Water and Wastewater Systems	Power Generation	SCADA	Waterway Surveillance	–	–

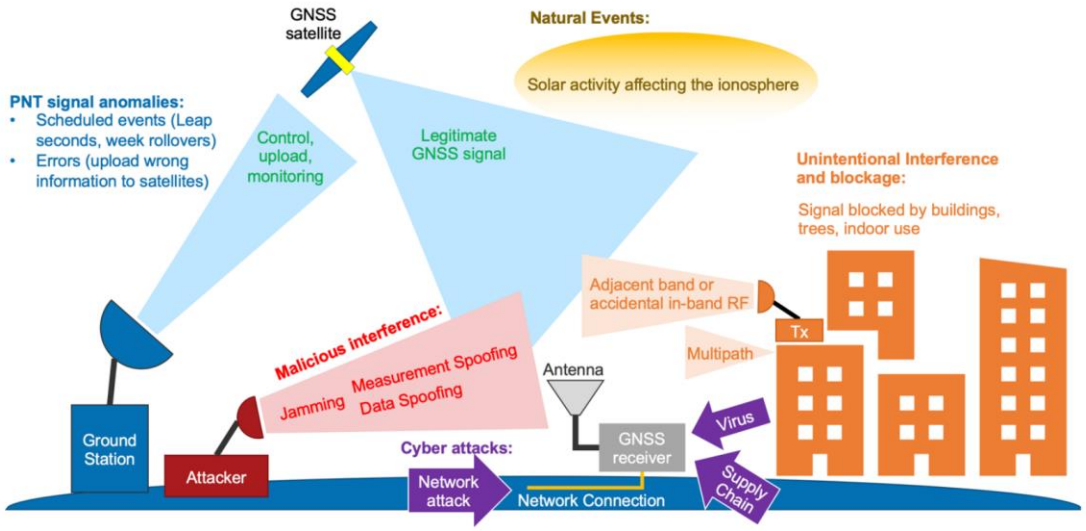
Public-Safety Reliance on PNT

Our first responders and emergency managers are increasingly aware of and concerned with the availability of accurate PNT to support citizens and communities. The move from analog to digital communications carries with it a dependence on accurate timing shared between each radio, phone, and computer. Our mobile lives often take us beyond our knowledge of landmarks required to describe where we are when we need help, and our smartphones provide location with the call or text to 9-1-1. Response assets use navigation tools to optimize their search and/or response to an emergency. Emergency alerts provide timely warnings of impending or present danger linked to the position of the threat and potential victims. We have optimized our public safety response around an interconnected system-of-systems that requires accurate, available, and resilient PNT services.

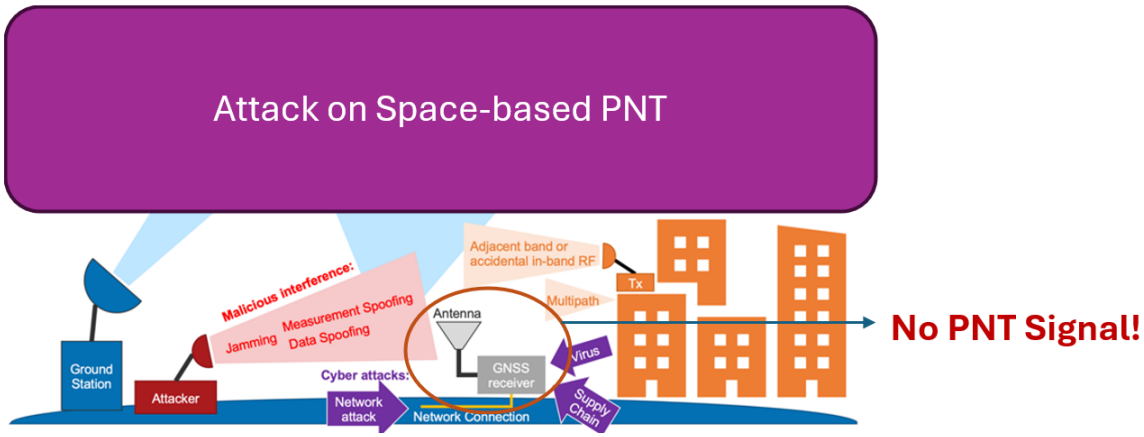
Current and Anticipated Threats to Space-Based PNT

Our dependence on space-based PNT system, primarily GPS, creates a vulnerability that adversaries are increasingly exploiting. Threats include:

- **Jamming:** Intentional interference with GPS signals can disrupt or block reception, effectively rendering PNT services unusable in affected areas. This can be achieved using relatively inexpensive equipment, making it a readily accessible tactic for malicious actors.[8]
- **Spoofing:** Malicious actors can broadcast fake GPS signals, causing receivers to display inaccurate positioning data. This can be particularly dangerous for navigation applications, potentially leading to accidents and misdirection.[9]
- **Cyberattacks:** Adversaries may target the infrastructure supporting GPS, such as ground control stations or satellites, potentially disrupting service or manipulating data. The increasing sophistication of cyberattacks makes GPS infrastructure a potential target.[10]
- **Kinetic Attack:** Counter-space capabilities continue to improve. Nations that possess the ability to launch satellites into orbit can develop the ability to damage or destroy satellites with an anti-satellite weapon. Advanced counter-space capabilities include the ability to take out whole constellations, generating a debris field that would make re-constitution problematic. At the high end, use of a variety of nuclear weapons could generate a range of significant and lasting damage.
- **Electro-Magnetic Pulse Weapons:** This category of counter-space weapons is intended to generate high, pulsed energy electro-magnetic radiation that can disrupt or destroy satellite electronics.
- **Severe Space Weather Events:** Solar activity is constantly changing. The strongest solar events can disrupt, destroy, and even de-orbit satellites. Many of the event categories impact multiple satellites across a wide area all at once. Strong Solar Flares and Coronal Mass Ejections (CME) can disrupt satellite radio communications, and in their most intense form, damage satellite electronic components and interfere with receiver equipment reception of signals on earth. In May 2024, while some were enjoying an unusual southerly display of the Northern Lights, many farmers across the Midwest reported loss of GPS signals, preventing their use of Farm Equipment relying on GPS-enabled navigation.[11] Longer duration Solar Storms, induced by massive CME, generate geomagnetic forces when they interact with the earth's magnetic field. This creates drag on satellites that rapidly degrades their orbits and can result in early earth reentry. In 2022, Starlink lost 40 satellites from an intense CME event.[12]



Resilient Positioning, Navigation and Timing Reference Architecture 1.0, DHS CISA, **Diagram of Threats and Disruptions for GNSS Signals**[13]



Positioning, Navigation and Timing without space-based GNSS – For most user equipment this results in the loss of PNT for extended durations. Terrestrial complement to space-based GNSS, provides backup when space is attacked and fills in gaps where signals are weak, missing or interfered on any given day.

Why the U.S. Needs a TCPNT System

Our reliance on space-based PNT systems necessitates the development and implementation of a robust TCPNT system. TCPNT offers several key advantages:

- **Redundancy:** TCPNT provides a backup option in case of disruptions to GPS and other space-based PNT systems. This redundancy ensures continued availability of PNT services critical for national security and civilian applications.
- **Improved Resilience:** TCPNT utilizes ground-based infrastructure, making it less susceptible to jamming and spoofing attacks that primarily target space-based systems.
- **Enhanced Accuracy:** TCPNT systems can potentially offer improved positioning accuracy in specific environments like urban canyons or areas with limited satellite visibility, such as indoors.
- **User Equipment Ecosystem:** Many consumer, industrial, and public safety devices receive both GPS signals and cellular signals. TCPNT strategies should take this into account. Adding TCPNT can and should leverage terrestrial-based transmission protocols that are fully compatible with an extensive device equipment ecosystem.

Universality: where we have mobile networks, we should have a terrestrial source for PNT. TCPNT should be widespread and a complement to GPS. Legacy navigation systems like Loran, Omega, VOR, DME, TACAN, and other NAVAIDS have limitations that detract from both their affordability and utility across the full device ecosystem. WiFi and other 'derived' location methods have widely varying accuracy and availability and can only be considered position gap fillers.[14]

Examples of TCPNT Systems:

- **Cellular Network-Based PNT:** Mobile network operators can utilize existing cell tower signals to provide PNT services, such as cell ID and signal-strength-based location. These signals, however, are built-for-purpose to make access and routing decisions for the user radios, cell phones, and the towers and distributed antenna systems they connect through. Repurposing them for PNT does not provide GPS-like quality of performance. Today, they utilize GPS to achieve timing synchronization across a wireless operator's network and are not ready to provide PNT-as-a-service without GPS.
- **WiFi and other Radio Network Derived PNT**: Where radio base stations are fixed, smart phone operating systems can also utilize crowd-sourced methods to identify their locations over time and then use those base station radios as reference points to fix the positions for other smart phones. This is why Uber, and other applications

were able to fix user equipment locations indoors, while the same device, when attempting to dial 9-1-1, a service reliant on GPS, often failed to accurately identify user location, resulting in emergency service failures. WiFi derived PNT is now an example where Location Based Services (LBS) have augmented GPS to reduce the impact of incomplete coverage, but it does not provide a GPS-equivalent quality of service.

- **Dedicated Terrestrial PNT (Complementary and Backup):** As industry and public safety recognized the value of widely available, accurate, and resilient PNT, a market developed to address gaps in GPS coverage and provide 3-dimensional accuracy. These everyday gaps include indoor locations where phones and other radios cannot connect to GPS, urban canyons, where tall buildings and other structures prevent reliable access to GPS, and rugged terrain areas with physical obstructions to clear space-based navigation signals. There are technologies today that provide Terrestrial PNT services that could be complementary, but the technologies are not used in many devices; spectrum assignments are not universal; and the technologies are not ready to provide widespread service should space-based PNT be lost:
    - **eLORAN–Enhanced Long-Range Navigation**: Mariners around the world are highly cognizant of their dependence on space-based PNT. The LORAN system provided accurate timing and navigation signals for decades until the system was decommissioned for commercial service in 2010. Since then, PNT professionals have noted that GPS alone does not provide the resiliency they need for assured operations where third parties may seek to attack space-based PNT. GPS utilizes high-frequency bands that are more susceptible to jamming and hacking than lower-frequency systems like LORAN. In a low-frequency system, the signal integrity is much stronger, which requires a more powerful transmitter to cause interference. Space-based PNT is easier to jam and is more prone to disruption from urban structures, space weather, and EMP (electromagnetic pulse) events. There is strong advocacy for reestablishing an operational Enhanced LORAN system. This would provide a useful layer of PNT resiliency, but only for ships and other endpoints that can easily add new radios and an antenna that does not easily integrate into smartphones and many other devices form factors that today rely on GPS signals.[15]
    - **Commercial Terrestrial Complementary PNT:** There is a growing need for PNT signals that can be received by the same device that supports GPS but are receivable in areas that space-based PNT can't penetrate and can provide a vertical, height reference (3D). Next Generation 9-1-1 highlighted the 'gaps' where GPS is either blocked or not reliable. As mobile users called

for help indoors, in urban canyons or rugged terrain, the lack of accurate position information in GPS blocked areas was creating significant issues connecting callers to the right Public Safety Answering Point (Emergency Call Center). Once the call for help got to the right center, response was too often delayed by missing or inaccurate location information. Lives were lost due to the 'GPS-gap'. As we complete the transition to NG911, the dependence on accurate geolocation that includes z-axis (3-dimensional positions - altitude) for large apartments and office buildings grows as NG911 communications employ Location Based Routing protocols.

The United States should designate Terrestrial Complementary PNT (TCPNT) as an enduring part of an overarching, integrated, resilient PNT system-of-systems designed to complement and back up space-based PNT systems. TCPNT should be governed along with GNSS, space- based PNT, to ensure that their supply chains and failure modes are intentionally orthogonal, without interdependencies.

Ground-Based Augmentation Systems

- Not to be confused with TCPNT, many areas bring systems in to make up for inherent inaccuracies for GNSS (GPS and other space-based PNT Systems). GPS, for example, was originally designed to support a higher level of accuracy for military use than for commercial use. This led to the introduction of **Ground-Based Augmentation Systems (GBAS).** GBAS use ground stations to improve the accuracy and integrity of GPS signals in specific locations. Some GBAS could be expanded to offer a wider range of coverage and redundancy within a layered CPNT construct. GBAS, however, are neither affordable nor widely available to most of the deployed receiver device ecosystem. Significantly, they only improve the space-based signals. Without space-based PNT, they don't work.

What Other Countries Are Doing with Respect to CPNT

Several countries recognize the importance of PNT resilience and are actively developing CPNT capabilities. Here are some examples:

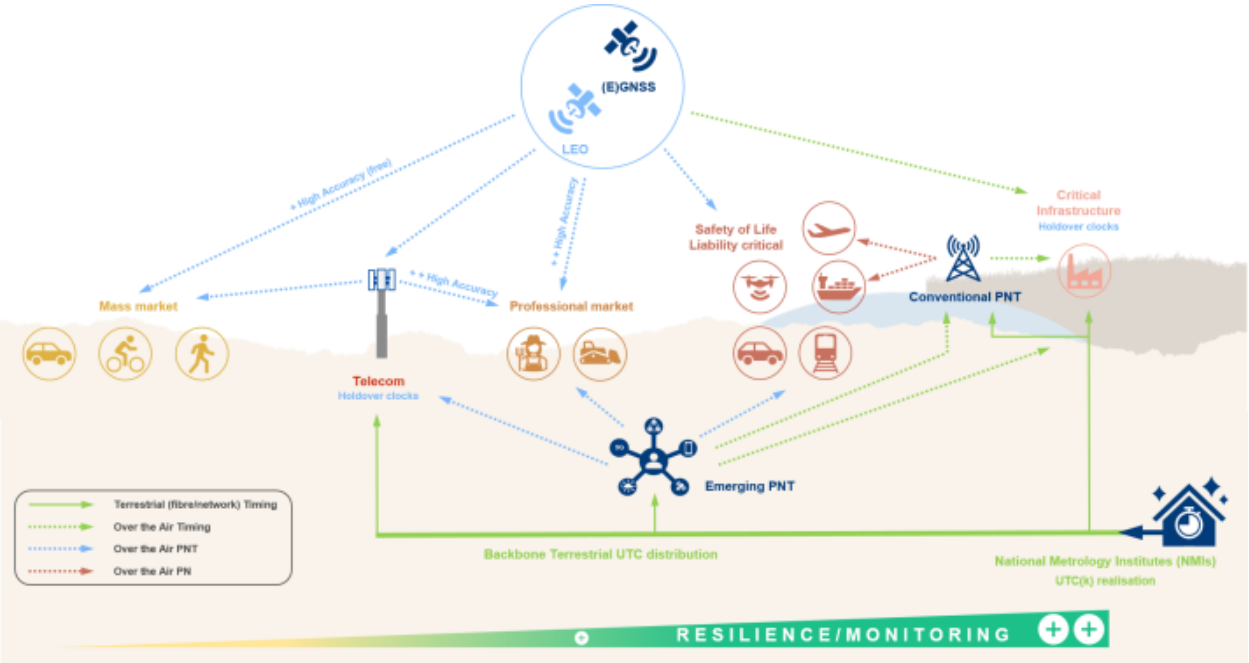
- **European Union (EU):** The EU is developing Galileo, a satellite navigation system that can serve as an alternative to GPS. Galileo offers enhanced accuracy and redundancy for European users.
- **Russia:** Russia operates GLONASS, another global navigation satellite system. GLONASS provides PNT services for Russia and complements GPS in other regions.

- **Japan:** Japan's Quasi-Zenith Satellite System (QZSS) is a regional augmentation system that enhances GPS performance in the Asia-Pacific region.
- **India:** NAVIC provides regional coverage for space-based PNT with an 8-satellite constellation optimized for India, adjacent countries, and the Indian Ocean.
- **China:** China's strides in PNT, particularly with its BeiDou Navigation Satellite System (BDS), have been remarkable, encompassing both military and commercial spheres. This multifaceted approach aims to reduce reliance on foreign systems like GPS and enhance China's global technological influence.[16]

Australia, the EU, Iran, Russia, Saudia Arabia, South Korea, the United Kingdom and China, have additionally taken affirmative steps to introduce terrestrial complements to space-based PNT. The U.K., for example, is developing a terrestrial timing source, from a new National Timing Center, to ensure continuity of accurate timing for communications should space-based PNT be lost. The U.K. National Physical Laboratory (NPL) has determined that loss of GNSS (space-based PNT) would result in a loss of $2.6 billion per day for the U.K. economy alone.[17] Australia provides another example, where commercial terrestrial based complement and backup pilot services are being fielded.[18]

The EU has embarked upon a concerted effort to develop a highly resilient approach to PNT that includes Alternative PNT (A-PNT) sources, completely independent of space-based GNSS, yet fully integrated in a coherent architecture. They are actively engaged with the A-PNT industry and are evaluating the results from demonstration rounds to make decisions that will deliver Terrestrial CPNT through a mix of A-PNT technologies outlined in their 2023 European Radio Navigation Plan (ERNP).

European Radio Navigation Plan 2023



The ERNP called for and tested mature terrestrial PNT commercial solutions that were capable of:

- Delivering positioning, and/or timing information independently from GNSS.
- Acting as a backup in the event of a GNSS disruption.
- Extending PNT signals to environments where current GNSS cannot be delivered.

Concerned about the increased risk from an over-dependence space-based PNT, the EU's Joint Research Center assessed multiple commercial technology solutions over seven months and found them all capable of providing important Terrestrial CPNT functions:

- Precise time keeping using stand-alone atomic clocks and without use of GNSS.
- Precise time transfers over long distances through fiber, computer networks, and over radio networks.
- Indoor and outdoor positioning using terrestrial as well as Low Earth Orbit (LEO) satellite signals.

The EU recognizes that while the probability of a PNT space attack is low, the impact of such an attack is so significant that a complementary terrestrial back up capability is essential. Like, the United States, space-based GNSS does not reach large parts of the

population where they work and live. The testing confirmed that Terrestrial CPNT could address critical coverage gaps where it is deployed, that the technologies were mature, but absent a coherent, integrated architecture, and selection of technologies receivable by existing user equipment, they would fall short of PNT resiliency needs.

China Leading PNT Initiatives Around the World–Terrestrial and Space

PNT service has become an integral part of China's Digital Silk Road. Chinese leaders have noted the criticality of available, resilient PNT as their Belt and Road initiative (BRI) provides cutting edge infrastructure with significant automation. Chinese military leaders have been closely watching as combatants around the world employ GNSS jamming and spoofing to disrupt attacks from smart weapons.

BeiDou was established, not just to provide a space-based PNT constellation, but to instead focus on providing PNT services broadly for both military and civil use. The BeiDou group includes:

1. PNT Services (Multiple layers, geometries and failure modes)
2. PNT Augmentation Services (increases accuracy and availability)
3. Short Messaging Service (SMS) (the BDS satellites can receive and forward calls for help)
4. International engagement and service support
5. A national Cloud platform (supporting calibration, Location-Based Services, PNT application development, AI-enablement)
6. Security and Privacy (Chinese Style) for Location Based Services

In November 2022, the Chinese State Council Information Office (SCIO), provided the following BeiDou mission objective:

We will establish a comprehensive national system for positioning, navigation and timing services, develop a **variety of navigation methods***, and pursue cross-sector innovation in cutting-edge technologies, synergy of different methods for higher performance, and* ***multi-source information fusion and sharing****. We* ***will extend BDS services to provide underwater, indoor and deep space coverage, and offer integrated spatiotemporal information services*** *that are based on unified reference and seamless coverage, and are flexible, intelligent, secure, reliable, convenient and efficient. This will contribute to building a global community of shared future and make the world a better place to live.* [19]

China recognizes that GNSS is an essential part of their national and homeland security future and has been funding integrated efforts to retain PNT advantage over a wide range of conflict scenarios, including the following aspects:

BeiDou Military Support: BeiDou plays a pivotal role in modernizing the People's Liberation Army (PLA). It enables precise missile guidance, enhances situational awareness for troops, and facilitates seamless coordination across various military domains. GPS has anti-jamming capabilities designed for use by a small percentage of military receivers, BeiDou provides system encryption and anti-jamming capabilities that are crucial for maintaining communication and operational security in contested environments. BeiDou anticipates adversary counter space operations and unlike GPS, is building terrestrial complement and back up in a coherent approach, like that envisioned by the European Radio Navigation Plan.

- **BeiDou Anticipates Counterspace Actions**: China recognizes that space-based systems are an asymmetric advantage for the U.S. and consequently China has developed and tested very capable Anti-Satellite (ASAT) Weapons. China's development of ASAT weapons directly and indirectly threatens space-based PNT systems like GPS and other GNSS constellations. These weapons have a variety of attack modes, some of which could disrupt satellite-based navigation services even if PNT satellites are not the primary objective of the attack. Like the U.S., China employs survivable VLF and LF communications to support underwater and other long distance PNT.[20]
- **Electronic Warfare Capabilities**: China is actively developing electronic warfare capabilities with the ability jam, spoof, or cyber-attack adversary GNSS satellites and their signals.[21]
- **Undersea PNT Needs and Resources**:_China recognizes the military utility of both manned and unmanned undersea vehicles. At the same time, China, like the EU and other regions, is looking to increase commercial use of the undersea environment to include the ocean floor and minerals underneath. The undersea environment in regions like the Arctic could significantly alter communications, energy and other commercial transport routes. While China uses Very Low Frequency (VLF) and Low Frequency (LF) for long distance undersea communications and navigation, this does not have either the availability or accuracy required for many commercial applications. Chinese researchers, like their European Space Agency (ESA) counterparts are evaluating the placement of acoustic PNT beacons as an integrated part of their layered service for emerging undersea commercial market areas and the potential, included military utility speaks for itself.[22][23]

BeiDou Economic and Diplomatic Leverage: Perhaps the most likely area in which BeiDou stands to advance Chinese national security objectives stems from growing Chinese space and PNT technology expertise. Chinese PNT systems are increasingly accurate, available, resilient, and cost effective. If the U.S. does not take affirmative steps soon, we risk losing influence in global markets as Chinese PNT alternatives become increasingly attractive.

- **BeiDou Global Expansion**: China is actively promoting BeiDou as a global competitor to GPS. The system is now operational worldwide, offering comparable accuracy and reliability to GPS. This expansion aligns with China's broader Belt and Road Initiative, which aims to strengthen economic ties with countries across Asia, Africa, and Europe.
- **Integration with Other Technologies**: BeiDou is increasingly integrated with other technologies, such as 5G and the Internet of Things (IoT), offering innovative solutions for various industries.[24] This integration enhances the system's appeal and expands its potential applications in areas like precision agriculture, autonomous vehicles, and smart city infrastructure.[25] Chinese researchers and engineers are very active in the development of Integrated Sensing and Communications (ISAC), advancing standards and technical solutions that will enable location aware, inexpensive sensors and actuators underpinning Artificial Intelligence deployments at the edge of networks. One current example of this is the new subway in Beijing, which created a fully integrated PNT, Location Based Services, and Wireless Communications network that provides consistent service fully independent of access to space-based PNT signals. This service supports subway train operations, underground retail use, and consumer user equipment with seamless service that greatly enhances market-based activity throughout the subway system, as well as enabling survivable critical infrastructure should attacks on their space-layer occur.[26] The BeiDou architecture also include Inertial Measurement Units (IMUs), essentially small accelerometers, gyroscopes and sometimes magnetometers that are now at the chip level, keeping track of all of the movements of a device, providing a local position reference to bridge between periods where external navigation signals are lost. This is useful for unmanned automobiles and aviation systems that need continuous guidance. It also can enable PNT receivers to detect corrupted signaling by comparing the local navigation reference with an external reference like GPS or other space-based PNT signal. Similarly, China has also included resilient time sources, able to maintain network synchronization between ever smaller communications nodes and user equipment by bringing Atomic Clocks down to the chip level. Both RF and Optical

Atomic Clocks have reached production using Coherent Population Trapping (CPT) technology.[27] Currently Advanced Driver Assistance System (ADAS) and Autonomous Vehicle markets are driving rapid advances, with downward price pressure as Communications, Compute, Storage and PNT convergence supports multiple industry verticals.

- **Competitive Pricing**: While both GPS and BeiDou are free services for user equipment, China has several advantages when bundling PNT with other technologies. China often offers BeiDou-based, integrated solutions at competitive prices compared to GPS alternatives.[28] This pricing strategy, combined with the system's growing capabilities, is attracting users in developing countries where cost is a significant factor.[29] In its early days, choosing BeiDou meant a degraded experience over GPS. This is no longer the case, as BeiDou's accuracy rivals GPS, with signal calibration ground stations deployed around the world. The increased constellation size and multiple orbits provide useful geometries for hard-to-reach user locations, and BeiDou now supports a fully integrated terrestrial layer providing complementary and backup service. Perhaps the most compelling, advantage Chinese companies have is the lower cost of PNT system integration coupled with advanced communication systems supporting critical infrastructure, mission, and weapon systems.
- **Leveraging Market-based Incentives**: China clearly intends to improve and expand BDS capabilities through public/private means. Their integrated governance allows them to utilize government funding where large capital investment is required, while creating an objective, vibrant ecosystem that will allow them to sustain regular improvements through private venture. The SCIO's November 2022 Whitepaper lays this out in detail, but the following summary provides a sense of their approach: *China will promote large-scale BDS applications and encourage their market-oriented, industrialized and globalized development to offer a broader range of public services of higher quality. We will further unleash market potential, expand application scenarios, increase application scale, create new mechanisms and dynamics, improve the industrial system, strengthen international industrial cooperation, and forge a fuller, more resilient industrial chain. The goal is to share our achievements in BDS development with people all over the world for their benefit.*[30]

Enduring Market Value: Resilient, accurate, and widely available PNT has significant market value. The EU's previously mentioned ERNP placed the U.S. PNT market value at $300B. In addition, an aftermarket has been formed to provide PNT-as-a-service where GNSS fails to provide consistent, accurate, and resilient service. Location Based Services

(LBS) provide public safety, utility control, IOT, retail, and other business functions reference that are essential. The global LBS market was valued at over $26 billion in 2023, and it is projected to continue to grow at double digits over the next decade. LBS is just a fraction of the total value of Resilient PNT, and the U.S. is now competing with other countries for dominant roles in standards, technology, and provision of PNT service.[31] BeiDou's full integration of accurate, available, and resilient capabilities will compete for both PNT and LBS global markets.

PNT Resiliency Advantage:

China's layered, space, and terrestrial approach to PNT is an approach that the U.S. needs but to which it has not committed: China is anticipating that potential adversaries will take steps to deny space-based PNT counter to Chinese interests or to the interests of their allies. They plan and exercise for loss of space-based PNT and have made development and fielding of both Low Earth Orbit and terrestrial-based PNT complements a priority.[32] This gives them useful diplomatic leverage as rest-of-world nations seek support options for PNT-dependent critical infrastructure.

Specific Instances of BeiDou's Terrestrial Integration:

"Next-generation PNT network including integrated processing, basic platform and experimental verification" CETC, October 2020 Layered with TCPNT[33]

Continuing PNT Innovation Velocity: Chinese researchers have steadily been pushing the science and developing Integrated Sensing and Communications (ISAC) capabilities that are more advanced with each new 5G release cycle. Their 6G goals include the design of commercial networks so that available and resilient PNT is a fully integrated part of network services. Their research has included using advanced antennas and artificial intelligence to conduct spectrum environment sensing wherever commercial wireless networks are deployed, with accurate reference elements wherever there are static network elements providing PNT to support ISAC for elements with dynamic attributes. Current research is focused on adding LEO and VLEO constellations into the mix of layered, resilient, converged 6G communication and PNT support. Huawei engineers are laser-focused on providing ISAC for wireless customers and communities throughout their 6G networks with integrated PNT support increasing their competitive advantage around the world.[34] 6G-enabled networks will introduce modulation that enables even greater function support across the wide range of user equipment, edge networks, and spectrum properties. 5G employs OFDM, with stringent frequency division across a given channel

and less stringent time division. 6G employs OFTS modulation, which will create greater efficiency and function support, through greatly increased time division accuracy working in conjunction with frequency division to optimize utilization of signal resource blocks. With an even greater dependence on accurate time, getting the timing reference right will be critical to 6G success. 6G's greater focus on time will also enable accurate PNT distribution as an included part of the multi-function architecture. Establishing a terrestrial CPNT layer in the U.S. market as soon as possible, should be a priority to ensure that our engineers and operators are ready to compete as 6G capabilities are introduced, with centimeter position accuracy, fully integrated real-time navigation supporting dynamic routing decisions, and highly accurate time support for network synchronization challenges stemming from diverse node geometries, and quantum-resistant encryption.

Specific Instances of BeiDou's Terrestrial Integration: BeiDou is primarily a satellite-based navigation system, like GPS, GLONASS, and Galileo. Its core functionality relies on signals transmitted from a constellation of satellites orbiting the Earth. However, there are some instances where BeiDou is integrated with terrestrial systems to enhance its performance and provide additional functionalities:

1. **Ground-Based Augmentation Systems (GBAS):** These systems utilize ground stations to transmit correction signals to BeiDou receivers, improving the accuracy and reliability of positioning and timing information. GBAS is often used in critical applications such as aviation, where precise navigation is essential.
2. **Integration with Cellular Networks:** BeiDou can be integrated with cellular networks to provide location-based services (LBS) for mobile devices. This integration leverages the existing infrastructure of cellular towers and base stations to enhance the availability and accuracy of BeiDou positioning data.
3. **Terrestrial Radio Beacons:** In certain regions, BeiDou signals may be supplemented by terrestrial radio beacons, which transmit additional navigation signals. These beacons can help improve BeiDou coverage in areas with limited satellite visibility, such as urban canyons or mountainous regions. These can be pseudolites, deriving their reference signals from satellite constellations or independent, with survey positions and satellite independent signaling.

U.S. Forces Working to Address the Risk

The National Security Council across several administrations has expressed concerns, and various legislative and executive branch directives have sought to lower the risk from a potential PNT service disruption. Although each directive points to the lack of PNT resiliency as a serious and growing problem, the lack of clear leadership designation for a

layered, survivable, broadly available CPNT system-of-systems has hindered actual risk reduction. Meanwhile, examples of GPS denial, disruption, and deception operations to protect belligerent forces from GPS enabled weapons or to create civil and military disruptions continue to increase.

An Executive Order 13905 signed on February 12, 2020 observed that "*since the United States made the Global Positioning System available worldwide, positioning, navigation, and timing (PNT) services provided by space-based systems have become a largely invisible utility for technology and infrastructure, including the electrical power grid, communications infrastructure and mobile devices, all modes of transportation, precision agriculture, weather forecasting, and emergency response.*"[35]

Space Policy Directive-7 included *implementation actions and guidance for U.S. space-based positioning, navigation, and timing programs and activities for U.S. national and homeland security, civil, commercial, and scientific purposes. It highlighted the United States' ever-growing dependence on space-based positioning, navigation and timing, and suggests* ***government and commercial organizations should have access to backup PNT technologies as GPS signals are likely to be disrupted.***[36]

The EO also pointed out that *"Responsible use of PNT services means the deliberate, risk-informed use of PNT services, including their acquisition, integration, and deployment, such that disruption or manipulation of PNT services minimally affects national security, the economy, public health, and the critical functions of the Federal Government."* This led DHS to evaluate risk reduction options focused on user equipment, resulting in a DHS (CISA and S&T) Conformance Framework, its second version, published in 2022. The framework outlines Prevent, Response, and Recover activities designed to improve PNT device robustness, ability to detect attacks and apply mitigations, and the ability to recover from a failed state in a timely manner. The research and other activities motivated by the framework will help improve critical infrastructure PNT readiness but will not address failure modes associated with loss of space-based PNT, where reconstitution of the space-based service is likely to take months to years.

DOT, as the executive agent for GPS, completed an assessment in response to the EO and developed the DOT Complementary PNT Action Plan,[37] outlining an essential role for Terrestrial alternatives to PNT. It corroborated PNT resiliency shortfalls and reported on a demonstration conducted to validate the efficacy of complimentary PNT service alternatives. The report stated: *Resilient PNT is not only important to support critical infrastructure in the transportation sector but is also essential for national and economic security. The primary and most recognizable PNT service supporting critical infrastructure*

is the Global Positioning System (GPS). However, because GPS relies on signals broadcast from satellites in Medium Earth Orbit (MEO), signal strength at the receiver is low and thus vulnerable to intentional and unintentional disruptions. The impact areas identified in DOT's 2001 report, "Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System," have, if anything, increased the scope and exposure to public sector economic and safety losses in the event of a GPS disruption.[38]

The report included good news about Terrestrial PNT alternatives. The need is so great that a market has formed to provide TCPNT capabilities. Six vendors demonstrated terrestrial radiofrequency (RF) PNT technologies across low frequency (LF), medium frequency (MF), ultra-high frequency (UHF), and Wi-Fi/802.11 spectrum bands. The nation does not need to fund a new-start, government program to address the lack of universal Terrestrial CPNT, it can instead, designate a national TCPNT service category. Designating a category for commercial PNT services as part of an Integrated U.S. PNT plan, would properly incent development and operation of TCPNT systems in an efficient manner. Tests in the EU and in the U.S. have demonstrated the efficacy of existing commercial TCPNT technologies. Leveraging mobile network operator infrastructure in place today would allow TCPNT providers to rapidly extend coverage across the country.

The DOT National PNT Objective Architecture published in 2008 and updated last in 2019 illustrates the complex set of users and functions served today by a primary service from space, GPS and additional constellations making up a Global Navigation Satellite System (GNSS). It calls for complementary capabilities from terrestrial providers in the articulation of a "should be" National PNT Architecture for 2025. We have not achieved the called for terrestrial layer and do not have coordinated plans to deliver it. Where we do find limited Location Based Services (LBS), these are sparse, focused on a niche need, and are not interoperable with most user equipment PNT receivers.[39]

NITRO–Nationwide Integration of Time Resiliency for Operations. The U.S. National Guard (NG) has two institutional roles; they train and operate to fully integrate with Active Duty forces in the Department of Defense. This gives them deep insight into the importance of PNT to military operations as well as adversary capabilities and intent to attack PNT. The NG also has a state mission working directly for their Governors or U.S. Territory leaders. In this role, they have direct knowledge of the increasing community and citizen dependency on GPS. They have deep insight on the range of threats to public safety and are concerned about the current lack of resiliency for PNT.[40]

The NG Bureau team formed to examine the unaddressed risk factors, focused on the loss of available and accurate timing, and concluded that a loss of space-based timing signals

would create “cascading consequences of infrastructure failure” at the National, State, and Local levels. Required mitigations include Time Resiliency thru redundancy to provide the following:

- Maintain availability of uncorrupted and non-degraded timing signal
- Maintain integrity of timing data
- Reliable back-up time source
- Reducing dependency and reliance on single system for timing signal

They noted that our Nation’s communications networks introduced what we now know as the Internet, to eliminate single point failures inherent in the circuit-based networks of the day. The internet is a grid that is designed intentionally to withstand the loss of many, many nodes. Our power and electricity distribution grids and many other utilities are operated as networks designed intentionally to withstand failure in several nodes so that the grids will degrade ‘gracefully’. Since then, timing sources have become space-based, which, on good days, allows synchronization of utilities to go beyond local communities and states, and include half the nation in the case of electricity. The dependence on GPS for the distribution of synchronized timing has led to unacceptable risk. The NGB NITRO program seeks to develop a highly resilient timing ‘grid’ for the nation, with the ability to integrate numerous, synchronized timing sources in a highly redundant, self-healing network of systems. Unfortunately, it looks like funding for this important PNT risk reduction initiative is in jeopardy, as reported by the Resilient Space-based PNT advisory board in July 2024.

While NITRO would, if implemented, provide the framework for graceful degradation of timing distribution, it will need the complementary alternative sources of timing … the grid for timing.

While the NGB focused on timing for their mission responsibilities, citizens and communities know that the continuous availability of position and navigation data is a fast-growing dependency as important as timing. We must address the full PNT resiliency gap.

In the military, we use the PACE acronym. PACE stands for Primary, Alternate, Contingency, and Emergency. When units do their mission planning, communications for an operation have become so foundational to the way we have structured our forces that four separate means of communications are the minimum essential elements for an operational plan. If one fails, you have three more back-ups. As layers of a units planned PACE communications are lost during an operation, the decision-making calculus for

continuation of the mission changes with each degradation. We don't have an effective **PACE plan for PNT,** and this is a critical readiness shortfall. PACE PNT should be an essential, included part of the communications grid underpinning the introduction of AI, Public Safety IOT, Distributed Energy Source Grids, electronic financial transactions replacing cash, and many, many more transformational changes on their way.

While GPS provides the Primary source for Space-based PNT, the introduction of new GNSS and other Space-based PNT sources provide Alternate PNT capacity, with similar delivery modes and source diversity. Both Primary and Alternate are vulnerable to counterspace attacks. Terrestrial PNT (TCPNT) layers bring an orthogonal set of failure modes that are independent of space-based sources. TCPNT should be the Contingency PACE for PNT layer. Finally, the Emergency PNT component should be 'hyper local', ensuring that loss of distant PNT sources, in the worst case, will have limited harm to critical infrastructure, communities, and the citizens they serve. Adding robustness and graceful degradation principles to UE and other PNT receivers will provide significant risk reduction. IMUs, Chip Level Atomic Clocks, ISAC derived positioning, all contribute to device level robustness. DHS has developed a useful taxonomy for this; Prevent, Respond, Recover. The DHS Resilient PNT Conformance Framework 2.0 does a good job of identifying affirmative steps to ensure the external disruptions to Primary, Alternate, and Contingency PNT Sources are not debilitating. It calls for steps to ensure that supply chain attacks are anticipated and in worst-case scenarios Emergency local mitigations are in place until an external PNT source is restored.[41] An integrated resilient PNT program should regularly exercise response.

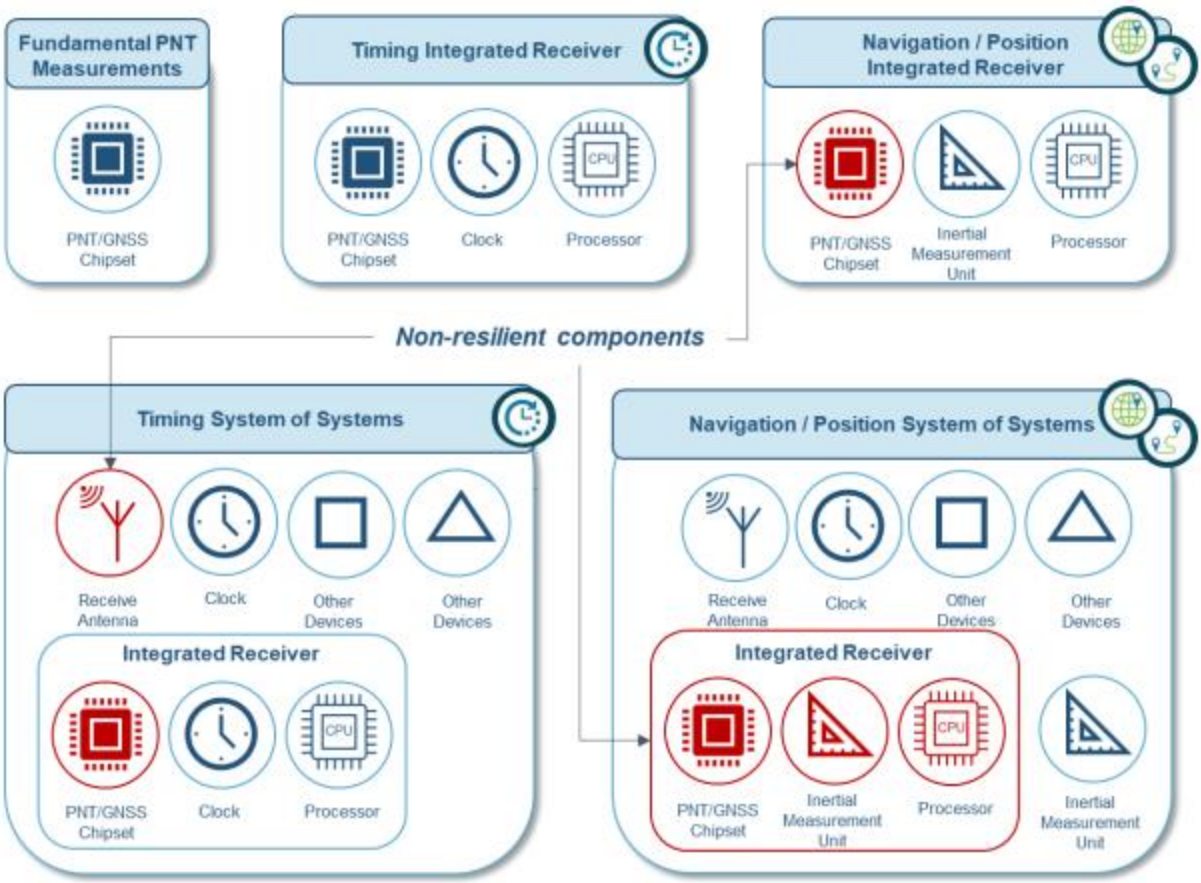


Figure 1. Examples of PNT UE boundaries across (1) Fundamental PNT measurements, (2) integrated receivers, and (3) system of systems.

If attacks on the space-based GNSS PNT sources are successfully executed, the time to recover would be months to years.

The Department of Transportation (DOT) Volpe National Transportation Systems Center report earlier this year called for the following actions:

1. Raise standards on PNT services to a level suitable for safety-critical application
2. Establish field trial testing, monitoring, and situational awareness capability that is suitable for assessing PNT performance to fulfill the sandbox need
3. Drive Complementary PNT adoption through government purchasing power of PNT services at the stringent levels of performance required by critical infrastructure.

Each of these recommendations should be followed up on, but while necessary, they are not sufficient to address the needs of most citizens, communities, and companies or the national security and critical infrastructure threats posed by an attack or failure of space-based PNT. Driving complementary adoption solely through government purchasing power

will fall short of the mark. Government spending on resilient alternatives has not driven the public safety communications market, nor has it changed market dynamics for other critical infrastructure deployments where 'sunny day' deployments don't account for worst-case, but appreciable, risk scenarios. Terrestrial PNT solutions are a classic challenge of 'The Commons' where a single company has difficulty rationalizing the capital expenditure for wide area risk reduction solutions without a coherent U.S. National policy for TCPNT.

TCPNT in the U.S Market Would Reduce Multiple Risk Categories and Help to Futureproof U.S. PNT Global Leadership

Implementing a robust TCPNT system with both space-based and terrestrial components would offer a substantial reduction in U.S. vulnerabilities to disruptions in PNT services. Here's how:

- **Reduced Reliance on Single Source:** TCPNT provides an alternative to GPS, diminishing dependence on a single system of vulnerability.
- **Enhanced Jamming and Spoofing Resistance:** TCPNT utilizes ground-based infrastructure, making it less susceptible to jamming and spoofing attacks targeting space-based systems.
- **Improved System Resilience:** The combined capabilities of TCPNT and GPS create a more robust and resilient PNT ecosystem, minimizing the impact of single-point failures.
- **Close the Indoor and Urban Canyon GPS Gap:** TCPNT will eliminate the confusion GPS receivers often encounter in urban canyons, difficult geographies and indoors.
- **Deterrence:** A widely available Terrestrial Complement to Space-based PNT in the U.S. will eliminate the asymmetric advantage an adversary might seek from an attack on our space assets. The availability of the terrestrial backup capability, that is complementary, will protect the space-based capability. Adding the physically diverse TCPNT would greatly reduce risk (likelihood x impact).
- **U.S. Resilient PNT Global Leadership:** Developing and operating Integrated, multi-layer PNT capabilities will drive sustained PNT workforce development and research activities. Supporting emerging markets in Africa, Latin America, and Southeast Asia by offering affordable, scalable, and resilient PNT solutions would be a useful counter to the expansion of Chinese PNT influence around the world. By investing in training and education programs in these developing regions, U.S. companies will help cultivate positive relationships with local governments and companies, establishing a foundation for long-term partnerships as they extend

PNT to the edge of wireless networks to support devices critical to their AI-enabled future.

These advantages translate into a significant net reduction in U.S. vulnerabilities to PNT disruptions. From a national security standpoint, a robust TPNT system safeguards critical military operations. From a civilian perspective, TCPNT ensures continued functionality of vital services, minimizing economic and societal disruptions.

Conclusion

A day without accurate and available PNT services is a scenario the U.S. cannot afford. The growing threats to space-based PNT necessitate a comprehensive approach that includes robust terrestrial PNT capabilities. By taking decisive action, the U.S. can ensure the continued resilience of critical infrastructure, maintain national security, and unlock the full potential of emerging technologies like 6G. Advanced PNT will be a fully integrated part of 6G terrestrial and space-based network resources. Without bold and effective actions today, we risk ceding technical leadership in both areas.

Investing in a comprehensive terrestrial complement to GPS is not a luxury but a necessity. It is an investment in our national security, economic well-being, and technological future. Low-cost, easily adopted alternatives that responsibly address the greatest risk areas are immediately available. Longer-term, accurate, available and resilient PNT that doesn't depend on space needs to be fully integrated into our digital future and support the full range of our sovereign and commercial interests.

We should organize the approach around three pillars:

1. Bring the PACE approach to PNT resiliency. Continue to add space-based PNT capabilities so that GPS (Primary), has alternate delivery mechanisms from GNSS and other constellations (Iridium, Starlink, Kuiper). Add a Contingency Element by extending Terrestrial CPNT using today's mature solutions across the country in a fully integrated part of a National Resilient PNT Plan. Address the Emergency element through PNT-dependent critical infrastructure systems and receiver risk reduction actions.

2. Develop an objective National PNT Strategy that integrates current and future PNT sources, codifies a PNT PACE Plan with the design and implementation of 6G, and exercises contingency and emergency PNT modes for response and recover after loss of space-based PNT.

3. Pass legislation that fully articulates domestic and international PNT objectives to recapture U.S. leadership in national security, critical infrastructure and commercial PNT. Assign a strong mandate with broad scope and clear lines of authority to address the multiple stakeholder PNT equities. Employ a new public/private business model that brings resource agility to the full range of PNT potential. Create PNT innovation velocity, through a market-based approach that provides compelling global solutions and generates enduring, cutting-edge, asymmetric capabilities for evolving U.S. National Security priorities and competitive international advantage.

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