UNITED STATES DEPARTMENT OF COMMERCE
National Telecommunications and
Information Administration
Washington, D.C. 20230

May 27, 2025

VIA ECFS

Marlene H. Dortch
Secretary
Federal Communications Commission
45 L Street NE
Washington, DC 20554

Re: Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110

Dear Ms. Dortch:

The National Telecommunications and Information Administration (NTIA)[1] applauds the above-referenced initiative of the Federal Communications Commission (Commission). The Commission is seeking to understand and solve the challenges facing the Nation's current Position, Navigation, and Timing (PNT) system. NTIA submits the attached "Inventory of Complementary, Alternative, and Augmentative PNT Solutions" to aid this important work.

This survey is not intended to be exhaustive. Rather, NTIA intends to provide the Commission with an additional considered and vetted resource. NTIA stands ready to assist in the Commission's "whole of government" approach on this matter.[2]

Sincerely,

DAVID BRODIAN
Digitally signed by DAVID BRODIAN
Date: 2025.05.27 10:24:13 -04'00'

David Brodian
Chief Counsel

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[1] NTIA is the Executive Branch agency principally responsible for the development of communications policies pertaining to the Nation's economic and technological advancement and to the regulation of the communications industry, for the coordination of the communications activities of the Executive Branch, and for the effective presentation of the views of the Executive Branch to the Commission. *See* 47 U.S.C. § 902 (b)(2).

[2] Notice of Inquiry, Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110 (released Mar.28, 2025) ¶ 4. NTIA has submitted initial comments on April 28, 2025, *available at* https://www.fcc.gov/ecfs/document/1042889209712/1.

National Telecommunications and Information Administration
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Enc.: “Inventory of Complementary, Alternative, and Augmentative PNT Solutions”

Inventory of Complementary, Alternative, and Augmentative PNT Solutions

This inventory examines space-based, terrestrial-based, and independent positioning, navigation, and timing (PNT) solutions capable of augmenting or complementing GPS service, or serving as an alternative source of positioning, navigation, or timing to form a resilient and secure PNT system of systems in the United States. Although this inventory describes various PNT systems with domestic coverage as a primary consideration, efforts to evaluate the international utilization and coordination of PNT systems are also ongoing. The purpose of this document is to discuss certain technologies and companies and to provide context on various PNT solutions. The United States Government does not endorse any of the technologies or companies listed in this document.

Contents

Space-Based PNT Solutions

GPS Modernization and Augmentation

The United States is supporting multiple efforts to bolster the security and strength of GPS signals. The United States Air Force (USAF) and United States Space Force (USSF) are implementing the GPS modernization program to upgrade the GPS space segment with the capabilities to transmit "a more jam-resistant, encrypted, military specific" M-code signal for military users, as well as the L2C (1227 MHz), L5 (1176 MHz), and L1C (1575 MHz) civil signals to improve GPS performance for civilian users.[1] GPS.gov explains that the L2C signal "enables faster signal acquisition, enhanced reliability, and greater operating range;" the L5 signal "features higher power, greater bandwidth, and an advanced signal design" for "safety-of-life transportation and other high-performance applications;" and the L1C signal improves "mobile GPS reception" and "enables international cooperation" with foreign GNSS, such as Europe's Galileo.[2] USAF launched the first GPS satellite featuring and L2C capabilities in 2005 and the first GPS satellite with L5 capabilities in 2009 under GPS Block IIR-M (2005-2009).[3] USAF launched the first GPS Block III (2018-2025) satellite with L1C capabilities in December 2018.[4] USSF launched the most recent GPS Block III satellite in December 2024, which brought the total GPS constellation to 31 operational satellites, including seven L1C-capable satellites (Block III), 19 L5-capable satellites (Blocks III and IIF), and 25 L2C-capable satellites (Blocks III, IIF, and IIR-M).[5]

Unfortunately, the GPS modernization program has experienced delays across its space and ground segments that have prevented the upgraded civil signals from reaching full operational capacity (FOC). Blocks 1 and 2 of the GPS Next Generation Operational Control System (OCX) program, which will provide command and control for GPS Block III and older-generation GPS satellites as well as "monitoring and control for both modernized and current signals," must undergo further testing ahead of the December 2025 projected deadline for "operational acceptance of the system."[6] Block 3F of the OCX program will "build on OCX Blocks 1 and 2 software to add capabilities to control and use the GPS IIIF space segment," but "factors such as the ongoing delays with Blocks 1 and 2 have complicated" the delivery

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[1] Ludwigson, Jon, "GPS MODERNIZATION Delays Continue in Delivering More Secure Capability for the Warfighter," *United States Government Accountability Office* (September 2024), p. 1-2, https://www.gao.gov/assets/gao-24-106841.pdf; GPS.gov, "New Civil Signals," (August 10, 2020), https://www.gps.gov/systems/gps/modernization/civilsignals/.

[2] GPS.gov, "New Civil Signals," (August 10, 2020), https://www.gps.gov/systems/gps/modernization/civilsignals/

[3] Federal Aviation Administration, "First of New Generation of GPS Satellites Launched Into Orbit," (April 7, 2009), https://www.faa.gov/sites/faa.gov/files/about/office_org/headquarters_offices/ato/FirstL5_GPS_SV_LE_040709.pdf.

[4] Inside GNSS, "Launch of First GPS III Satellite Begins Modernization of the GPS Constellation," (December 24, 2018), https://insidegnss.com/launch-of-first-gps-iii-satellite-begins-modernization-of-the-gps-constellation/.

[5] Khalil, Jesse, "GPS III SV-07 becomes operational," *GPS World* (January 27, 2025), https://www.gpsworld.com/gps-iii-sv-07-receives-operational-acceptance/; GPS.gov, "Space Segment," (July 3, 2023), https://www.gps.gov/systems/gps/space/.

[6] Ludwigson, Jon, "GPS MODERNIZATION Delays Continue in Delivering More Secure Capability for the Warfighter," *United States Government Accountability Office* (September 2024), p. 4, 14, https://www.gao.gov/assets/gao-24-106841.pdf

timeline for Block 3F.[7] With over 24 L2C-capable GPS satellites already in orbit, the L2C signal will reach FOC when the corresponding OCX ground system is delivered, possibly in early 2026.[8] The L5 signal will reach initial operational capacity (IOC) when OCX monitoring of L5 comes fully online, but efforts to launch 24 L5-capable GPS satellites are also "years behind schedule" and the will likely not reach FOC until "around 2027."[9] The L1C signal will remain pre-operational until future GPS Block III and IIIF launches bring the number of L1C-capable GPS satellites to 24, which is not expected until the "late 2020s."[10]

The US is also engaging in efforts to increase the number of friendly GNSS satellites in orbit. In September 2024, USSF Space Systems Command (SSC) awarded its first contracts under the Resilient-GPS (R-GPS) program, which was authorized under the Department of Defense's (DOD) "Quick Start" authority to augment the existing GPS constellation with "proliferated small satellites transmitting a core set of widely-utilized GPS signals."[11] Under the continuing resolution passed by Congress in March 2025, USSF is authorized to transfer "$30 million from the Protected Tactical Satellite (PTS) program to fund a new procurement" of R-GPS satellites.[12] The exact capabilities of the R-GPS satellites are not publicly available, but USSF SSC emphasized that the R-GPS space segment will provide "resilience to military and civil GPS users," indicating some level of support for the legacy L1C/A civil signal or the newer L2C, L5, or L1C civil signals.[13] Multiple countries, including the United States, also bolster regional GPS/GNSS performance by operating Satellite Based Augmentation Systems (SBAS), which increase the reliability and accuracy of GPS signals with "wide-area corrections for GNSS range errors."[14] The FAA operates the Wide Area Augmentation System (WAAS) for North America, which provides more precise GPS signals for the civil aviation industry, including "horizontal and vertical navigation for approach operations."[15]

These modernization and augmentation efforts will ultimately contribute to a more reliable and secure GPS constellation, but solely relying on a stronger version of GPS does not align

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[7] *Id*.

[8] GPS.gov, "Codeless/Semi-Codeless GPS Access Commitments," (August 23, 2021), https://www.gps.gov/technical/codeless/; Heckmann, Laura, "Timeline for Troubled GPS Programs Continues to Grow," *National Defense* (November 19, 2024), https://www.nationaldefensemagazine.org/articles/2024/11/19/timeline-for-troubled-gps-programs-continues-to-grow.

[9] Erwin, Sandra, "GPS startup bets on advanced signal to counter jamming threats," *SpaceNews* (July 17, 2024), https://spacenews.com/gps-startup-bets-on-advanced-signal-to-counter-jamming-threats/.

[10] GPS.gov, "New Civil Signals," (August 10, 2020), https://www.gps.gov/systems/gps/modernization/civilsignals/.

[11] Press Release, "United States Space Force, "Space Force awards four 'Quick Start' Resilient GPS agreements," (September 23, 2024), https://www.spaceforce.mil/News/Article-Display/Article/3914829/space-force-awards-four-quick-start-resilient-gps-agreements/.

[12] Erwin, Sandra, "U.S. Space Force budget trimmed in full-year continuing resolution," *SpaceNews* (March 20, 2025), https://spacenews.com/u-s-space-force-budget-trimmed-in-full-year-continuing-resolution/.

[13] Press Release, "United States Space Force, "Space Force awards four 'Quick Start' Resilient GPS agreements," (September 23, 2024), https://www.spaceforce.mil/News/Article-Display/Article/3914829/space-force-awards-four-quick-start-resilient-gps-agreements/.

[14] NovAtel, "Satellite Based Augmentation System (SBAS)," https://novatel.com/an-introduction-to-gnss/resolving-errors/sbas *(accessed April 7, 2025)*.

[15] Federal Aviation Administration, "Satellite Navigation – Wide Area Augmentation System (WAAS)," https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas *(accessed April 7, 2025)*.

with "the goal of achieving a robust and resilient PNT system of systems."[16] Besides further improvements to GPS, the complementary, alternative, and augmentative PNT systems outlined below have been proposed to bolster PNT resiliency in the United States.

Low Earth Orbit (LEO) PNT Systems

Most GNSS systems, including GPS, Galileo, GLONASS, and BeiDou, primarily operate in medium Earth orbit (MEO).[17] Satellites in MEO circle the Earth approximately twice per day, require "significantly less momentum to stay on course," and "have a higher vantage point" compared to LEO, meaning a limited number of satellites can "provide full coverage of the Earth."[18] While MEO offers key advantages that have benefitted GNSS operations for decades, its drawbacks have prompted some PNT stakeholders to explore the viability of LEO for space-based PNT systems. The NOI noted that GNSS signals from MEO are typically "high-frequency and low power," leaving them more vulnerable to accidental or intentional interference and less capable of penetrating physical barriers compared to higher-power alternatives.[19] LEO satellites are not inherently more powerful due to their orbital height, but their proximity to Earth enables them to achieve a given signal strength with less transmit power than MEO satellites.[20] The NOI also noted that LEO satellites offer lower latency and, "due to the greater number of satellites in orbit," could "provide better positioning accuracy as compared to MEO satellites."[21] Once seen as a drawback, the greater number of LEO satellites required for global coverage naturally provides "greater resilience against attack or interference because many satellites share the same mission."[22] A variety of private venture capital firms, domestic and international public sector and defense organizations, and strategic industry partnerships are now financially backing efforts to develop LEO PNT systems, with global revenues expected to grow more than fourfold by 2032.[23]

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[16] Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110, *Notice of Inquiry*, para. 16 (2025).
[17] Sodders, Lisa, "LEO, MEO, or GEO? Diversifying orbits is not a one-size-fits-all mission (Part 2 of 3)," *USSF Space Systems Command* (July 20, 2023), *https://www.ssc.spaceforce.mil/Newsroom/Article-Display/Article/3465697/leo-meo-or-geo-diversifying-orbits-is-not-a-one-size-fits-all-mission-part-2-of*.
[18] *Id*.
[19] Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110, *Notice of Inquiry*, para. 10-11 (2025); Dennehy, Kevin, "Is LEO PNT the Next Big Thing?" *Institute of Navigation Quarterly Newsletter*, Vol. 33, No. 1 (2023), *https://www.ion.org/publications/upload/ION-Winter2023.pdf*.
[20] Sodders, Lisa, "LEO, MEO, or GEO? Diversifying orbits is not a one-size-fits-all mission (Part 1 of 3)," *USSF Space Systems Command* (July 18, 2023), *https://www.ssc.spaceforce.mil/Newsroom/Article-Display/Article/3462074/leo-meo-or-geo-diversifying-orbits-is-not-a-one-size-fits-all-mission-part-1-of*.
[21] Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110, *Notice of Inquiry*, para. 22 (2025).
[22] Congressional Budget Office, *Large Constellations of Low-Altitude Satellites: A Primer* (May 2023), https://www.cbo.gov/system/files/2023-05/58794-satellite-primer.pdf.
[23] Inside GNSS, "Xona Raises $19 Million Series A for LEO Satellite Network," *https://insidegnss.com/xona-raises-19-million-series-a-for-leo-satellite-network/ (accessed May 2, 2025)*; The European Space Agency, "ESA kicks off two new navigation missions," *https://www.esa.int/Applications/Satellite_navigation/ESA_kicks_off_two_new_navigation_missions (accessed May 2, 2025);* Navistrat Analytics, "Low Earth Orbit (LEO) PNT Market Size to Reach USD 17,314.6 Million in 2032," *https://navistratanalytics.com/press_release/low-earth-orbit-leo-pnt-market-size-to-reach-usd-17314-6-million-in-2032/ (accessed May 2, 2025).*

Multiple commercial startups and legacy satellite operators are developing PNT-dedicated LEO constellations, which are launched "for the sole purpose of providing PNT services," as well as LEO-augmented GNSS systems, through which "signals from LEO are fused with MEO GNSS signals for improved PNT."[24] The PNT NOI identified Iridium's Satellite Time and Location (STL) service, TrustPoint's commercial GNSS, and Xona Space System's Pulsar service as three leading examples of cooperative LEO PNT capabilities.[25] STL uses Iridium's network of 66 LEO satellites to transmit signals in an L-band channel (1616-1626 MHz) previously dedicated to paging at levels "about 1,000 times stronger than GPS or GNSS, allowing it to penetrate buildings and other hard-to-reach areas."[26] TrustPoint, a small startup which won a $3.8 million SpaceWERX contract in 2024, plans to establish a C-band LEO constellation that will provide "frequency diversity" from the "nearly 200 L-band GNSS and PNT satellites in orbit today."[27] Xona, another startup which won a $4.6 million Air Force Research Laboratory contract in 2025, plans to deploy 258 Pulsar LEO satellites to provide complementary and backup PNT services to GPS in the L- and C-bands.[28] Iridium's STL is currently the only commercially available LEO-based PNT constellation as other competitors are still working to develop their technologies or launch satellites.[29] NAL Research produces a series of "Iridium STL receivers that provide PNT information, independent of GPS."[30]

A growing body of academic and industry research has proposed frameworks for leveraging signals from semi-cooperative or non-cooperative LEO constellations for PNT purposes.[31] The FCC NOI explains that establishing a semi-cooperative LEO constellation would require that non-PNT LEO systems "provide PNT services or data" as "either an additional primary function or a secondary source of data for PNT services."[32] Requiring that non-PNT satellites' hardware and spectrum be "dual-purposed for PNT" would place an additional burden on LEO network operators, but some commentors in WT Docket No. 25-110 have supported such a requirement given that spectrum is a public resource and providing additional PNT services

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[24] Kassas, Zak M., "The Truth is Out There: LEO PNT with Uncooperative Satellites," *Institute of Navigation, Joint Navigation Conference* (2025), https://www.ion.org/jnc/abstracts.cfm?paperID=15692.
[25] Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110, *Notice of Inquiry*, para. 23 (2025).
[26] Iridium, "Iridium Satellite Time and Location," https://www.iridium.com/satellite-time-location/ *(accessed April 7, 2025)*; Luccio, Matteo, "Iridium focuses on timing and critical infrastructure," *GPS World* (July 11, 2024), https://www.gpsworld.com/iridium-focuses-on-timing-and-critical-infrastructure/.
[27] Werner, Debra, "TrustPoint wins SpaceWERX contracts for alternative PNT," *SpaceNews* (August 21, 2024), https://spacenews.com/trustpoint-wins-spacewerx-contracts-for-alternative-pnt/.
[28] Erwin, Sandra, "U.S. Air Force to explore Xona Space's commercial alternative to GPS," *SpaceNews* (February 25, 2025), https://spacenews.com/u-s-air-force-to-explore-xona-spaces-commercial-alternative-to-gps/; Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110, *Notice of Inquiry*, para. 23 (2025).
[29] Iridium, "Iridium Satellite Time and Location," https://www.iridium.com/satellite-time-location/ *(accessed April 7, 2025)*.
[30] NAL Research, "ALTM GEN4," https://www.nalresearch.com/product/altm-gen4/ *(accessed May 20, 2025).*
[31] Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110, *Notice of Inquiry*, para. 6 (2025); Gutierrez, Peter, "Using LEO Signals of Opportunity for PNT," *Inside GNSS* (June 10, 2024), https://insidegnss.com/using-leo-signals-of-opportunity-for-pnt/. Cooperative satellite systems refer to those that can share resources and coordinate operations.
[32] Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110, *Notice of Inquiry*, para. 48 (2025).

would be a public service.[33] For instance, The Boulder Regional Emergency Telephone Service Authority said that all LEO satellites should be required to "include positioning objects or beacons in their signals", which would transform non-PNT LEO constellations into semi-cooperative networks with limited support for PNT services.[34] As noted in the PNT NOI, pre-existing signals of opportunity (SoOPs) from non-cooperative LEO satellites "are also a potential source for PNT capabilities."[35] Researchers have theorized that it is possible to derive PNT information by measuring the Doppler effects of SoOPs transmitted by communications and broadband LEO satellites as they move across the sky relative to users on the ground.[36] A recent work published in the Journal of the Institute of Navigation achieved the "first positioning solution obtained exclusively with OFDM-based (Orthogonal Frequency Division Multiplexing) Doppler shift" calculated from Starlink Ku-band downlink channels.[37] The authors claimed that their solution achieved "meter-level 3D position" accuracy within 10 seconds using SoOPs from just three active Starlink satellites.[38] Parsons Corporation currently offers Assured Positioning System (APS) user devices that leverage this technique to provide GPS/GNSS-independent PNT services.[39]

Two-Way Satellite Time Transfer (TWSTT) and Two-Way Satellite Time and Frequency Transfer (TWSTFT)

The National Institute of Standards and Technology (NIST) provides a GNSS-independent time calibration service through a link between the NIST time scale in Boulder, Colorado, and a given customer's facility using commercial geosynchronous orbit (GSO) communication satellites and spectrum already available for use by these satellites. [40] The service provides UTC(NIST) to customers with suitable equipment (satellite dish, transponder, and modem) who need the highest possible time accuracy and precision, such as critical infrastructure sectors and providers of alternative PNT services to the public.[41] This remote calibration service is useful for customers that require precise timing beyond the capabilities of GPS time transfer techniques, but the "added complexity of having to have both transmit and receive hardware

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[33] Kassas, Zak M., "The Truth is Out There: LEO PNT with Uncooperative Satellites," *Institute of Navigation, Joint Navigation Conference* (2025), *https://www.ion.org/jnc/abstracts.cfm?paperID=15692*; Boulder Regional Telephone Service Authority (BRETSA), In the Matter of Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110, *Comment* (April 29, 2025), https://www.fcc.gov/ecfs/search/search-filings/filing/1042870957636.

[34] *Id.*

[35] Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110, *Notice of Inquiry*, para. 6 (2025).

[36] Gutierrez, Peter, "Using LEO Signals of Opportunity for PNT," *Inside GNSS* (June 10, 2024), *https://insidegnss.com/using-leo-signals-of-opportunity-for-pnt/*.

[37] Kozhaya, Sharbel, Joe Saroufim, and Zaher (Zak) M. Kassas, "Unveiling Starlink for PNT," *Journal for the Institute of Navigation*, Vol 72, Issue 1 (March 2025), *https://doi.org/10.33012/navi.685*.

[38] *Id.*

[39] Parsons Corporation, "Resilient PNT: Assured Positioning System," *https://www.parsons.com/products/aps/ (accessed May 20, 2025).*

[40] NIST, "Two-Way Satellite Time and Frequency Transfer (TWSTFT)," (May 10, 2016), *https://www.nist.gov/pml/time-and-frequency-division/time-distribution/two-way-satellite-time-and-frequency-transfer*.

[41] NIST, "Time over Satellite Special Test," *https://shop.nist.gov/ccrz__ProductDetails?sku=78500S&cclcl=en_US (accessed May 19, 2025)*.

at each station" raises the logistical and financial cost of using the service.[42] Microchip Technology (formerly Microsemi) also offers TWSTT services via commercial geostationary (GEO) to synchronize end-user clocks with an authoritative time source.[43]

Terrestrial-Based PNT Solutions

Broadcast Positioning System (BPS)

Broadcast television infrastructure equipped with "ATSC 3.0, an international standard for broadcast television," can transmit precise timing signals from television towers already deployed across the country.[44] The National Association of Broadcasters (NAB) describes BPS as a "reliable, complementary service to GPS," capable of providing terrestrial-based timing services "even if GPS is hacked, jammed, or spoofed."[45] NAB explains that BPS will initially have the capability to provide timing services to "known locations of critical infrastructure" using the ATSC 3.0 signal from a "single BPS-enabled TV station," but as more stations are equipped with BPS capabilities, "the signals from multiple TV stations can also be used to independently determine the position of a user, similar to how GPS does today."[46] The latter capability is emphasized in the PNT NOI, which explains that, although BPS is primarily a timing service, users can "determine their location based on their calculation of the time difference of arrival (TDOA) of the received signals."[47] ATSC claimed that "as of early 2025, approximately 76% of U.S. households across 78 viewing markets have access to ATSC 3.0 broadcasts," and NAB highlighted that the BPS signal is much stronger than GNSS signals and therefore harder to jam.[48] NAB also noted that "TV signals operate on a variety of frequencies, spanning 210 megahertz of spectrum over 35 6-MHz channels," which further mitigates the risk of accidental or intentional disruptions of the BPS signal.[49]

NAB, Sinclair Broadcast, and UrsaNav recently demonstrated a combined BPS-eLoran system that could "provide a nationwide backup to GPS" using "10 eLoran towers and the bulk of the nation's TV stations running on ATSC 3.0," but this proposal would require the creation of a

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[42] NIST, "Two-Way Satellite Time and Frequency Transfer (TWSTFT)," (May 10, 2016), *https://www.nist.gov/pml/time-and-frequency-division/time-distribution/two-way-satellite-time-and-frequency-transfer*.

[43] Microchip Technology, "PNT Capabilities and Solutions," *https://ww1.microchip.com/downloads/aemDocuments/documents/FTD/ProductDocuments/Brochures/PNT-Capabilities-and-Solutions-DS00005608.pdf (accessed May 20, 2025).*

[44] Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110, *Notice of Inquiry*, para. 25 (2025).

[45] National Association of Broadcasters, "Broadcast Positioning System (BPS): Securing U.S. Infrastructure," *https://www.nab.org/bps/ (accessed April 7, 2025).*

[46] National Association of Broadcasters, "Protecting Critical Infrastructure: Augmenting GPS with the Broadcast Positioning System (BPS)," *https://www.nab.org/bps/BPS_Protecting-Critical-Infrastructure.pdf (accessed May 19, 2025).*

[47] Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110, *Notice of Inquiry*, para. 25 (2025).

[48] *Id*; ATSC, "Comments of ATSC: The Broadcast Standards Association," FCC WT Docket No. 25-110, *Comment* (April 28, 2025), *https://www.fcc.gov/ecfs/document/1042879374953/1*.

[49] National Association of Broadcasters, "Protecting Critical Infrastructure: Augmenting GPS with the Broadcast Positioning System (BPS)," *https://www.nab.org/bps/BPS_Protecting-Critical-Infrastructure.pdf (accessed April 7, 2025).*

national eLoran network and widespread adoption of ATSC 3.0.[50] Importantly, eLoran and BPS are not inherently linked: eLoran is a separate terrestrial navigation and timing system (described below) that transmits 100 KHz signals using dedicated radio towers while BPS leverages multiple existing TV broadcast frequencies from 30 MHz to 3 GHz and relies on TV transmission infrastructure.[51] NAB filed a petition on February 26, 2025, urging the FCC to mandate a two-phase ATSC 3.0 transition under which full-power stations in the top 55 markets (covering 70% of viewers) would have to switch to ATSC 3.0 by February 2028, and stations in all remaining markets would have to complete the transition by February 2030.[52] Outside of this FCC proceeding, the ATSC 3.0 transition is facing resistance on the end-user equipment front, including complications stemming from a patent dispute between LG Electronics Inc. and Constellation Designs, LLC, which has compelled LG to "suspend the inclusion of ATSC 3.0-compatability" in its television units since September 2023.[53] In an amicus brief filed with the U.S. Court of Appeals in August 2024, a pro-ATSC 3.0 consortium said that the district court's ruling "erased the profitability of NEXTGEN (ATSC 3.0-enabled) TVs" for LG and warned that "the consequences of the judgement may reverberate beyond one manufacturer."[54] The widespread deployment of BPS inherently depends upon the willingness of a range of broadcast industry stakeholders and consumers to participate in the ATSC 3.0 transition.

Enhanced Long-Range Navigation (eLoran)

The PNT NOI explained that Enhanced Long-Range Navigation, known as eLoran, "is a terrestrial radio navigation timing system" that operates primarily in the 90-110 kHz range and uses "hyperbolic navigation, a method of positioning based on TDOA technology," to determine a user's location.[55] The eLoran system has a "reported accuracy as good as ±8 meters," and some eLoran broadcast stations are capable of sending additional pulses with

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[50] Tayloe, Monty, "Broadcasters Looking at BPS to Justify ATSC 3.0 Transition," *Communications Daily* (April 8, 2025), *https://communicationsdaily.com/article/view?BC=bc_67f45d056f37a&search_id=23907&id=2298614*.

[51] Resilient Navigation and Timing Foundation, "NAB, Sinclair, UrsaNav Demonstrate GPS Backup System," (April 4, 2025), *https://rntfnd.org/2025/04/04/nab-sinclair-ursanav-demonstrate-gps-backup-system-location-business-news*; Helwig, Art, Dr. Gerard Offermans, Christopher Stout, Charles Schue III, "eLoran System Definition and Signal Specification Tutorial," *UrsaNav* (November 2011), *https://www.ursanav.com/wp-content/uploads/UrsaNav-ILA-40-eLoran-Signal-Specification-Tutorial.pdf*.

[52] *Id;* Kirby, Kathleen, John Burgett, Ari Meltzer, and Stephanie Rigizadeh, "FCC Seeks Comment on ATSC 3.0/Next Gen TV Transition," *Wiley*, (April 18, 2025), *https://www.wiley.law/alert-FCC-Seeks-Comment-on-Next-Gen-TV-Transition;* Authorizing Permissive Use of the "Next Generation" Broadcast Television Standard, GN Docket No. 16-142, *Petition for Rulemaking*, (February 26, 2025).

[53] LG Electronics USA Inc., "Third Report and Order and Fourth Further Notice of Proposed Rulemaking Comments of LG Electronics USA Inc.," GN Docket No. 16-142, *Comment* (September 15, 2023), *https://www.fcc.gov/ecfs/search/search-filings/filing/1091504742573*.

[54] Brief of Amicus Curiae Pearl TV in Support of Appellant and Reversal at 13-15, Constellation Designs, LLC, v. LG Electronics, Inc., et al., Case No. 24-1822, United States Court of Appeals for the Federal Circuit, https://fedcircuitblog.com/wp-content/uploads/2024/08/Amicus-Pearl.pdf.

[55] Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110, *Notice of Inquiry*, para. 27 (2025).

differential GPS (DGPS) corrections.[56] DGPS enhances the positional accuracy of standard GPS by using ground-based reference stations to measure and broadcast corrections for satellite signal errors, with "accuracy levels on the order of one to 10 meters."[57] Although the United States developed the first generation of Loran technology during World War II, modern eLoran and Loran-C systems are primarily deployed in other countries, including the United Kingdom, South Korea, China, and Russia.[58] China completed its eLoran network in October 2024, which covers up to 1,000 miles offshore, including the Taiwan Strait, and integrates with fiber-optic infrastructure to provide accurate positioning and timing services across the entire country.[59] Russia's *Chayka* network, similar to Loran-C, covers large swathes of its eastern, western, and northern coastlines, as well as most of Ukraine.[60] With widespread jamming along the Russia-Ukraine border, military analysts have suspected that the Russian military used its terrestrial network for navigation purposes in the GNSS-degraded environment.[61]

A 2009 Office of Management and Budget (OMB) memo cited cost savings to the tune of "$190 million over five years" as justification for terminating the US Coast Guard-operated (USCG) Loran-C network, which the administration argued was "not capable as a backup for GPS."[62] Congress approved a Department of Homeland Security (DHS) appropriations measure allowing the USCG to begin shutting down the Loran-C network in 2010.[63] Although the network is no longer operational, the USCG retained ownership of many of its former Loran-C transmission sites.[64] The 2023 National Defense Authorization Act permitted the USCG to dispose of its Loran-C transmission sites after the Departments of Transportation and Defense affirmed that they did not wish to accept transfer of the properties, but the Federal Government still retains custody of most transmission sites.[65] Repurposing old Loran-C

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[56] Stanford Engineering GPS Lab, "Enhanced Long-Range Navigation (eLORAN)," *https://gps.stanford.edu/research/early-gpspnt-research/enhanced-long-range-navigation-eloran (accessed April 7, 2025)*.
[57] Chivers, Morag, "Differential GPS Explained," *ESRI,* (Winter 2003), *https://www.esri.com/about/newsroom/arcuser/differential-gps-explained*.
[58] *Id*.
[59] Resilient Navigation and Timing Foundation, "China completes national eLoran network – The Paper," (October 3, 2024), *https://rntfnd.org/2024/10/03/china-completes-national-eloran-network-the-paper/*; Goward, Dana and Martin C. Faga, "Defending Taiwan by countering China's biggest threat," *SpaceNews* (May 22, 2023), *https://spacenews.com/defending-taiwan-by-countering-chinas-biggest-threat/*.
[60] Resilient Navigation and Timing Foundation, "GPS Problems in Russia? – Try Chayka," (August 9, 2017), *https://rntfnd.org/2017/08/09/gps-problems-in-russia-try-chayka/*.
[61] Cozzens, Tracy, "Russia expected to ditch GLONASS for Loran in Ukraine invasion," *GPS World* (February 17, 2022), *https://www.gpsworld.com/russia-expected-to-ditch-glonass-for-loran-in-ukraine-invasion/*.
[62] Office of Management and Budget, *Terminations, Reductions, and Savings: Budget of the U.S. Government Fiscal Year 2010* (May 24, 2009), https://www.govinfo.gov/content/pkg/BUDGET-2010-TRS/pdf/BUDGET-2010-TRS.pdf.
[63] GPS.gov, "LORAN-C Infrastructure and E-LORAN," (last updated February 2025), https://www.gps.gov/policy/legislation/loran-c/.
[64] Resilient Navigation and Timing Foundation, "U.S. preparing to dispose of old Loran sites – Is that important?" (February 25, 2024), *https://rntfnd.org/2024/02/25/u-s-preparing-to-dispose-of-old-loran-sites-is-that-important/*.
[65] 89 FR 13147; Grant, Alan, and Dana Goward, "10 answers about eLoran," (April 11, 2022), *https://www.gpsworld.com/10-answers-about-eloran/*; McNeff, Jules, "Is there a silver bullet for resilient PNT?" (April 25, 2025), *https://www.gpsworld.com/is-there-a-silver-bullet-for-resilient-pnt/*.

transmission sites for a future eLoran network would offer some cost savings, but revamping the properties to support "the construction of additional larger, high-power transmitters to provide accurate positioning nationwide," as described in the PNT NOI, would require significant renovations, as many Loran-C sites are now derelict or entirely abandoned.[66] UrsaNav, an eLoran and Loran-C company, explained that there are three Loran transmission sites "still operating in the US under license from DHS for test purposes," and "if two of these stations were brought up to eLoran standards and the third one relocated, it would only require an additional five stations to cover the Continental US (CONUS), the majority of which would have double coverage."[67] Interest in eLoran is also rising internationally: South Korea is upgrading its Loran-C network to the eLoran standard, the United Kingdom's Ministry of Defense is developing a deployable eLoran system to enhance national PNT resilience, outlining plans for an eLoran network to backup critical infrastructure, and there is significant interest in East Asia and Europe, particularly in the Baltic and Eastern Mediterranean, for enhancing existing systems.[68]

NextNav

NextNav's TerraPoiNT solution is an "overlay network" capable of providing resilient PNT services to most GPS-enabled devices in a covered area.[69] TerraPoiNT's network of terrestrial beacons transmits signals in the 919.75-927.75 MHz band, which NextNav claims are 100,000 times more powerful than GPS signals, "fully encrypted," and resistant to "GPS spoofing and jamming."[70] TerraPoiNT can coordinate with NextNav's Pinnacle solution, which is a terrestrial pressure sensor network that offers "floor-level altitude measurements" by communicating with "existing barometric pressure sensors" in most consumer electronics, to provide z-axis location services.[71] NextNav claims that its TerraPoiNT system is currently deployed in the "72 top US markets."[72] NextNav filed a petition for rulemaking with the FCC in April 2024 to request a 15 MHz flexible use license in the lower 900 MHz band for its multilateration

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[66] Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110, *Notice of Inquiry*, para. 28 (2025); McGrath, Gareth, "What's the future of the Coast Guard's 210-acre LORAN station site near Carolina Beach?" *Wilmington Star-News* (February 6, 2024), *https://www.starnewsonline.com/story/news/local/2024/02/06/whats-up-with-the-coast-guards-loran-station-near-carolina-beach-in-southern-new-hanover-county/72338664007/*; Meek, Glen, "First wave: Is a comeback in store for Searchlight's radio positioning station?" *Las Vegas Sun* (January 8, 2017), https://lasvegassun.com/news/2017/jan/08/first-wave-is-a-comeback-in-store-for-searchlights/.

[67] UrsaNav, "Comments in Response to Notice of Inquiry WT-Docket 25-110," FCC WT Docket No. 25-110, *Comment* (April 25, 2025), *https://www.fcc.gov/ecfs/search/search-filings/filing/10425106741527*.

[68] Goward, Dana, "South Korea partners with broadcaster on eLoran and 10-cm GPS," *GPS World*, (November 23, 2020), *https://www.gpsworld.com/south-korea-partners-with-broadcaster-on-eloran-and-10-cm-gps*; Cozzens, Tracy, "UrsaNav installs eLoran testbed in South Korea," *GPS World*, (July 22, 2020), *https://www.gpsworld.com/ursanav-installs-eloran-testbed-in-south-korea*; Goward, Dana, "UK MOD investigating deployable eLoran," *GPS World*, (September 30, 2024), *https://www.gpsworld.com/uk-mod-investigating-in-deployable-eloran*.

[69] NextNav, "NextNav TerraPoiNT Accurate, Secure, Resilient 3D PNT Solutions," *https://nextnav.com/terrapoint/* *(accessed April 7, 2025)*.

[70] *Id*.

[71] NextNav, "NextNav Pinnacle Accurate, floor-level vertical location," *https://nextnav.com/pinnacle/* *(accessed April 7, 2025)*.

[72] NextNav, "NextNav TerraPoiNT Accurate, Secure, Resilient 3D PNT Solutions," *https://nextnav.com/terrapoint/* *(accessed April 7, 2025)*.

NextGen PNT system.[73] The new solution would require mobile network operators to deploy 5G infrastructure in the lower 900 MHz band, and then NextNav would "implement, operate, and manage additional PNT-optimized infrastructure over the 5G network" to offer PNT services based on "5G positioning reference signals."[74] Thus, NextNav will maintain its own PNT-optimized infrastructure, including atomic clocks and barometric pressure sensors, while integrating with partner 5G networks, ensuring both GPS backup functionality and compliance with coexistence requirements in the Lower 900 MHz band.[75] The PNT NOI requests comments on "the various solutions that NextNav is providing or could provide." [76] Many stakeholders have already voiced their opinion on NextNav's 900 MHz proposal in WT Docket No. 24-240.

Mobile Broadband Systems

The PNT NOI noted that 3GPP has integrated "support for consumer user equipment (UE) positioning" into existing LTE and 5G mobile broadband systems, and that "3GPP is considering standardization of [a] resilient GNSS-independent positioning solution" in future 6G systems "to provide positioning services when GNSS services" are unavailable.[77] In essence, this means that 3GPP makes it possible for smartphones to figure out their location using 4G and 5G networks without reliance on GPS and also that 3GPP is working on new standards so devices can still find their location if GPS or GNSS isn't available, increasing reliability. Ericsson explained that the 5G New Radio (NR) specifications include a positioning reference signal for positioning in the downlink and a "sounding reference signal (SRS) for positioning in the uplink."[78] 5G NR is capable of supporting a "variety of positioning methods," including fine angle of arrival (AOA) measurements, observed time difference of arrival (OTDOA), uplink time difference of arrival (UL-TDOA), "positioning methods based on power measurements," and "round trip time (RTT) and angle-based positioning."[79] While 5G positioning can provide high accuracy, especially indoors and in dense urban areas, it is heavily dependent on network coverage and infrastructure, meaning that it can't fully replace or solve all the limitations of GPS, particularly in rural areas or places with limited 5G deployment.[80] Mobile broadband positioning systems are also capable of augmenting GPS to

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[73] Enabling Next-Generation Terrestrial Positioning, Navigation, and Timing and 5G: A Plan for the Lower 900 MHz Band (902-928 MHz), *Petition for Rulemaking*, NextNav Inc. (April 16, 2024), https://www.fcc.gov/ecfs/search/search-filings/filing/10416238018537.

[74] NextNav, "Next Generation 3D PNT Terrestrial 3D PNT powered by low band spectrum," *https://nextnav.com/new-nextgen/ (accessed April 8, 2025)*.

[75] Inside GNSS, "NextNav Successfully Demonstrates Positioning Reference Signal-Based PNT Technology," (February 27, 2025), *https://insidegnss.com/nextnav-successfully-demonstrates-positioning-reference-signal-based-pnt-technology*; Jeffs, Elisabeth, "FCC Takes Important Step Towards New Band Plan and Creation of Complement and Backup to GPS," (August 6, 2024), https://nextnav.com/fcc-public-notice-august-2024/.

[76] Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110, *Notice of Inquiry*, para. 29 (2025)

[77] Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110, *Notice of Inquiry*, para. 30 (2025).

[78] Dwivedi, Satyam, "5G positioning: What you need to know," *Ericsson* (December 18, 2020), *https://www.ericsson.com/en/blog/2020/12/5g-positioning--what-you-need-to-know*.

[79] *Id*.

[80] ASOCS, "8 5G Positioning Myths Busted!" (May 28, 2025), *https://asocscloud.com/8-5g-positioning-myths-busted/*; Mapsted, "The Pros and Cons of 5G Positioning Systems for Indoor Navigation," (December 3, 2024), *https://mapsted.com/blog/5g-indoor-positioning-explained*; Van de Valde, Samuel, "Is 5G positioning ready for industrial asset tracking?" *Pozyx*, (July 20, 2023), https://www.pozyx.io/newsroom/is-5g-ready-or-not-for-industrial-asset-tracking.

provide greater location accuracy in urban areas where structures block or degrade GNSS signals.[81]

"Time over Fiber" Calibration Services

NIST provides GNSS-independent time traceable to UTC(NIST) from Gaithersburg, Maryland and Boulder, Colorado through third-party optical fiber to a customer's facility. The initial goal is to realize an accuracy of 1 microsecond in a remote location, with the eventual improvement to 100 ns or better. The calibration services are 78110S (Time over Fiber Special Test, Boulder)[82] and 78100S (Time over Fiber Special Test, Gaithersburg)[83]. Customers may include providers of alternative PNT services to the public.

Independent PNT Solutions

Inertial Navigation System (INS)

INS systems use precisely calibrated accelerometers, gyroscopes, and magnetometers to detect and measure changes in motion through a process called "dead reckoning,"[84] which determines the position, orientation, and velocity of an object relative to a previously known location.[85] Inertial systems can operate completely independently from GPS, but they are not a preferred solution for long-duration journeys because INS systems without "sophisticated algorithms that account for drift or magnetic anomalies" are subject to "large cumulative errors over time or distance travelled."[86] Some have argued this presents an opportunity for the US Government to highlight the use of INS as an independent verification of measurements received from radionavigation sources.

Recent breakthroughs in artificial intelligence have helped overcome some of these limitations by "improving estimates of navigational outputs including position and velocity, predicting inaccuracies, and classifying motion to identify the system's specific application."[87] Tern AI currently offers its Independently Derived Positioning System (IDPS), which is an inertial-based navigation system that uses "AI-driven analysis" to take in data from sensors on board vehicles or on consumer devices and continuously apply corrections that offer "significantly improved accuracy and reliability over long distances" compared to traditional INS "without requiring GPS corrections."[88]

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[81] Promoting the Development of Positioning, Navigation, and Timing Technologies and Solutions, WT Docket No. 25-110, *Notice of Inquiry*, para. 30 (2025).

[82] NIST, "Time over Fiber Special Test (Boulder)," *https://shop.nist.gov/ccrz__ProductDetails?sku=78110S&cclcl=en_US (accessed May 20, 2025).*

[83] NIST, "Time over Fiber Special Test (Gaithersburg)," *https://shop.nist.gov/ccrz__ProductDetails?sku=78100S&cclcl=en_US (accessed May 20, 2025).*

[84] The primary visual navigation (see "Visual Navigation," *infra*) technique available to mariners such as Christopher Columbus in the Age of Discovery in determining longitude.

[85] Positioning Navigation Intelligence, "Inertial Navigation Systems and How INS Works?" (January 19, 2024), *https://www.pnisensor.com/inertial-navigation-systems/*.

[86] *Id.*

[87] Van Rees, Eric, "How AI-based Navigation Solutions Are Changing Land and Marine Surveying," *Commercial UAV News* (December 18, 2024), *https://www.commercialuavnews.com/how-ai-based-navigation-solutions-are-changing-land-and-marine-surveying*.

[88] Tern AI, "How IDPS works," *https://www.tern.ai/how-it-works/ (accessed May 20, 2025).*

Quantum Inertial Navigation System (Q-INS)

Quantum navigation systems operate under the same principles as traditional INS, but Q-INS systems use accelerometers and gyroscopes based on the wave-particle duality of nature at the atomic level. [89] Both accelerometers and gyros are at the edge of commercialization with accelerometers outpacing gyros. When functional, Q-INS systems are highly accurate and totally independent from GNSS systems.[90]

Quantum accelerometers are currently "about the size of two washing machines," but researchers are working to scale down the size of Q-INS systems for widespread deployment on larger vehicles.[91] The Army, Navy, and Air Force Research Laboratories are all testing Q-INS applications for use "in dynamic environments like military ships, submarines, or aircraft," and Boeing reported that it successfully completed a four-hour flight test in 2024 using a six-axis quantum inertial measurement unit.[92] Despite recent developments in the quantum navigation field, even optimistic estimates suggest that Q-INS systems will not be practical for broad application for another 10 to 15 years.[93]

Quantum Atomic Clocks and Optical Clocks

Recent advancements in rack-mountable atomic clocks are enhancing precision timing for critical infrastructure. Microchip Technology offers the 8040C, a 1U rackmount rubidium standard with coherent population trapping technology, providing <5e-11 monthly aging and configurable outputs for test and measurement systems.[94] Vector Atomic's Evergreen-30 (EG-30), the first commercial rackmount optical clock, achieves 25-femtosecond stability (1 second) and sub-nanosecond holdover over days in a 3U chassis, addressing GNSS resilience and quantum computing.[95] AOSense provides a rack-mountable Cold-Atom Frequency Standard using laser-cooled rubidium atoms, achieving 2e-12 Allan deviation at 1 second and

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[89] Martinez, Isabella, and Dylan Rudy, "Quantum Tech for Positioning, Navigation, and Timing," *Booz Allen Hamilton* (September 28, 2023), https://www.boozallen.com/expertise/analytics/quantum-sensing.html; Press Release, Lockheed Martin, "Unlocking the Power of Quantum Navigation: Lockheed Martin and Partners Awarded Contract," (March 12, 2025), https://www.lockheedmartin.com/en-us/news/features/2025/unlocking-the-power-of-quantum-navigation-lockheed-martin-and-partners-awarded-contract.html.

[90] Swayne, Matt, "The Tale of Two GPS Stories — How Quantum Tech Could Solve The Growing GPS-Jamming And Spoofing Problem," *Quantum Insider* (May 13, 2024), https://thequantuminsider.com/2024/05/13/the-tale-of-two-gps-stories-how-quantum-tech-could-solve-the-growing-gps-jamming-and-spoofing-problem/.

[91] Choi, Charles, "A Quantum of Sensing—Atomic Scale Bolsters New Sensor Boom," *IEEE Spectrum* (April 29, 2022), https://spectrum.ieee.org/quantum-sensors.

[92] Tegler, Jan, "Quantum Sensors Have Potential to Replace GPS," *National Defense* (July 27, 2023), https://www.nationaldefensemagazine.org/articles/2023/7/27/quantum-sensors-have-potential-to-replace-gps; Press Release, Boeing, "Boeing completes world's 1st quantum navigation flight test," *Boeing News Now* (August 6, 2024), https://onfirstup.com/boeing/BNN/articles/boeing-completes-worlds-1st-quantum-navigation-flight-test?bypass_deeplink=true.

[93] Anderson, Margo, "Quantum Navigational Tech Takes Flight in New Trial," *IEEE Spectrum* (June 3, 2024), https://spectrum.ieee.org/accelerometer-quantum-bose-einstein.

[94] Microchip, "8040C Rackmount Rubidium Instrument," https://www.microchip.com/en-us/products/clock-and-timing/components/atomic-clocks/atomic-system-clocks/8040c.

[95] Press Release, "Vector Atomic brings world's first rackmount optical clock to market," *Business Wire,* (November 13, 2023), https://www.businesswire.com/news/home/20231113157771/en/Vector-Atomic-brings-worlds-first-rackmount-optical-clock-to-market.

<1e-13 absolute accuracy.[96] Importantly, experts concur that most chip-scale atomic clocks are set to disappear from the market in about 3-4 years because there is not enough demand for the vertical-cavity surface-emitting lasers (VCEL) that they depend on, and that the best miniaturization effort likely is the mini-Hg+ ion clock under DOD's Next Generation Atomic Clock program (NGAC).

DARPA's Robust Optical Clock Network (ROCkN) program is attempting to miniaturize optical clocks, which use light instead of microwaves "to measure the frequency of the target atoms."[97] Optical clocks can be 100 times more accurate than atomic clocks and "wouldn't gain or lose a second through the entire lifespan of the universe," but these devices are "huge, delicate, room-filling machines that aren't practical for military" or commercial applications.[98] Like quantum navigation systems, recent advancements in quantum timing technology — beyond the atomic clocks already in use today — are not ready for widespread civil use.

Magnetic Navigation (MagNav)

Magnetic Navigation systems use scalar magnetometers to take precise measurements of the magnetic field and match readings with "accurate maps of the field's anomalies and variations" to "extract useful position and navigation data."[99] The technology is less accurate than GPS, but it is available worldwide and is "nearly impossible to deliberately jam or distort, especially at a distance."[100] The Department of the Air Force-Massachusetts Institute of Technology Artificial Intelligence Accelerator successfully tested magnetic navigation in 2023 and harnessed AI to help process the data in real-time.[101] Commercial MagNav provider SandboxAQ announced in 2024 that the USAF, Airbus, and Boeing tested its "geo-magnetic navigation system that leverages proprietary AI algorithms, powerful quantum sensors, and the Earth's crustal magnetic field" to provide positioning and navigation information for aviators.[102] Additional commercial innovations include AstraNav's M-GPS, a software-defined platform achieving sub-meter accuracy indoors and outdoors by analyzing ambient magnetic fields, and Balboa Geo POINTER technology, which uses magnetoquasistatic (MQS) fields to penetrate structures with its 3D positioning, offering 12.6 cm mean uncertainty in various

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[96] AOSense, "Cold-Atom Frequency Standard," *https://aosense.com/products/frequency-standards/cold-atom-frequency-standard*.
[97] Szondy, David, "DARPA's ROCKn program aims to make optical atomic clocks portable," *New Atlas* (January 30, 2022), *https://newatlas.com/military/darpas-rockn-program-optical-atomic-clocks-fighter-planes/*.
[98] *Id*.
[99] Schweber, Bill, "Magnetic-Field Navigation as an "Alternative" GPS?" *Electronic Design* (November 20, 2020), *https://www.electronicdesign.com/markets/automation/article/21145842/electronic-design-magnetic-field-navigation-as-an-alternative-gps*.
[100] *Id*.
[101] Press Release, Department of the Air Force-Massachusetts Institute of Technology AI Accelerator, "MagNav project successfully demonstrates real-time magnetic navigation," (May 26, 2023), *https://www.af.mil/News/Article-Display/Article/3408951/magnav-project-successfully-demonstrates-real-time-magnetic-navigation/*.
[102] Press Release, SandboxAQ, "SandboxAQ Announces AQNav – World's First Commercial Real-Time Navigation System Powered by AI and Quantum to Address GPS Jamming," (June 25, 2024), *https://www.sandboxaq.com/press/sandboxaq-announces-aqnav---worlds-first-commercial-real-time-navigation-system-powered-by-ai-and-quantum-to-address-gps-jamming*.

real-world tests.[103] While magnetic navigation is limited to positioning and navigation, meaning it could not serve as a complete GPS replacement, it is a strong backup system that could provide critical capabilities for aviators in the event of sudden GPS disruption or outage.

Visual Navigation

Visual navigation technologies gather data from live camera feeds and cross-reference imagery with map databases to determine a user's position.[104] The US Army Combat Capabilities Development Command (DEVCOM) tested a visual based navigation system on board a Black Hawk helicopter in 2023 and noted the utility of a backup positioning system for manned and unmanned aerial platforms in the event of GPS signal loss during flight.[105] Although visual navigation systems do not rely on communications with satellite or terrestrial networks, any issues with subpar lighting or inclement weather could hinder the quality of visual inputs and jeopardize navigation accuracy.[106] Seasonal changes in the surrounding environment could also decrease the reliability of visual based navigation.

Celestial Navigation

Celestial navigation technologies use the location of stars, planets, and other resident space objects (RSOs), such as satellites, as reference points to determine a user's position on the ground, in the air, or in space.[107] Honeywell tested its Celestial Aided Navigation system on board an Embraer E170 jet in 2022 and achieved "an accuracy of 25 meters circular error probability of 50%."[108] In 2024, NASA highlighted the utility of celestial navigation systems for spacecraft positioning "within the solar system for both cislunar and deep space missions."[109] NASA said that it plans to test celestial navigation capabilities on board the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) spacecraft that is currently in a Lunar Near Rectilinear Halo Orbit (NRHO).[110] Like visual navigation, celestial navigation is also limited by environmental factors that might degrade the quality of visual inputs. Celestial navigation is especially unreliable for ground users, as clear skies are necessary to make quality celestial observations.[111]

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[103] AstraNav, "Our Vision," *https://www.astranav.com/solutions*; Inside GNSS, "Balboa Geo's POINTER Dual-Use PNT Tech Demonstrates Performance in GPS-Denied Environments, Including "Z" Axis," (April 29, 2025), *https://insidegnss.com/balboa-geos-pointer-dual-use-pnt-tech-demonstrates-performance-in-gps-denied-environments-including-z-axis*.

[104] Thurber, Matt, "When GPS Denied, Honeywell Has a Solution," *AIN* (June 5, 2022), *https://www.ainonline.com/aviation-news/aerospace/2022-06-05/when-gps-denied-honeywell-has-solution*.

[105] Skelley, Katie, "Aviation & Missile Center tests new visual navigational technology," *US Army* (July 17, 2023), *https://www.army.mil/article/268390/aviation_missile_center_tests_new_visual_navigational_technology*.

[106] Alpha Pixel, "Vision Navigation Part 1: Overview of Vision Navigation," (July 27, 2022), *https://alphapixeldev.com/vision-navigation-part-1-overview-of-vision-navigation/#/*.

[107] Rai, Ahjay, "Honeywell Successfully Demonstrates Alternative Navigation Capabilities in GPS-Denied Environments," *Honeywell* (April 20, 2022), *https://aerospace.honeywell.com/us/en/about-us/press-release/2022/04/honeywell-demonstrates-alternative-navigation-capabilities*.

[108] *Id*.

[109] NASA, "Celestial Navigation in Cislunar Space with autoNGC," (December 4, 2024), *https://ntrs.nasa.gov/citations/20240014841*.

[110] *Id*.

[111] Inside GNSS, "Trust the Sky to Guide You Home," (June 14, 2023), https://insidegnss.com/trust-the-sky-to-guide-you-home/.

Quantum Aviation and Flight Tracking

Additional innovative flight tracking technologies have been adopted by a broad array of companies seeking to ensure "safety, efficiency, and compliance with international standards."[112] Current mainstream tracking technologies include ADS-B, Mode S Radar Beacon Systems, Primary Radar, Secondary Surveillance Radar, Multilateration, Automatic dependent Surveillance-Contract, Aircraft Communications Addressing and Reporting System (ACARS), and Satellite-Based ADS-B. Aireon uses pioneering space-based ADS-B technology and Iridium NEXT satellites to provide global coverage with minute-by-minute tracking, including in previously unmonitored areas.[113] FlightAware provides GlobalBeacon, a satellite-based ADS-B solution that assists with compliance for ICAO's Global Aeronautical Distress Safety System (GADSS).[114] Flightradar24 maintains a network of over 35,000 ground stations for ADS-B tracking and Multilateration (MLAT) to supplement tracking of aircraft without ADS-B transponders.[115] Lastly, Collins Aerospace offers OpsCore and PPS Flight Planning systems that integrate multiple tracking technologies, including ACARS for multi-source tracking.[116]

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[112] Lenahan, Brian, "Quantum's Aviation Commercialization," *Quantum's Business*, (April 22, 2025), *https://brianlenahan.substack.com/p/quantums-aviation-commercialization*.
[113] *Id.*
[114] *Id.*
[115] *Id.*
[116] *Id.*

Appendix: PNT Providers

Vendor Name	NTIA CPNT Category
Adtran Oscilloquartz	Space-based PNT
Anello Photonics	Independent PNT
Astra Navigation	Space-based PNT
AST & Science	Space-based PNT
Balboa Geolocation	Independent PNT
Castanet 5G	Terrestrial-based PNT
Collins Aerospace	Space-based PNT
Echo Ridge	Space-based PNT
ENSCO	Space-based and Independent PNT
Hellen Systems	Terrestrial-based PNT
Hoptroff	Independent PNT
Infleqtion	Independent PNT
Iridium	Space-based PNT
IS4S	Space-based, Terrestrial-based, and/or Independent PNT
Locata	Terrestrial-based PNT
Merlin	Terrestrial-based PNT
Microchip	Space-based and Independent PNT
NAB	Terrestrial-based PNT
NAL Research Corp.	Space-based PNT
NavSys	Independent PNT
NextNav	Terrestrial-based PNT
Oscilloquartz	Independent PNT
oneNav	Space-based PNT
OneWeb Technologies	Space-based PNT
Origin PNT	Terrestrial-based PNT
Parsons	Space-based PNT
PhasorLab	Terrestrial-based PNT
PSIONIC	Space-based and Independent PNT
SAFRAN	Space-based and Independent PNT
Satelles	Space-based PNT
Serco	Terrestrial-based PNT
Setter Research	Terrestrial-based PNT
Seven Solutions	Terrestrial-based PNT
Skyhook Wireless	Terrestrial-based PNT
Skyline Nav AI	Independent PNT
SRI International	Space-based and Terrestrial-based PNT
Technology Advancement Group	Space-based PNT
TERN AI	Independent PNT
TerraPixel	Independent PNT
TrustPoint	Space-based PNT

TRX Systems	Terrestrial-based PNT
Tualcom	Terrestrial-based PNT
OPNT B.V.	Terrestrial-based PNT
UHU Technologies	Space-based PNT
Ursa Navigation Solutions	Terrestrial-based PNT
Verizon	Space-based and Independent PNT
VIAVI	Space-based PNT
Xairos Systems	Independent PNT
Xona Space Systems	Space-based PNT
Zenotronic	Terrestrial-based PNT