GAO

United States Government Accountability Office

Report to Congressional Requesters

May 2021

TECHNOLOGY ASSESSMENT

Defense Navigation Capabilities

DOD is Developing Positioning, Navigation, and Timing Technologies to Complement GPS

Accessible Version

GAO-21-320SP

GAO@100
A Century of Non-Partisan Fact-Based Work

The cover image displays a compass with stylized representations of elements of positioning, navigation, and timing (PNT): satellites orbiting Earth (upper-right); a clock face and an atomic fountain clock (lower-right); the electronics in PNT sensors and electronic data provided by PNT hardware (lower-left); and various military platforms using different PNT technologies, such as those based on the environment, radiofrequency signals, and satellites (upper-left). Source: GAO.

GAO Highlights

Highlights of GAO-21-320SP, a report to Committee on Armed Services, United States Senate

May 2021

Why GAO did this study

For decades, the satellite-based GPS has transmitted PNT data to receivers used by military platforms and personnel worldwide. PNT information is essential in many facets of DOD operations. Given the ubiquity of GPS, the failure, malfunction, or jamming of its signals or equipment could disrupt military activities involving aircraft, ships, munitions, land vehicles, and ground troops. This possibility has led DOD to explore alternatives to GPS.

GAO was asked to assess the alternative PNT technologies DOD is developing. This report discusses (1) how DOD plans to meet future PNT needs and the capabilities and limitations of alternative PNT technologies, (2) how alternative PNT technologies integrate with one another and with current PNT capabilities, and (3) policy options that may help address challenges with the development and integration of alternative PNT technologies.

To address these objectives, GAO reviewed technical studies, agency documents, and other key reports; interviewed government officials and researchers about alternative PNT technologies; and convened a 3-day meeting of experts from government, non-governmental organizations, academia, and industry. GAO is identifying policy options in this report.

View GAO-21-320SP. For more information, contact Karen L. Howard at (202) 512-6888, HowardK@gao.gov or Jon Ludwigson at (202) 512-4841, LudwigsonJ@gao.gov.

TECHNOLOGY ASSESSMENT

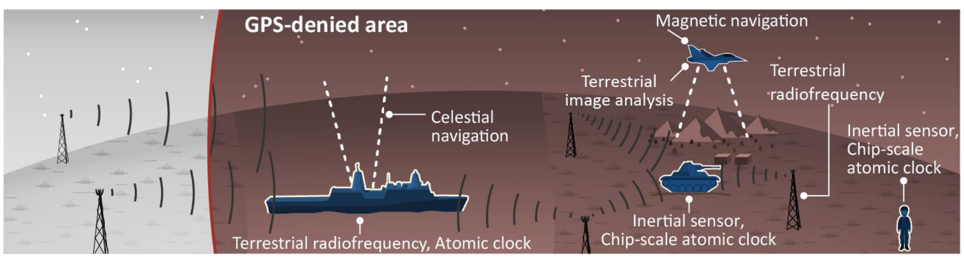
Defense Navigation Capabilities

DOD is Developing Positioning, Navigation, and Timing Technologies to Complement GPS

What GAO found

The Department of Defense (DOD) plans to keep the Global Positioning System (GPS) at the core of its positioning, navigation, and timing (PNT) solution, using other PNT technology to complement GPS or as an alternative for when GPS is degraded or unavailable. DOD's alternative PNT science and technology portfolio explores two approaches: improved sensors to provide relative PNT information, and external sources to provide absolute positioning and navigation. Relative PNT technologies include inertial sensors and clocks to allow a platform to track its position and keep track of time without an external signal like GPS. However, relative PNT technologies require another PNT technology to correct errors that can accumulate with such systems. Absolute PNT technologies allow a platform to use external sources of information to determine its position but rely on the availability of those external sources. Absolute PNT technologies include celestial and magnetic navigation as well as the use of very low radiofrequencies or low Earth orbit satellites to transmit information.

Technologies that could be used in GPS-denied environment



Source: GAO analysis of DOD information. | GAO-21-320SP

DOD may use multiple PNT technologies to provide sufficient PNT information to its various military platforms. DOD is pursuing approaches, such as creating common standards and interfaces, to aid in integrating and fielding new PNT technologies faster and at lower cost. DOD is developing its PNT modeling and simulation capabilities to evaluate the performance of new PNT technologies.

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.

GAO developed six policy options that may help address challenges with developing and integrating alternative PNT technologies. The policy options identify possible new actions by policymakers, who may include Congress, federal agencies, and industry groups. See below for details of the policy options and relevant opportunities and considerations.

Policy options that may help address challenges with developing and integrating alternative PNT technologies

	Opportunities	Considerations
Increase Collaboration Policymakers could consider mechanisms to coordinate across DOD to clarify responsibilities and authorities in prioritizing the need for alternative PNT technologies.	• Increased coordination could allow the military services to leverage one another's research and development activities. • Prioritization of alternative PNT could increase the technology's visibility, allowing more programs and platforms within DOD to better understand available technologies.	• PNT solutions for a particular mission or platform may still need significant customization, possibly offsetting the benefits from centralized coordination. • Current mechanisms, such as the PNT Oversight Council, may not have the capacity to take on alternative PNT coordination.
Focus on Resiliency Policymakers could consider selecting the most resilient technologies as the cornerstone of the PNT suite for military missions, rather than defaulting to GPS.	• By focusing on resiliency, technologies that add to resilient PNT could receive higher priority for development, even if they are not full replacements for GPS.	• A PNT solution will likely need multiple technologies to meet full PNT requirements, because no single alternative PNT technology is currently able to provide all of the required information. • DOD will need to continue maintaining GPS, as it will remain a part of the PNT solution.
Clarify Requirements Policymakers could consider opportunities for DOD to clarify what level of PNT performance is actually needed for missions, rather than defaulting to requirements that match GPS performance.	• With performance requirements that better reflect mission needs, DOD could make more informed decisions (such as savings in cost or integration time) in developing viable alternative technologies that will meet the actual mission needs, but not necessarily have GPS-level performance.	• GAO previously reported that creating requirements involves appropriately skilled personnel. • Programs may still want GPS-level performance because more precise PNT information is always desired, even when it goes beyond what is needed to complete a specific mission.
Coordinate with Industry Policymakers could consider ensuring that DOD and commercial industry coordinate so industry is prepared to meet DOD's needs, and DOD can leverage industry advances.	• DOD clearly communicating its needs to industry could allow industry to be better positioned to meet those needs. • Industry may have alternative PNT technologies that could be applied to defense.	• Commercial industry may not be incentivized to develop and manufacture alternative PNT technologies if the market is too small. • A lack of transparency into proprietary commercial technology may mask vulnerabilities of different PNT technologies.
Institutionalize Open Architecture Policymakers could consider making the open architecture initiative more permanent, including providing funding.	• With appropriate resources, DOD's open architecture initiative has the potential to greatly reduce integration costs and time for all PNT technologies. • Open architecture could keep DOD ahead of evolving threats to PNT, as it would be easier to field new alternative PNT technologies.	• The open architecture initiative will need buy-in across the military services, as well as with commercial industry partners, which may be difficult to achieve. • Once implemented, the open architecture initiative could need continued resources and governance, as the architecture will likely evolve.
Analyze Vulnerabilities Policymakers could consider having DOD conduct ongoing analysis of vulnerabilities of different PNT systems.	• Given that a future solution will likely require a PNT system comprised of a combination of different technologies, users could be better informed about each combination's overall vulnerabilities. • Users could better match PNT solutions to the mission and threat.	• The complexity of having a unique PNT system for each mission and platform could make this analysis difficult. • If DOD relies more on alternative PNT, the threats will evolve in response to that strategy, which may mean the vulnerability analysis needs to be updated regularly.

Source: GAO. | GAO-21-320SP

Table of Contents

Abbreviations

AI	artificial intelligence
DOD	Department of Defense
GPS	Global Positioning System
MOSA	modular open systems approach
PNT	positioning, navigation, and timing
R&D	research and development

U.S. GOVERNMENT ACCOUNTABILITY OFFICE
441 G St. N.W.
Washington, DC 20548

Introduction

May 10, 2021

The Honorable Jack Reed
Chairman
The Honorable James Inhofe
Ranking Member
Committee on Armed Services
United States Senate

For more than 30 years, the satellite-based Global Positioning System (GPS) has transmitted positioning, navigation, and timing (PNT) data to receivers used by military personnel worldwide, among others. PNT information provides U.S. military forces with the ability to determine location and orientation, plan a route to a desired location, and fuse intelligence, surveillance, and reconnaissance data. PNT information is essential in many facets of Department of Defense (DOD) operations. However, the potential exists for adversaries to disrupt or deny the capabilities provided by GPS to both military and civilian users. Given its ubiquity, the failure, malfunction, jamming, or spoofing of GPS signals or equipment could disrupt aircraft, ships, munitions, land vehicles, and ground troops in military operations and conflicts.

Due to the risk of disruption or denial of GPS-based PNT, DOD is pursuing alternative PNT technologies that are not dependent on GPS signals being continuously available. DOD has funded and executed research and development (R&D) for technologies and approaches that can provide reliable, highly accurate alternative PNT capabilities to U.S. military forces.

Given the potential for alternative technologies to help improve access to PNT information if GPS becomes unavailable, you asked us to conduct a technology assessment on alternative PNT technologies. This technology assessment discusses (1) how DOD plans to meet future PNT needs and the capabilities and limitations of alternative PNT technologies, (2) how alternative PNT technologies integrate with one another and with current PNT capabilities, and (3) policy options to address challenges with the development and integration of alternative PNT technologies.[1]

[1] Military units could potentially overcome some threats to GPS information through non-technological solutions, such as military training, tactics, techniques, and procedures. However, this review is focused only on alternative PNT technologies.

For all three objectives, we reviewed key reports and scientific literature describing current and emerging alternative PNT technologies and interviewed a variety of stakeholders, including agency officials, industry representatives, and academic researchers. With the assistance of the National Academies of Sciences, Engineering, and Medicine, we convened a 3-day expert meeting on current and emerging alternative PNT technologies. The meeting included experts from government, non-governmental organizations, academia, and industry, with expertise covering all significant areas of our review. Following the meeting, we continued to use the experts' insight to clarify and expand on the discussions. Based on the evidence, we identified policy options that may address challenges observed during our work and inform each option's potential opportunities and considerations. Consistent with our quality assurance framework, we provided the relevant agencies with a draft of our report and solicited their feedback, which we incorporated as appropriate. See appendix I for additional information on our scope and methodology.

We conducted our work from March 2020 through May 2021 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

1 Background

American military and civilian users depend on assured PNT information, which is essential to effective military operations and critical defense and civil infrastructure. GPS is the primary source of space-based PNT for U.S. and multinational warfighters and is operated by the U.S. Space Force on behalf of DOD.[2] GPS includes a constellation of 31 medium Earth orbit satellites operating at an altitude of about 12,550 miles. In addition to the space segment, GPS also includes a control segment, consisting of worldwide monitor and control stations, and a user segment of GPS receivers and associated antenna equipment. DOD began developing a space-based navigation satellite constellation in the 1970s. The system was initially available only to U.S. Navy vessels using large receivers. By the 1991 Persian Gulf War, GPS equipment was small and inexpensive enough to also be used on ground force vehicles. Since then, further advances, such as development of smaller receivers, have allowed GPS to provide precise PNT information for individual soldiers, munitions, military systems, and civilian applications.

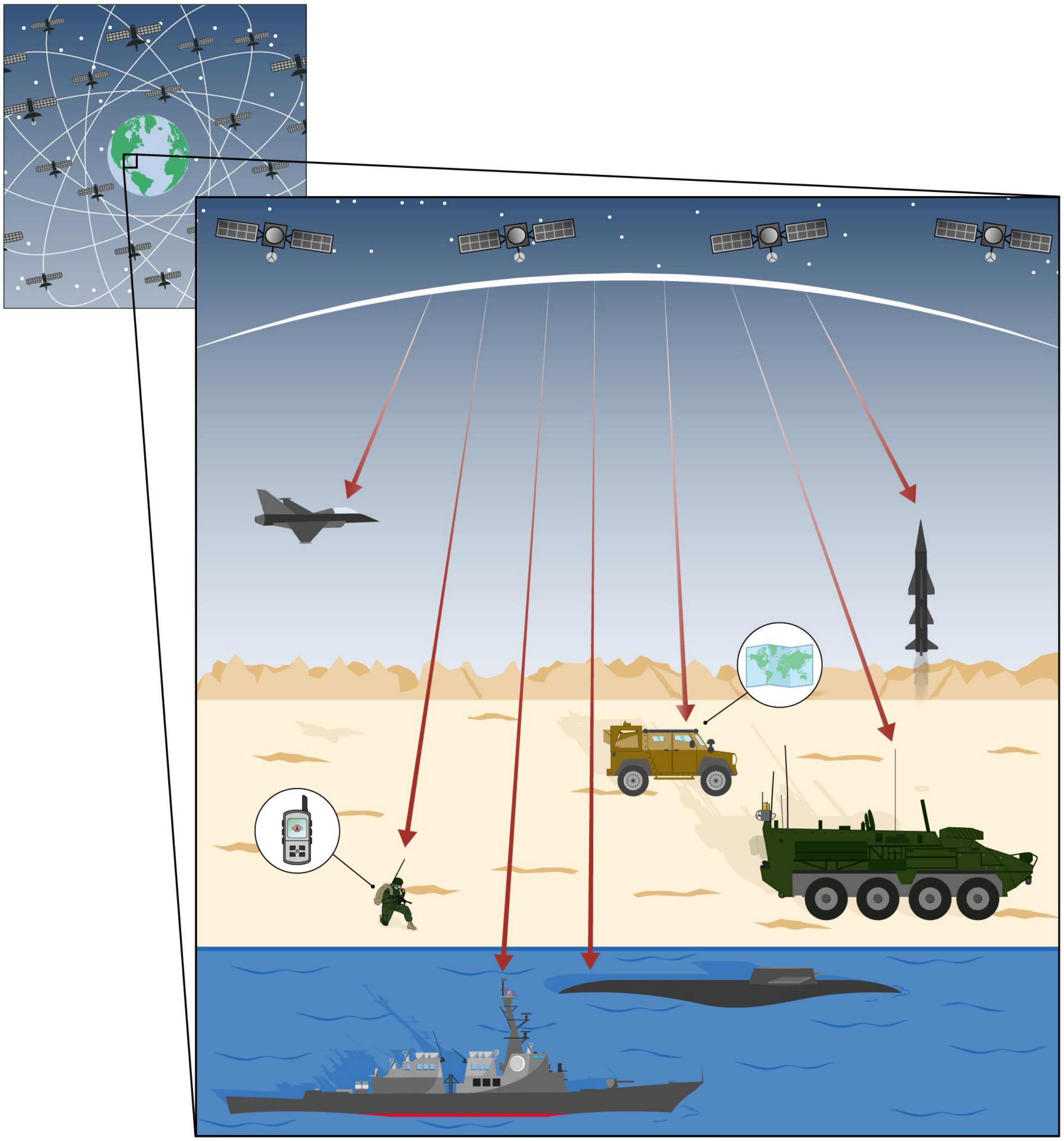
DOD has a variety of platforms, such as bombers, unmanned vehicles, surface ships, submarines, munitions, mounted soldiers, and dismounted soldiers. Each platform has varying constraints on the cost, size, weight, and power of its particular PNT systems. For example, an aircraft carrier can accommodate PNT systems with higher cost, larger size and weight, and greater power requirements than would be appropriate for a dismounted solider. Furthermore, the various platforms have varying missions and operating environments. For example, a fighter aircraft maneuvering in combat would have different PNT requirements than a submarine below the water's surface. Figure 1 shows different uses by U.S. military forces of the space-based GPS satellite constellation.

1.1 Threats to GPS-supplied PNT information

While GPS provides significant capabilities to both military and civilian users under normal conditions, it is subject to interference by adversaries. Recognizing U.S. reliance on GPS, potential adversaries are developing and using increasingly capable jammers and spoofers to deny the use of GPS by U.S. military forces. GPS satellites' low-power signals are vulnerable to jamming on the ground by adversaries using radiofrequency jamming systems available to smaller militaries. GPS satellites are also vulnerable to physical attacks, such as from adversaries' ground-based anti-satellite weapons. Denial, or disruption, of GPS can create a significant challenge for military units in combat and during daily operations by making it difficult to conduct coordinated movements and maneuvers, accurately fire at enemy forces, or know where friendly or hostile units are in relation to their own locations. Military units may also lack GPS signals in environments such as dense urban areas where a clear line-of-sight to GPS satellites is impossible.

[2] The U.S. Space Force is a branch of the Armed Forces established on December 20, 2019, within the Department of the Air Force.

Figure 1: Global Positioning System used by U.S. military forces

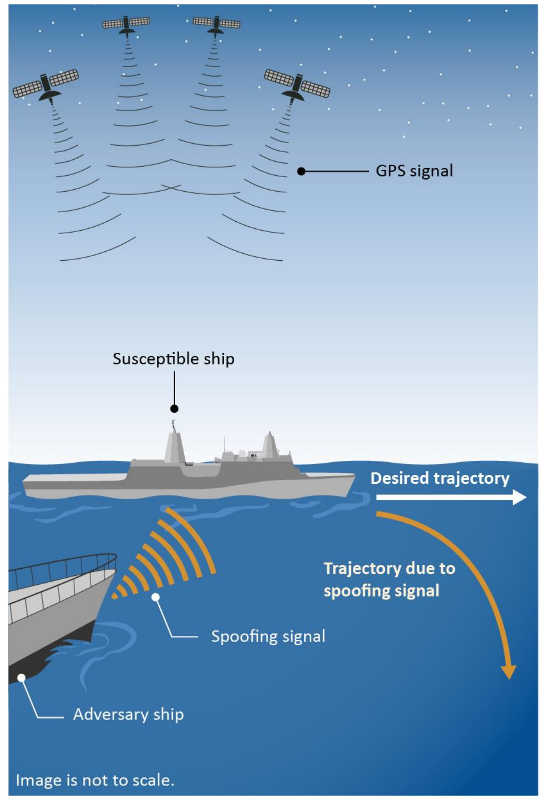


Source: GAO analysis of DOD information. | GAO-21-320SP

We reported in December 2020 that a Ukrainian military official stated that Russia was able to successfully jam GPS and cellular communications and conduct electromagnetic attacks on communications devices in eastern Ukraine.[3] A congressional defense task force reported in 2020 that GPS could be a single point of failure for the United States military.[4] Both DOD and the congressional defense task force have recognized that the United States has not kept pace with adversaries in this regard.

In addition to denying GPS through electronic jamming attacks, foreign militaries could also potentially provide DOD's GPS users with falsified PNT data through spoofing attacks, leading military units to move or fire weapons in an unintended direction. Figure 2 shows a potential adversary spoofing attack against a U.S. naval vessel using GPS and the potential results of such an attack.

Figure 2: Potential results of a GPS spoofing attack on a naval vessel



Source: GAO analysis of DOD information. | GAO-21-320SP

A 2019 Defense Intelligence Agency report highlighted emerging risks to U.S. military forces' space-enabled services, including GPS. The report noted that foreign governments are developing capabilities that threaten others' ability to use space. Military doctrine of potential adversaries places importance on decreasing the effectiveness of the U.S. and its allies by reducing their space-based capabilities. Adversary countries' space surveillance networks can search, track, and characterize satellites in all Earth orbits, supporting these countries' space operations and counterspace systems. Adversary countries are also developing cyberspace capabilities, directed energy weapons, ground-based antisatellite missiles, and other capabilities that could potentially disrupt, damage, or destroy U.S. satellites.[5]

[3]GAO, *Electromagnetic Spectrum Operations: DOD Needs to Address Governance and Oversight Issues to Help Ensure Superiority*, GAO-21-64 (Washington, D.C.: Dec. 10, 2020).

[4]House of Representatives Armed Services Committee, *Future of Defense Task Force Report* (Washington, D.C.: Sept. 23, 2020).

[5]Defense Intelligence Agency, *Challenges to Security in Space,* (January 2019).

1.2 Efforts to mitigate threats to GPS-supplied PNT

DOD is attempting to mitigate the risk of disruptions to GPS systems through planned GPS upgrades currently in development. The Space Force's GPS III program is building and fielding a new generation of satellites to supplement, and eventually replace, the GPS satellites currently in use. GPS III provides a stronger military navigation signal, referred to as M-code, to improve jamming resistance. Using this new M-code signal will require the development and deployment of specialized receivers. A new ground control system will control these satellites. Our prior work has shown that GPS upgrade programs have experienced significant cost increases and schedule delays. For example, the Next Generation Operational Control System upgrades to systems responsible for controlling GPS have been delayed by more than 5 years. In 2021, we reported that the program continued to face challenges related to the development of critical equipment for the use of M-code and that widespread use of M-code was years away.[6]

1.3 PNT policies and related laws

Various U.S. government laws and policies have, over the last 20 years, called for an increased focus on addressing potential threats to DOD's use of PNT information and consideration of alternatives that could minimize the risks. Table 1 summarizes some of the relevant Executive Orders, federal statutes, Department of Defense guidance, and other policies requiring oversight, consideration, and development of alternative PNT technologies at DOD.

[6]GAO, *GPS Modernization: DOD Continuing to Develop New Jam-Resistant Capability, But Widespread Use Remains Years Away*, GAO-21-145 (Washington D.C.: January 2021).

Table 1: Selected laws and policies relevant to DOD positioning, navigation, and timing (PNT) technologies

Document	Key Provisions
William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021, Pub. L. No. 116-283, § 1611, 134 Stat. 3388, 4048-49	Directs the Secretary of Defense to mature, test, and produce prioritized elements needed to generate resilient alternative PNT.
Space Policy Directive/SPD-7—*The United States Space-Based Positioning, Navigation, and Timing Policy* (Jan. 15, 2021)	Establishes implementation actions and guidance for U.S. space-based PNT programs and activities for U.S. national and homeland security, civil, commercial, and scientific purposes.
10 U.S.C. § 2279b: Council on Oversight of the DOD PNT Enterprise	Establishes a council responsible for general oversight of the DOD PNT enterprise.
Executive Order 13905, 85 Fed. Reg. 9359, Strengthening National Resilience Through Responsible Use of Positioning, Navigation, and Timing Services (Feb.12, 2020)	Directs the identification of systems dependent on PNT services and management of risks related to the disruption and manipulation of PNT services.
National Space Policy of the United States of America, December 9, 2020	Establishes general policies related to space operations, including those for GPS and requires identification of multiple complementary PNT systems.
Space Policy Directive/SPD-5—*Cybersecurity Principles for Space Systems* (Sept. 4, 2020)	Directs that cybersecurity principles and practices that apply to terrestrial systems also apply to space systems, and that systems be developed to continuously adapt to mitigate evolving malicious cyber activities.
DOD Directive 4650.05, Positioning, Navigation and Timing (PNT)	Establishes policy and assigns responsibilities for the DOD PNT enterprise. Establishes the Council on Oversight of the DOD PNT Enterprise to provide oversight.
DOD Instruction 4650.06, Positioning, Navigation and Timing (PNT) Management	Assigns responsibilities and defines procedures for the DOD PNT enterprise, including use of the DOD PNT Science and Technology Roadmap.
DOD Instruction 4650.08, PNT and Navigation Warfare (NAVWAR)	Requires acquisition programs to conduct analysis and testing of PNT-enabled equipment against measures of effectiveness based on performance standards.
Strategy for the Department of Defense PNT Enterprise, November 2018	Describes the means by which DOD will employ the PNT Enterprise to achieve and maintain a military advantage.

Source: GAO analysis of DOD information. | GAO-21-320SP

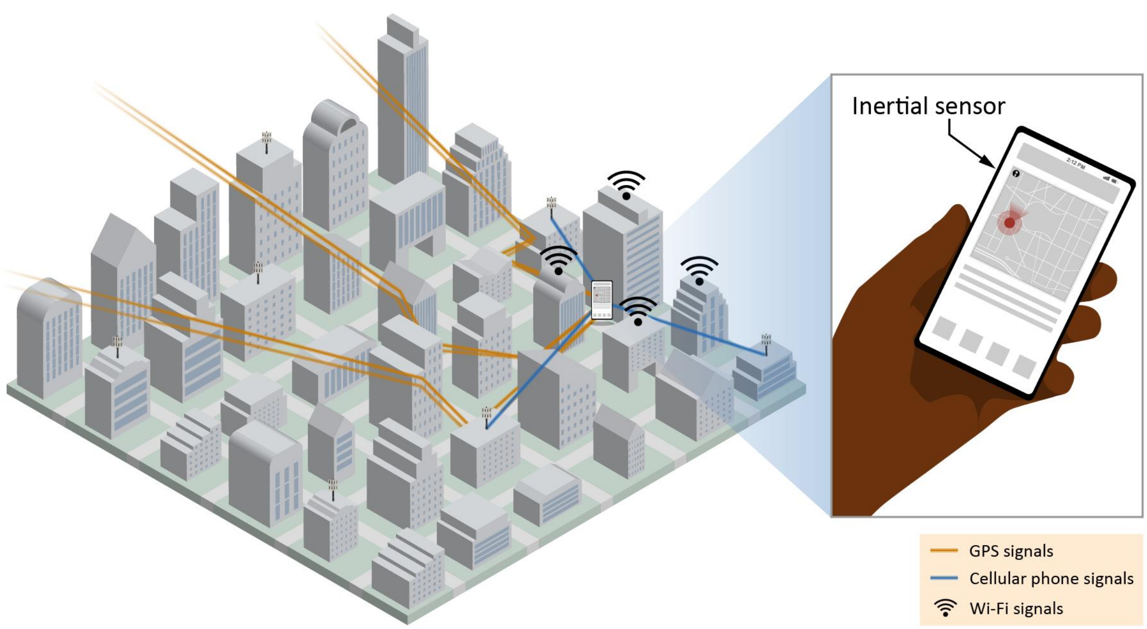
2 DOD's Future Plans Continue to Focus on Using GPS While Pursuing Several Alternative PNT Technologies

2.1 DOD plans to keep GPS at the core of its PNT architecture, with alternate PNT sources providing complementary capabilities

DOD has laid out a strategy for providing PNT information with GPS remaining the centerpiece of its PNT architecture. In particular, in the 2020 PNT Science and Technology Roadmap (PNT Roadmap), DOD stated that GPS will continue to be the primary source of PNT information, but that "no single PNT system is capable of supporting all DOD PNT requirements."[7] DOD program officials and experts that we spoke with concurred that a variety of solutions are required to provide PNT information across all DOD platforms. To that end, DOD's approach is to develop a range of alternative PNT sources, with a focus on complementing GPS. Using this approach, these alternative sources would work together, even when GPS is available, to check the accuracy of each source, including GPS, and combine information if the quality of a single source degrades.

DOD's alternative PNT portfolio explores two technology approaches:

Figure 3: Consumer cell phones use a variety of signals and sensors to determine position and direction



Source: GAO analysis of Android documentation. | GAO-21-320SP

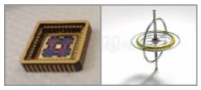
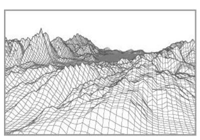
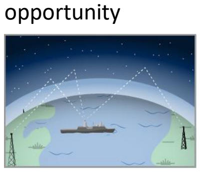
[7]Department of Defense, Office of the Under Secretary of Defense for Research and Engineering, *2020 Positioning, Navigation, and Timing Science and Technology Roadmap* (Alexandria, Va.: July 2020).

- **Relative PNT technologies** use onboard sensors to track the position of a platform and keep time without the use of an external signal.
- **Absolute PNT technologies** use external sources of information, other than GPS, to determine the position of a platform, geo-referenced to Earth.

Alternative PNT technologies can complement each other to provide more resilient PNT information. The modern cell phone provides a commercial analogy to the advantages of GPS combined with absolute and relative PNT sensors. As illustrated in figure 3, cell phones have a GPS receiver to provide position information, but also use local cell towers and onboard sensors to provide more consistent quality position information. This also allows the cell phone to determine position with limited GPS signal or even without GPS entirely.

Table 2 describes each PNT approach and examples of technologies currently under development at DOD. In some cases, these technologies build upon existing technology in use by the DOD, but the current research aims to expand the capabilities of that technology, improve precision and accuracy, and reduce manufacturing costs. For example, the Navy has used celestial navigation for centuries using manual tools like sextants, but DOD's current research aims to create an automated system for celestial navigation that works during the day as well as at night.

Table 2: PNT approaches and technologies under development at DOD

	Approach	Potential technologies	Capabilities	Limitations
Relative PNT	Inertial sensors 	Mechanical: e.g., microelectromechanical systems	New materials could improve performance and lower cost	Mechanical noise limits performance
		Non-mechanical: e.g., thermal beam atomic	Could exceed performance of fiber optic gyros	High precision sensor alignment makes production challenging; environmental sensitivity
	Clocks 	Chip-scale atomic clocks	Compact and low power	Expensive and limited precision – efforts underway to improve with algorithms and manufacturing
		High precision atomic and optical clocks	Potential GPS-level timing	Manufacturing challenges; larger size and power requirements
Absolute PNT	Environmental maps 	Celestial navigation (stars and satellites)	Day/night coverage 50 meter accuracy	Limited access to stars and satellites (e.g., clouds)
		Magnetic	100 meter accuracy	Need for magnetic maps; electromagnetic noise from the system platform
		Terrestrial image analysis (landmarks and terrain)	10 meter accuracy	Restricted by weather (e.g., clouds); need for landmarks in images
	Radiofrequency-including signals of opportunity 	Terrestrial: e.g., very low frequency	500 meter accuracy – sufficient for sea	Limited network; corrections for ionosphere
		Space: e.g., low Earth orbit satellites	Radiofrequency bands complementary to GPS and stronger signal	Potentially lower precision than GPS; requires many satellites for global coverage

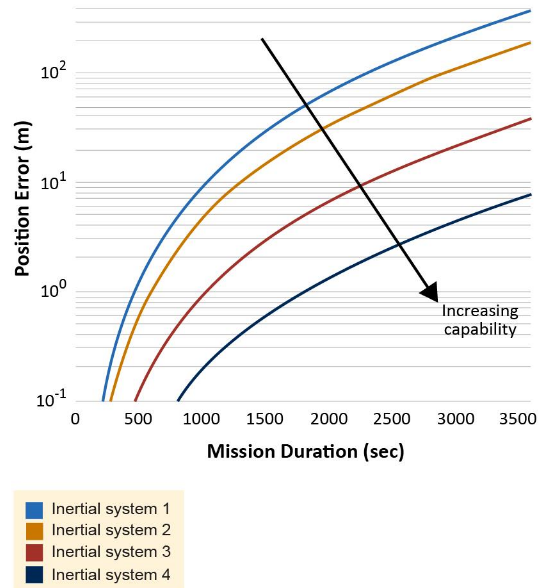
Source: GAO analysis of DOD information. Photos obtained from DOD (inertial sensors—left, clocks), stockedup/stock.adobe.com (inertial sensors—right), Петро Сливчук/stock.adobe.com (environmental maps), and GAO analysis of DOD information (radiofrequency signals). | GAO-21-320SP

2.2 Improved sensors can provide relative PNT information locally to platforms without GPS, but errors cause them to become less accurate over time

2.2.1 Inertial sensors

Inertial sensors (sometimes known as inertial measurement units or inertial navigation units) measure position by tracking the relative movements from a known position. These sensors measure the accelerations and rotations experienced by a small, well-known test system, such as a ball on a spring. When the platform moves, the test system also moves and the sensor measures those movements. By adding up the incremental accelerations and rotations over time, the inertial sensor can track the position of a platform. The positional accuracy of the inertial sensors will diminish over time due to small errors in measuring the movements of the system. More sophisticated sensors will have smaller errors but may be large or expensive, which would limit their applicability. Inertial sensors can be used with absolute positioning systems, such as GPS, to reset their location. A key consideration for systems based on these sensors is how long the system can maintain an accurate position without the need for a reset to a geo-referenced position (see fig. 4).[8]

Figure 4: Different levels of performance for inertial sensors



Source: GAO adaptation of image in Defense Science Board report titled *Applications of Quantum Technologies.* | GAO-21-320SP

To balance the needs of different missions and platforms, DOD is investing in several technologies that use different approaches. Some systems rely on a small mechanical system—such as a cantilever or the ball on a spring described earlier—to measure the accelerations or rotations of the platform. However, such mechanical devices introduce noise, which reduces the sensor's precision. DOD is currently investing in new microelectromechanical system inertial sensors with new materials. These sensors could perform better and cost less than existing microelectromechanical inertial sensors.

High-precision inertial sensors can also be built using atomic sensing techniques that take advantage of the fundamental properties

[8]A "geo-referenced" position refers to a known location on the surface of the earth.

of atoms. These sensors use a cloud of atoms, probed with lasers, to measure accelerations and rotations of the platform. This approach eliminates the noise-producing mechanical connection. DOD is developing a thermal beam atomic sensor which produces a stream of heated atoms and uses lasers to very precisely measure the atoms' motions in response to acceleration or rotation. This technology can be used to make inertial sensors that perform as well as or better than high-end commercial inertial sensors. The construction of these sensors, however, requires many high-precision components and specialized assembly, which would make them challenging to produce. Thermal beam sensors are also vulnerable to changes in temperature and other environmental interference. Thus, atomic sensors could offer improved performance but may have greater costs and limited applications compared with traditional mechanical sensors.

2.2.2 Clocks

Clocks can provide relative timing information that complements the position information provided by inertial sensors. Clocks operate by creating a very stable oscillating system like a pendulum and precisely counting the passage of time. Modern, high-precision timekeeping techniques rely on measuring oscillations of atoms. Similar to inertial systems, clocks will experience increasing errors over time with their performance assessed based on how long they can maintain accurate time. Different designs trade off precision for cost, size, weight, and power.

DOD currently has investments in a variety of different clock options. For example, DOD is investing in improving low-power, chip-scale atomic clocks which could provide timing to smaller platforms such as handheld radio systems. Currently, chip-scale atomic clocks provide timing in a small package that fits onto an electronic circuit board (see fig. 5), which makes them ideal to provide a timing source to a variety of platforms. However, their precision lags behind that of GPS.[9] DOD is trying to increase the performance of chip-scale atomic clocks with better algorithms. DOD also aims to improve the manufacturing process to make the clocks less expensive than the current price of $2,000 per clock.

Figure 5: Image of cesium atomic clocks (left) and a chip-scale atomic clock (right)

Sources (left to right): United States Naval Observatory (USNO); U.S. Army. | GAO-21-320SP

DOD is also investigating high-precision clocks for applications that require GPS-level timing. For example, one DOD project is developing an optical clock. Optical clocks operate on the same principle as a traditional atomic clock but can achieve better precision by using a higher frequency of light.[10] The expectation is that optical clocks could provide GPS-level time precision for up to one day, but would

[9]Current chip-scale atomic clock precision is about 100 times worse than GPS after 1 day of use.

[10]Optical clocks use a visible laser light while traditional atomic clocks use microwaves.

be larger, rack-mounted units and require 10 to 20 times the power of a chip-scale atomic clock. Such a design could be suitable for larger platforms such as forward command centers.

Some clock designs under development aim to bridge the divide between high precision and low power, but these designs have faced challenges. For example, DOD is investigating the development of a new atomic clock architecture that can deliver GPS time precision, while consuming the same amount of power as a chip-scale atomic clock. DOD, however, has encountered challenges in manufacturing the specialized components needed for this clock, such as the light source and vacuum chambers. These challenges may ultimately make it difficult, or impossible, to implement these kinds of clock designs without innovations in manufacturing techniques. This work highlights the challenges in balancing the tradeoffs between performance and power in designing clocks.

2.3 Several methods using external sources show promise to provide absolute PNT information, but none can match the performance of GPS

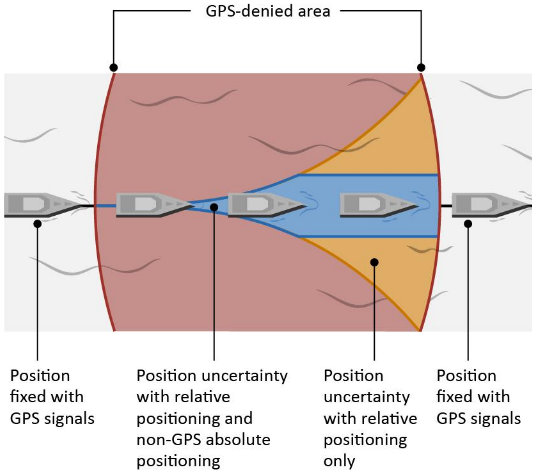
Non-GPS sources of absolute PNT information are an important part of DOD's alternative PNT research. As discussed above, sources of relative PNT information, such as clocks and inertial sensors, only provide accurate PNT information for a limited period of time. Over time, the compounding errors will cause the PNT measurements from the sensors to be inaccurate and the sensors will need to be reset to a geo-referenced position on Earth and a time reference from the United States Naval Observatory. GPS can provide this resetting capability to an accuracy of under 10 meters.[11] In GPS-denied environments or even in situations with limited GPS signal, however, other sources will need to provide absolute PNT information.

Mission times and requirements for how long a platform can operate without absolute PNT information vary, as does the accuracy of the absolute PNT data. For example, a munition may require frequent absolute PNT data to achieve high precision in hitting its target. A ship, by contrast, may be able to operate with less accurate absolute position data for an extended period of time.

In a GPS-denied environment, use of relative PNT sources will result in increasing errors in position over time (see fig. 6). Absolute PNT sources can help limit those errors until GPS is available again. DOD is currently pursuing several approaches to provide absolute PNT information to its platforms.

[11] This section will focus only on techniques to provide absolute position information. DOD's techniques for transferring time between platforms are discussed in more detail in the next chapter.

Figure 6: Increasing uncertainty in position over time in GPS-denied environments



Source: GAO analysis of DOD and Defense Science Board information. | GAO-21-320SP

2.3.1 Environmental maps

One approach to providing absolute position information is to use sensors to identify distinct features in the environment around the platform and compare that information with known maps. This approach can be applied in a number of different ways. For example, DOD is pursuing environmental mapping and navigation strategies using celestial navigation, magnetic navigation, and terrestrial image analysis.[12]

One technology for environmental mapping that DOD is investigating is automated celestial positioning technology. Celestial navigation has existed for centuries, but current R&D focuses on using both stars and the reflection of the sun off of satellites to determine position. By imaging the sky and analyzing the orientation of multiple stars or satellites, a platform can determine its position.

This approach depends on accurate star maps and satellite orbit data, both of which have reliable sources of information, but, according to an expert, this data must be updated periodically (days to months) to provide the required accuracy. According to a DOD official, an automated system performing this imaging and analysis could determine absolute position to within 50 meters—a degree of accuracy that meets navigation requirements for many naval surface ships.

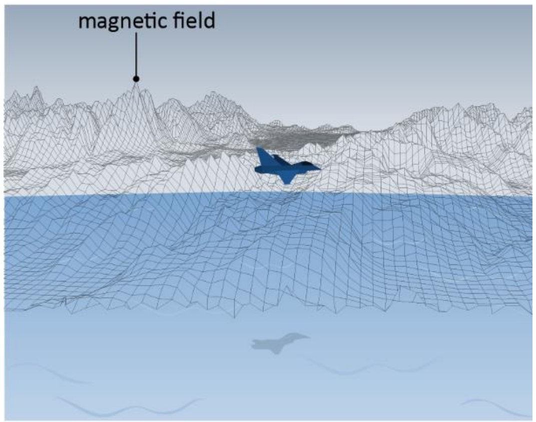
This automated system would also be able to operate during the day, which provides a different capability. Celestial systems still face limitations based on weather. Clouds can block the visibility of stars and satellites and the sun's position can limit the ability to spot satellites.

DOD is also researching magnetic navigation. This approach uses distinct variations in the Earth's magnetic field as landmarks to determine position (see fig. 7). A platform with a magnetic sensor can compare its readings to known magnetic field maps and determine its position to within around 100 meters. One challenge is the need for magnetic maps of all regions of interest. In addition, the accuracy of position measurements is limited by the noise from the platform itself. For example, moving flaps on an airplane can induce magnetic fields that interfere with measurements of the Earth's magnetic field. DOD is investigating how to mitigate this effect by characterizing the

[12]Terrestrial image analysis is also referred to as vision-aided navigation.

sources of noise on a given platform, which would improve the system's accuracy.

Figure 7: Aircraft using magnetic navigation to detect changes in the Earth's magnetic field as it flies over water



Source: GAO analysis of DOD information; Петро Сливчук/stock.adobe.com. | GAO-21-320SP

A third mapping technology under investigation to obtain absolute PNT information is terrestrial image analysis. This approach uses a camera to capture images of the platform's surroundings and applies algorithms to identify features in the local environment (e.g., buildings) and compare those features with reference databases of satellite images.

Alternatively, the terrestrial image analysis system could use a separate algorithm to track changes in the relative orientation of a landmark (e.g., the landmark gets smaller in the camera as the platform moves farther away) to infer changes in the position of the platform. DOD has demonstrated terrestrial image analysis on aircraft and found that it can determine a position to an accuracy of 10 meters. Accurate reference images of the entire Earth are available from various state Departments of Transportation, the National Geospatial-Intelligence Agency, and Google. However, adverse weather (e.g., clouds) and areas without clear features (e.g., over the ocean) limit the use of terrestrial image analysis.

2.3.2 Radiofrequency positioning

Another approach for obtaining absolute PNT information is the use of radiofrequency signals. DOD is investigating non-GPS radiofrequency signals (either terrestrial or space-based) that can be used to determine position. These signals can either be deliberate networks put into place to deliver PNT or can be so-called signals of opportunity which take advantage of a range of pre-existing signals—from commercial satellites to TV towers—to extract PNT information.[13] According to experts in PNT technologies, using a variety of radiofrequency signals decreases vulnerability to jamming and spoofing because it is more difficult to jam multiple frequencies and because these alternative sources may have a stronger signal than GPS.

One terrestrial radiofrequency technology under development by DOD uses an existing network of transmitters operating in the very low frequency range. This system uses a network of 10 very low frequency transmitters around the globe whose signals can bounce off the ionosphere to travel a long distance (see fig. 8).[14] By measuring its distance from multiple transmitters, a

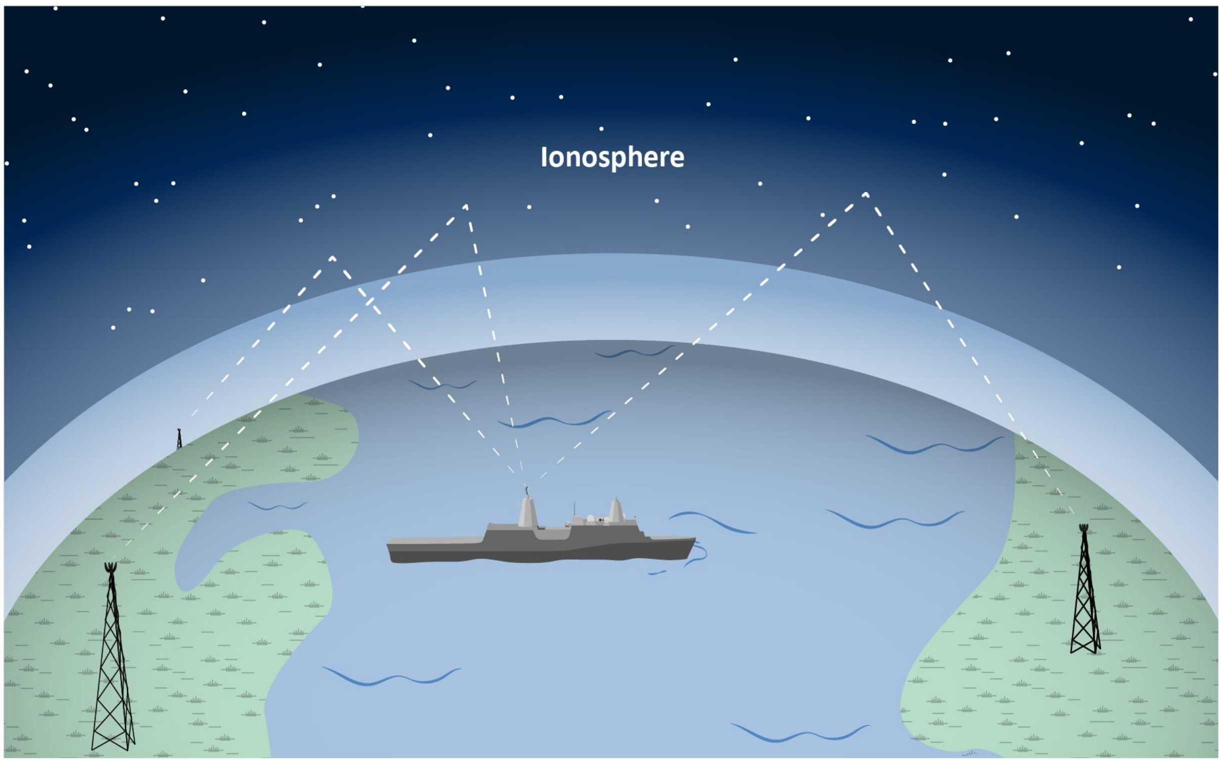
[13] According to experts, definitions of "signals of opportunity" vary.

[14] The ionosphere is the region of the Earth's atmosphere that contains charged particles. It stretches from around 50 to 400 miles above the Earth's surface.

platform can determine its position to within 500 meters—an accuracy that is sufficient for ship-based platforms. While bouncing signals off the ionosphere allows this system to have much longer range, accuracy is limited by the need to make repeated corrections for signal travel times from these bounces, especially since the corrections depend on the conditions in the ionosphere, which can change depending on the time of day and other factors.

DOD is also pursuing alternative space-based radiofrequency systems. One system uses commercial communications satellites to provide PNT. The system uses a very similar positioning approach to GPS, but the satellites are in low Earth orbit.[15] The use of low Earth

Figure 8: A ship using radiofrequency technology to receive signals with positioning information



Note: Image not to scale

Source: GAO analysis of DOD information. | GAO-21-320SP

[15]Because the satellites move much faster, a platform can determine its position with only two satellites in view, rather than the four necessary for GPS.

orbit satellites means the signals are stronger and harder to jam than the GPS signal. These satellites also broadcast at a different frequency, further increasing resilience to jamming, according to experts. However, since the current low Earth orbit satellites provide a signal of opportunity and are not designed specifically for navigation, the position information from this system is less accurate than GPS. In addition, the commercial system has a limited network of satellites, and more satellites would be required to provide coverage of the entire earth.

3 DOD Is Working to Integrate, Communicate, and Evaluate PNT Information from Multiple Sources

3.1 DOD has established PNT science and technology initiatives to support PNT development

To help understand the capabilities and limitations of new PNT technologies and to provide a cost-effective and timely integration path into the military platforms, the DOD PNT science and technology community has established three initiatives under the Office of the Under Secretary of Defense for Research and Engineering: open architecture, non-GPS time dissemination, and modeling and simulation (see table 3). According to the PNT Roadmap, these initiatives address broad problems that do not necessarily have service-unique solutions, and though each initiative is led by one of the military services, perspectives and information from each of the military services are needed to achieve the initiatives' objectives.

DOD intends to use these initiatives to help manage and leverage the numerous potential PNT technology development efforts. The open architecture initiative discussed in section 3.2 aims to integrate the diverse array of PNT technologies, which will enable PNT resilience. The time dissemination initiative discussed in section 3.3.1 aims to transfer time information to mobile users over other mediums in GPS-denied or GPS-degraded environments. The modeling and simulation initiative discussed in section 3.4 aims to evaluate PNT technologies and identify promising technologies to inform operational planning and investment decisions.

3.2 DOD is pursuing a modular open systems approach to integrate multiple PNT sources

According to DOD officials and experts, no alternative PNT technology currently has the capability to replace GPS. Furthermore, DOD has stated that there is currently no single PNT technology capable of meeting all of its PNT requirements. The PNT Roadmap states

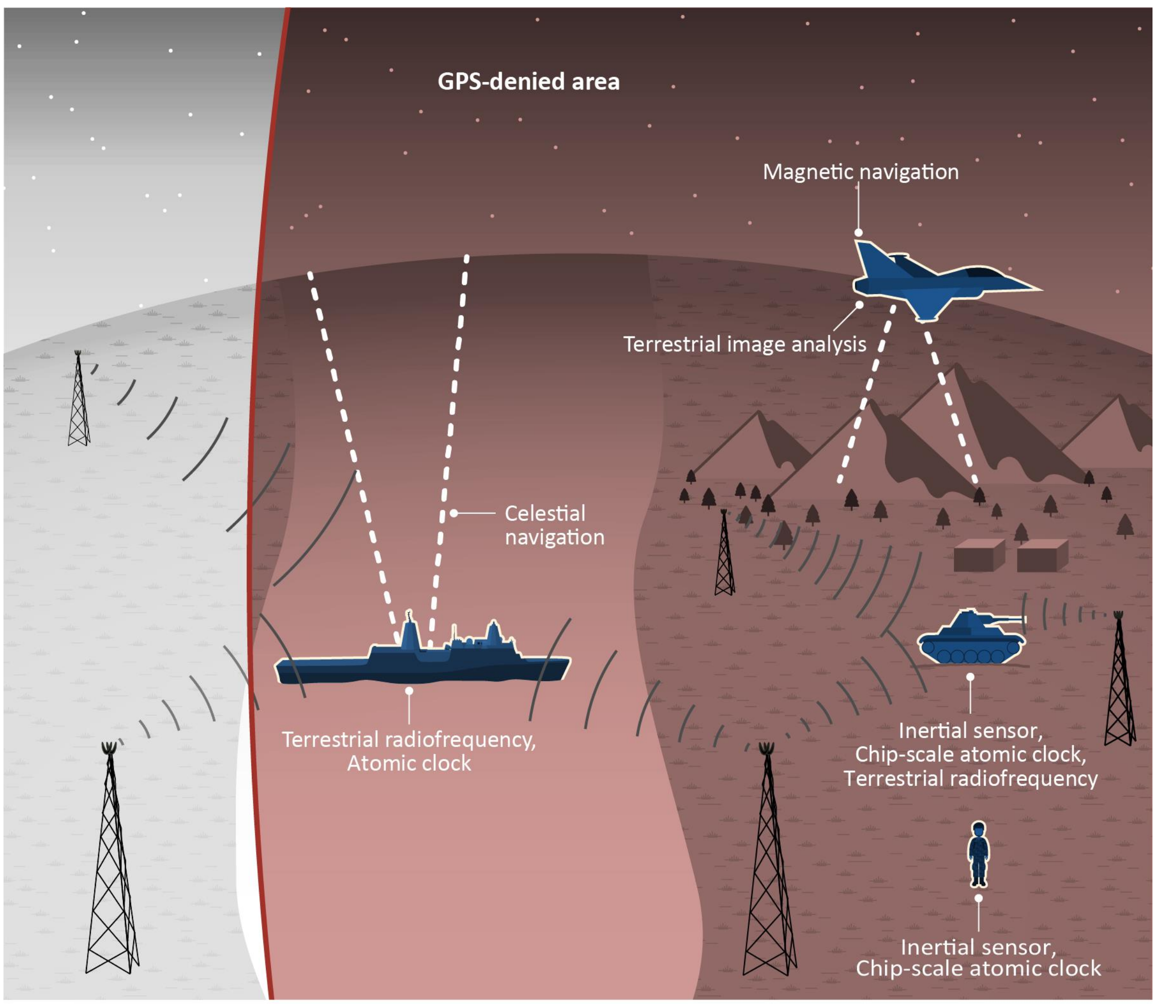
Table 3: DOD science and technology initiatives for positioning, navigation, and timing (PNT)

Initiative	Lead Service	Description
DOD-wide open architecture	Army	Create PNT interface standards and develop reference PNT module hardware to enable the rapid, agile, and affordable integration of new capabilities
Non-GPS time dissemination to mobile platforms	Navy	Develop methods to provide all communications systems with the ability to distribute time from one platform to another
Modeling and simulation	Army	Integrate models of different alternative PNT technologies with GPS and navigation algorithms to predict PNT system performance under variable mission scenarios and environmental conditions

Source: GAO analysis of DOD document. | GAO-21-320SP that the goal is for platforms to have independent PNT systems combined in various ways to obtain sufficient PNT information to satisfy mission requirements regardless of threat environments (see fig. 9).

Development and integration of PNT solutions, however, is currently a long and costly process and results in proprietary solutions that cannot easily incorporate other solutions, if at all. For example, we have previously reported that it has taken more than a decade for the military services to transition from equipment that receives existing GPS signals to equipment that can receive the stronger, encrypted military-specific GPS M-code signal, and that the cost to transition will likely be billions of dollars greater than the $2.5 billion identified through fiscal year 2021 because of significant

Figure 9: Alternative positioning, navigation, and timing technologies that could be used in a GPS-denied environment



Source: GAO analysis of DOD information. | GAO-21-320SP

remaining work.[16] DOD officials and experts stated that new PNT capabilities must be integrated and fielded more rapidly to keep up with the pace of emerging threats to GPS.

To decrease the time and cost needed to integrate and field new PNT capabilities, several efforts are underway across DOD to implement modular open systems approaches (MOSA).[17] Modularity refers to the ability to easily swap out discrete hardware components or software functions of a system. Openness refers to PNT interface standards that are widely known and available to the development community.[18]

The Army and Navy have each developed a service-level PNT reference architecture that defines a MOSA for PNT, and the Air Force is just beginning to develop its own.[19] Under the open architecture initiative, the Army plans to draft and solicit input on a DOD-wide MOSA PNT reference architecture to standardize the common elements across the individual military services' reference architectures to ensure interoperability.[20]

One part of the service-level PNT reference architectures is interface standards. The Army PNT reference architecture specifies interface standards, whereas the Navy PNT reference architecture states that its next phase should further refine system interface standards. DARPA initiated development of an open interface standard for PNT, called the All-Source Positioning and Navigation standard, that the Army and Air Force have used, and an Army official considered it to be the *de facto* standard to communicate PNT information. The open architecture initiative is meeting with the military services and other key stakeholders, such as industry, and working to update the standard.

3.2.1 Potential benefits of a modular open systems approach for PNT

DOD is implementing MOSAs that, among other things, employ a modular design that uses major system interfaces between major

[16]GAO, *GPS Modernization: DOD Continuing to Develop New Jam-Resistant Capability, But Widespread Use Remains Years Away*, GAO-21-145 (Washington, D.C.: Jan. 19, 2021); and *Global Positioning System: Better Planning and Coordination Needed to Improve Prospects for Fielding Modernized Capability*, GAO-18-74 (Washington, D.C.: Dec. 12, 2017).

[17]GAO has previously reported on DOD weapon system requirements and systems engineering and DOD implementation of modular open systems approaches for unmanned aircraft systems. GAO, *Weapon System Requirements: Detailed Systems Engineering Prior to Product Development Positions Programs for Success*, GAO-17-77 (Washington, D.C.: Nov. 17, 2016); and *Defense Acquisitions: DOD Efforts to Adopt Open Systems for Its Unmanned Aircraft Systems Have Progressed Slowly*, GAO-13-651 (Washington, D.C.: July 31, 2013).

[18]DOD defines an interface standard as a standard that specifies the physical, functional, or military operational environment interface characteristics of systems, subsystems, equipment, assemblies, components, items, or parts to permit interchangeability, interconnection, interoperability, compatibility, or communications. Department of Defense, Department of Defense Standard Practice: Defense Standards Format and Content, MIL-STD-962D w/ Change 2 (Jan. 9, 2014).

[19]DOD defines a reference architecture as an authoritative source of information about a specific subject area that guides and constrains the instantiations of multiple architectures and solutions. Solution architectures are frameworks or structures that portray the relationships among all the elements of something that answers a problem. Department of Defense, Office of the Department of Defense Chief Information Officer, *Reference Architecture Description* (June 2010).

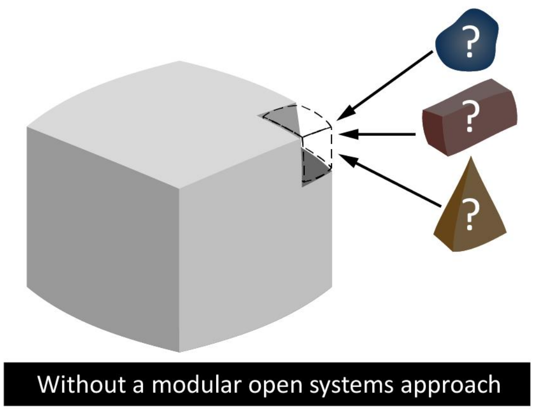
[20]A DOD-wide Reference Architecture provides information, guidance, and direction applicable across DOD in a specific subject area. The five elements of a DOD-wide Reference Architecture are strategic purpose, principles, technical positions, patterns (templates), and vocabulary. Department of Defense, Office of the Department of Defense Chief Information Officer, *Reference Architecture Description* (June 2010).

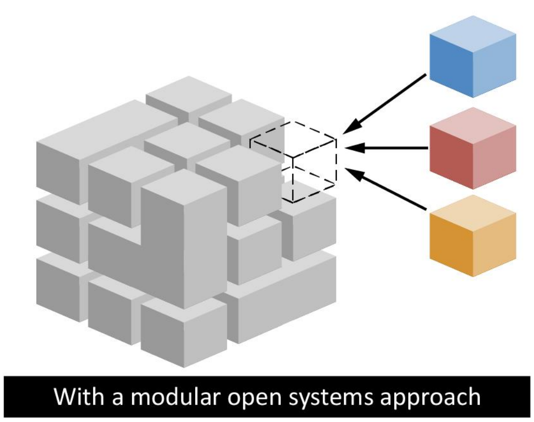
system components, such as PNT system components, in all of its major defense acquisition programs.[21] The department seeks to realize benefits such as significant cost savings or avoidance, schedule reductions and more rapid deployment of new technologies, opportunities for technology upgrades and refreshes, and increased interoperability. Many of these benefits are relevant to PNT.

Because the traditional method of technology integration is long and costly, DOD considers a PNT MOSA to be critical for integrating the alternative PNT technologies into the numerous types of platforms in use. In addition, one expert stated that a MOSA will allow integration of existing sensors on platforms to aid in the development, integrity, and assurance of a combined PNT solution independent of GPS. Using modularity and open standards can potentially reduce integration efforts since a MOSA architecture is designed to replace or refresh components and functions without significant impacts to the overall system. For example, one expert said that DOD is slow to issue updates to GPS receivers because of the cost associated with upgrading the numerous quantities of GPS receivers used in DOD (e.g., an Army official stated that the Army has 500,000 GPS receivers). Implementing a MOSA in receivers could reduce integration costs for future updates.

Using a MOSA can increase competition and innovation because DOD would not be as dependent on proprietary systems. A MOSA allows greater industry participation since companies can focus on the development of one or a few PNT components and functions that comply with the interfaces as defined in the MOSA and not be locked out because of other companies' proprietary interface standards (see fig. 10).

Figure 10: Greater availability of suitable replacements with a modular open systems approach





Source: GAO analysis of DOD information. | GAO-21-320SP

[21] 10 U.S.C. § 2446a requires that DOD major defense acquisition programs be designed and developed, to the maximum extent practicable, using a MOSA that, among other things, employs a modular design that uses major system interfaces between a major system platform and a major system component or between major system components.

As discussed in the summary of the 2018 National Defense Strategy, DOD states that it is pursuing a more lethal Joint Force and the strengthening of alliances.[22] The Strategy also states that interoperability is a priority for information sharing among the combined forces. Open interface standards can promote interoperability across the military services and allied forces since the standards make known what data are being communicated and how.

3.2.2 Considerations affecting modular open systems approaches

While there are potential benefits, there are also many considerations that can affect the development and use of a MOSA in PNT, such as acceptance by the relevant communities, system performance, cybersecurity, certification, and governance and sustainment.

One expert said a MOSA's success depends on it being able to provide benefits to relevant communities and making each of them successful. Advocates of a MOSA can inform the acquisition community that such an approach provides cost advantages while enabling the warfighter with the capability to respond to new threats. The principles of MOSA can also benefit the sustainment community (e.g., by potentially increasing the availability of replacement parts to address obsolescence) and provide useful operational capabilities to the user community through technology upgrades. Advocates can show the industry community how their proprietary capabilities are protected and how this approach enables companies to focus on development of specialized PNT components and functions without needing to invest in the development of entire PNT systems.

There are also potential performance considerations relevant to current PNT systems. An agency official with the open architecture initiative and experts stated that PNT systems such as combined GPS and inertial sensors achieve high performance because they are integrated such that they support, and are highly dependent on, one another. However, the agency official also said that in a MOSA, being modular requires the components to be discrete and less dependent on one another, which could result in a decrease in system performance. A contractor supporting the open architecture initiative hopes that a MOSA can be implemented that does not compromise system performance and that demonstrates the benefits of a MOSA, such as increased opportunities for future technology upgrades, outweigh the potential loss in performance.

Cybersecurity is another consideration with a MOSA. In transitioning from a traditionally closed PNT system developed by one prime contractor to a modular open system with known interfaces that uses components from many contractors, DOD has stated it is important that new vulnerabilities are not introduced and that architectures be protected from cybersecurity threats. Both the Army and Navy PNT reference architectures include cybersecurity requirements.[23]

[22]Department of Defense, *Summary of the 2018 National Defense Strategy of the United States of America* (Jan. 19, 2018).

[23]GAO has previously reported on DOD cybersecurity. GAO, *Information Technology: DOD Software Development Approaches and Cybersecurity Practices May Impact Cost and*

Another consideration is certification of a PNT MOSA for both internal and external compliance. Internal to the PNT system, an agency official with the open architecture initiative stated that the modular components and functions should conform to the reference architecture. External to the PNT system, an agency official with the open architecture initiative stated that certifying MOSA-compliant systems in general, which can have numerous configurations, for integration into military platforms can be complicated and is a work in progress. The agency official also said that the Army is investigating whether internal compliance of a system's components with the reference architecture can assist with determining the PNT system's external compliance with the platform that it is installed on. Although there are no PNT-specific efforts for certifying MOSA-compliant systems through test and evaluation, the official referred to similar programs that are working with operational test and evaluation commands to determine evaluation methods for MOSA-type systems.[24]

Finally, architectures and standards adapt to changing requirements and capabilities, requiring consideration of governance and sustainment of MOSA. The Army and Navy PNT reference architectures have been updated. In addition, the All-Source Positioning and Navigation interface standard is being updated to address discovered deficiencies and input from government and industry stakeholders. Though DOD currently governs and defines the DOD-wide and service reference architectures and the All-Source Positioning and Navigation interface standard, architectures and standards could be governed and sustained with consortia composed of both government and industry.[25] An expert said that sustainment of the PNT MOSA effort will require dedicated funding and continued coordination across the military services.

3.3 DOD is investigating methods to communicate and evaluate PNT information

In addition to developing numerous technologies to generate PNT information for a range of military platforms, DOD is also developing methods to communicate and evaluate PNT information.

3.3.1 Communication of PNT information

Communicating across military platforms is another way to provide PNT information to military platforms operating in GPS-denied environments.[26] One expert noted that DOD

Schedule, GAO-21-182 (Washington, D.C.: Dec. 23, 2020); and *Cybersecurity: DOD Needs to Take Decisive Actions to Improve Cyber Hygiene*, GAO-20-241 (Washington, D.C.: Apr. 13, 2020).

[24]VICTORY and CMOSS are Army MOSA efforts for C4ISR (command, control, communications, computers, intelligence, surveillance, and reconnaissance) and EW (electronic warfare). VICTORY is the Vehicle Integration for C4ISR/EW Interoperability initiative that includes an open architecture that will allow platforms to accept future technologies without the need for significant re-design. CMOSS is the C4ISR/EW Modular Open Suite of Standards, a MOSA that combines capabilities such as mission command, movement and maneuver, and fires (capability to deliver lethal and nonlethal effects) into one system.

[25]For example, the SOSA (Sensor Open Systems Architecture) Consortium is a government, industry, and academic alliance to develop an open technical standard used in military and commercial sensor systems.

[26]GAO has previously reported on the Air Force's Advanced Battle Management System (ABMS), which is intended to establish a network to connect sensors on multiple weapon systems to provide a real-time operational picture on threats across all domains. One of the 28 development areas for ABMS is to enable communication between platforms. GAO, *Defense*

has different military platforms with vastly different constraints on cost, size, weight, and power. These constraints affect the performance of a platform's PNT system. There are some platforms such as munitions, for example, that need quality PNT information but may have stringent cost, size, weight, or power constraints. To meet the PNT requirements in such situations, DOD is investigating methods to communicate quality PNT information across the various platforms (see table 4). In addition, one of the three DOD PNT science and technology initiatives focuses on non-GPS methods to disseminate time information to mobile platforms. The initiative's ultimate objective is to enable all communications systems with the ability to distribute time that is traceable to the United States Naval Observatory from one platform to another, which will minimize the need for specialized time transfer modems.

3.3.2 Evaluation of PNT information

During a mission, a fusion engine in the platform's PNT system manages and analyzes the various sources of PNT information to determine the position, velocity, and orientation of the platform (see fig. 11). Fusion of information from different sources is currently performed for existing PNT systems, such as units combining information from GPS and inertial sensors on aircraft. Fusion is also done by consumer cell phones to determine location and motion based on information from global navigation satellite systems (such as GPS), mobile networks, Wi-Fi hotspots, and onboard sensors such as accelerometers and magnetometers. Ongoing efforts such as the Army's PNT Operating System, which is a PNT manager that functions as a fusion engine, are developing modular and open fusion engines for modular and open PNT architectures.

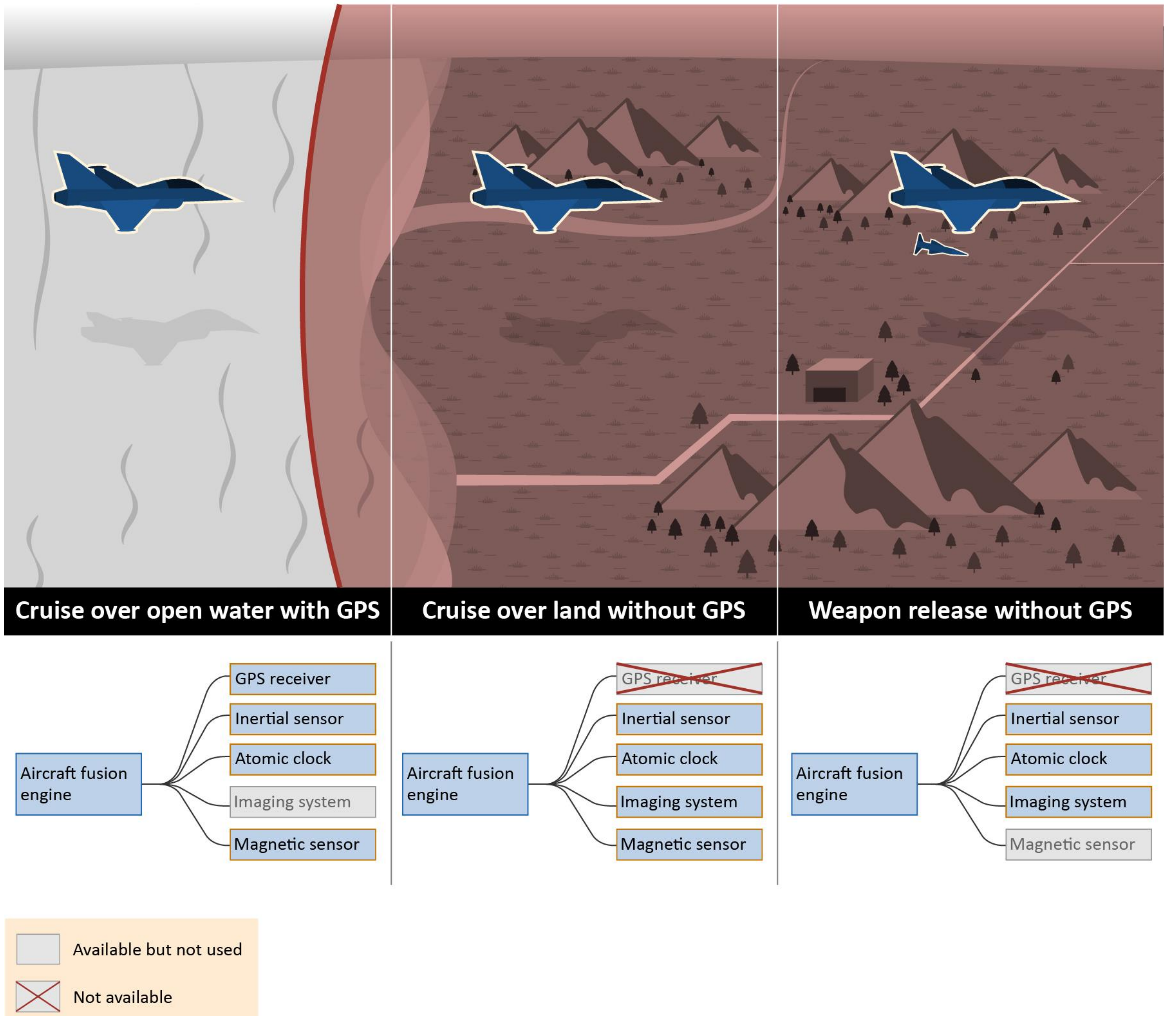
Table 4: Examples of techniques to communicate positioning, navigation, or timing information

Technique	Proposed capabilities	Performing organization
Common Data Link (CDL)	Data messages	Air Force
Cooperative Engagement Capability (CEC)	Collaborative navigation	Navy
Link 16	Time transfer	DARPA
	Time transfer	Navy
	Relative navigation	Air Force
Long-Range Navigation (LORAN)	Time transfer and positioning	Air Force
Protected Tactical Waveform (PTW)	Time transfer	Navy
Tactical Targeting Network Technology (TTNT)	Time transfer	DARPA

Source: GAO analysis of DOD information. | GAO-21-320SP

Acquisitions: Action Is Needed to Provide Clarity and Mitigate Risks of the Air Force's Planned Advanced Battle Management System, GAO-20-389 (Washington, D.C.: Apr. 16, 2020).

Figure 11: Fighter aircraft with a fusion engine that uses different sources of positioning, navigation, and timing inputs during different mission phases



Source: GAO analysis of DOD information. | GAO-21-320SP

In the Army PNT reference architecture, the PNT fusion engine is also responsible for evaluating the assurance of PNT information.[27] Although PNT information from onboard sources, such as inertial sensors, inherently have higher assurance than PNT information from external sources like GPS, they are still fallible. Army officials stated that the determination of assurance is an active research area and that there are two general methods to evaluate it. The first method is for the PNT source to evaluate assurance on its own. The second method is to use an aggregate or consensus approach by

[27]The Army PNT Reference Architecture defines PNT Information with Assurance as trustworthy PNT information that has been developed via access to one or more independent sources, depending upon PNT threat conditions. Department of Defense, Department of the Army, *Army Positioning, Navigation, and Timing (PNT) Reference Architecture*, Version 1.0, Unclassified, Dist. A (July 2018).

combining multiple information sources to determine whether there are outliers or anomalies. An Army official stated that artificial intelligence (AI) algorithms could be useful for the consensus approach in determining assurance. The official also stated that a PNT MOSA could provide a pathway to implement AI because other PNT sources can cross-check the results from the AI algorithms.[28]

DOD is considering performance in its development of a PNT fusion engine. As with the overall PNT system, there are cost, size, weight, and power tradeoffs with the performance of PNT fusion engines. Different kinds of fusion engine algorithms are used to integrate the different PNT sources and provide a PNT solution.[29] The algorithms vary, with more advanced algorithms possibly providing better fusion performance but may also need more computations. More computations likely involve higher size, weight, or power allocations.

An Army official stated that its PNT Operating System effort is a MOSA implementation for the PNT manager and fusion engine and that it is intended for operational use. The effort will define the MOSA specifications for a comprehensive software solution, and the effort will provide a government-developed baseline implementation of the MOSA specifications with modular plug-ins that other DOD and industry developers can customize using their own plug-ins.

DOD is considering how a MOSA-compliant PNT fusion engine, such as the Army's PNT Operating System, will be tested for compliance to an architecture and for integration into platforms. The Army plans to have a compliance toolkit that can automatically verify that plug-ins for the PNT Operating System comply with its architecture. An official with the open architecture initiative acknowledged that operational test and evaluation policies are a challenge to fielding capabilities enabled by MOSAs.

3.4 DOD is developing a PNT modeling and simulation framework to evaluate potential performance and guide investment decisions

Although many potential technologies and methods to provide PNT information in GPS-denied environments exist, DOD has finite resources to invest in their development. To assist in its decision-making, DOD is developing its PNT modeling and simulation capabilities to evaluate the mission effectiveness of PNT technologies and inform its alternative PNT investment decisions. The modeling and simulation initiative described in the PNT Roadmap integrates PNT

[28]GAO has previously issued a technology assessment on the emerging opportunities, challenges, and implications of artificial intelligence. GAO, *Technology Assessment: Artificial Intelligence: Emerging Opportunities, Challenges, and Implications*, GAO-18-142SP (Washington, D.C.: Mar. 28, 2018).

[29]Kalman filters are a common type of algorithm used in sensor fusion and in guidance, navigation, and control of vehicles, such as spacecraft, aircraft, and ships. Particle filters are another type of algorithm and are more complex than Kalman filters.

technology models into simulations.[30] The Army leads this initiative, which is developing a framework, called the Multi-Domain Quantitative Decision Aid, to understand how different PNT technologies work together in threat environments to provide PNT information. An official from the modeling and simulation initiative stated that two of the major benefits of the initiative are to assess the mission effectiveness of different PNT systems and guide PNT investment decisions. Officials also said that modeling and simulation can support decisions with data that would otherwise be costly or impossible to obtain. Other agency officials said that modeling and simulation could be used to challenge alternative PNT technologies in "red teaming" exercises and perform detailed assessments of their vulnerabilities.[31]

One expert stated that, rather than assessing performance of a technology, modeling and simulation are more beneficial in determining situations in which additional PNT sources are needed and if those sources will be available. Experts also stated that modeling and simulation are tools and not an outcome; that is, modeling and simulation are not meant to provide exact answers but are useful to assess tradeoffs and increase understanding.

Defense modeling and simulation can be categorized into different levels, which generally characterize their breadth of focus and resolution of detail.[32] The different levels and their corresponding characteristics serve different analytical purposes (see fig. 12). System-level models and simulations represent individual systems or components, such as inertial sensors and PNT fusion engines, to characterize their reliability or performance. Engagement-level models and simulations represent a conflict between a few systems or units; these can characterize the operational effectiveness of a PNT system on a platform and help consider tradeoffs in cost, size, weight, and power. Mission-level models and simulations represent many systems working together to accomplish mission objectives; these can evaluate how to employ different PNT technologies to achieve mission success. Campaign-level models and simulations represent force-on-force theater conflicts with large numbers of systems operating across missions; these evaluate force structure and acquisition tradeoffs, such as the combination of platforms, munitions, or PNT capabilities.

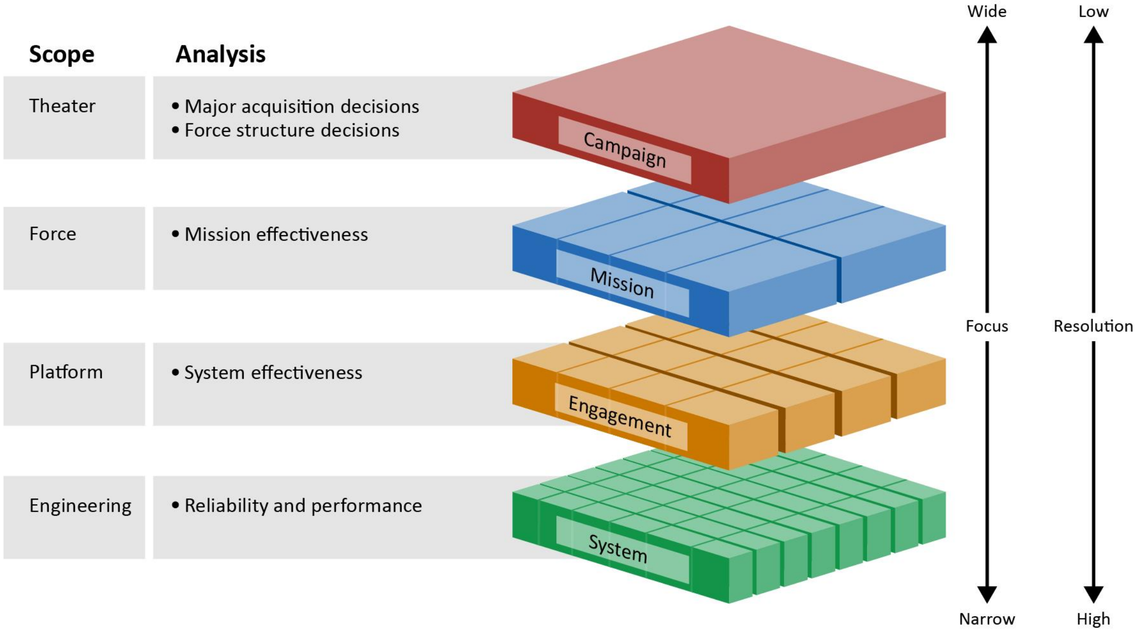
---

[30]A National Research Council report defines models as conceptual representations of some part of the real world; models can be expressed as equations, diagrams, or verbal descriptions. The report defines simulations as the implementation of models in computer programs or in exercises involving human decision-making. National Research Council, *Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st-Century Force: Volume 9: Modeling and Simulation* (Washington, D.C.: 1997).

[31]A 2003 Defense Science Board Task Force report on DOD red teaming activities considers a "red team" to be adversaries, competitors, and devil's advocates offering alternative interpretations and challenging established thinking. Defense Science Board, *The Role and Status of DOD Red Teaming Activities,* DTIC ADA430100 (Washington, D.C.: September 2003).

[32]Although there is a variety of terminologies for the levels in defense modeling and simulation, this report uses terminology that have persisted according to Gallagher et al. M A. Gallagher, D. J. Caswell, B. Hanlon, and J. M. Hill, "Rethinking the Hierarchy of Analytic Models and Simulations for Conflicts," *Military Operations Research*, vol. 19, no. 4 (2014).

Figure 12: Defense modeling and simulation have varying scopes, analytical purposes, and characteristics



Source: GAO analysis of *Military Operations Research* journal article and National Research Council report. | GAO-21-320SP

Army's Multi-Domain Quantitative Decision Aid uses high-fidelity models of PNT technologies and fusion engines in conjunction with DOD simulation environments and established GPS models to enhance mission-level modeling and simulation.[33] Agency officials stated that the primary users of the Multi-Domain Quantitative Decision Aid are service-level simulation laboratories, though it can also be used to support acquisition decisions for new systems and programs.

3.4.1 Considerations of modeling and simulation of PNT technologies

Though the modeling and simulation initiative is working to increase modeling and simulation capabilities for PNT to assess mission effectiveness and to provide evidence to guide investment decisions, experts have expressed several concerns.

For GPS, DOD has tools—such as the GPS Interference and Navigation Tool (GIANT)—that model how the radiofrequency environment affects GPS performance. Experts stated that signals from the GPS

[33] DOD simulation environments include the Army's One Semi-Automated Forces (OneSAF), the Navy's Next Generation Threat System (NGTS), and the Air Force's Advanced Framework for Simulation, Integration and Modeling (AFSIM) software. Established GPS models include the Army-developed CERDEC's Integrated GPS Navigation Model (CIGNM) and the Air Force-developed GPS Interference and Navigation Tool (GIANT). CERDEC was the Communications-Electronics Research, Development and Engineering Center; after the 2018 establishment of the Army Futures Command, CERDEC in 2019 became the Command, Control, Communications, Computers, Cyber, Intelligence, Surveillance, and Reconnaissance (C5ISR) Center.

constellation are well-modeled, but that there are challenges in modeling GPS receivers. One expert said that since no two GPS receivers are alike, high-level simulations require modeling hundreds of receivers to be accurate.

Laboratories developing PNT technologies typically use models for the individual technologies and the performance of these technologies combined with inertial sensors, clocks, or both. However, experts said the fidelity of the models of alternative PNT technologies tends to be poorer than those of satellite navigation models because of smaller investments as compared with satellite navigation models and because the performance of alternative PNT technologies is extremely dependent on the environment (e.g., terrestrial image analysis is not suitable over featureless terrain such as open water).

Experts also have concerns about higher-level simulations. For example, experts stated that models are not often set up to use information from the system levels to assess operational capability at the force and campaign levels, although the force-level simulations need only enough precision to provide accurate predictions of the outcomes against various threats. In addition, an expert told us that the ability to model multiple integrated technologies to assess performance tradeoffs and cost-benefit analyses for the platform at the engagement level does not yet exist and that this shortcoming exists up through mission and campaign levels. One expert said that some higher-level simulations may model PNT capability broadly as all-or-nothing and not with varying performance levels, and another expert stated that some simulations might be incapable of running when PNT information is unavailable.

One expert expressed concerns about verifying the performance of a technology using modeling and simulation, which can accurately assess a technology only against known threats. This creates a potential risk of underestimating adversaries' threats to both current and new PNT technologies.

Experts said that the development of a consistent and common PNT reference architecture could help develop common elements among modeling and simulation platforms, which is what has happened in the robotics community. Algorithms could then be ported between the modeling and simulation community and the open architecture community. For example, the DOD PNT modeling and simulation initiative has modeled a fusion engine developed by the DOD PNT open architecture initiative. The two initiatives are collaborating to share data and models and ensure they are using consistent databases. One expert stated that, like the open architecture initiative, the modeling and simulation initiative will require dedicated funding and continued coordination across the military services.

3.4.2 Role of field testing with modeling and simulation

Experts discussed the role of field testing relative to modeling and simulation. Experts stated that real-world testing is still beneficial, because some conditions in the simulation may not be modeled or invalid assumptions might be made.

One agency official said that special operations forces were reluctant to accept modeling and simulation results for alternative PNT technologies partly because there were no experimental data from field tests. One expert responded that interpretation and translation of the modeling and simulation results to military personnel, such as special operations forces, would equip them with usable information to be more operationally effective.

One expert said that field tests could not be the sole method to evaluate technologies, because the tests are expensive and cannot create the numerous kinds of environments relevant to future military operations (e.g., test design, quantity and type of platforms and systems, and quantity and type of jammers) without considerable effort and shutting down civil airspace. The Army has been conducting annual PNT Assessment Exercises that bring together hundreds of government and industry partners to conduct demonstrations, collect data, and assess capabilities in operationally representative environments. Experts stated that modeling and simulation can help select which field tests to perform, and the results for those field tests can be used to perform selective checks of a simulation.

Experts also stated that it is important to systematically collect, share, and assess the quality of simulation and test data. One potential benefit is that new sensors or algorithms can be tested with hundreds of hours of existing flight data in an automated way. The modeling and simulation initiative is working to make data, models, and databases accessible to others.

4 Alternative PNT Challenges and Options That May Help Address Them

4.1 Challenges in developing and integrating alternative PNT

4.1.1 Alternative PNT is not a priority

Officials from across DOD as well as experts told us that alternative PNT solutions are not prioritized across DOD. One expert said, “PNT—it’s everyone's need, but nobody's business.” Another expert said, “Everyone wants to use [PNT], no one wants to pay or care for [PNT]”. One DOD official characterized alternative PNT as an afterthought. DOD’s PNT Roadmap states that PNT capabilities, despite being mission critical, are not normally considered a key requirement, but rather may be treated as “a second-tier requirement.”

There is no central program office responsible for developing alternative PNT across DOD.[34] There is a PNT Oversight Council responsible for availability and interoperability of DOD PNT enterprise capabilities and applications.[35] However, according to DOD officials, the PNT Oversight Council primarily focuses on GPS.[36]

One DOD official said DOD’s slow actions with alternative PNT were due to a lack of central leadership. Several experts also stated that there is a lack of leadership.[37] For example, one expert stated, “There’s nobody in charge… There’s no one who is going to lose their job because PNT… goes offline.” One expert noted that the lack of alternative PNT capability is because there is no program office in DOD devoted to developing alternative PNT. Another expert said that programs may have to be directed to use alternative PNT.

Additionally, one DOD official said that bureaucratic and political obstacles represented the biggest challenges for alternative PNT.[38] Specifically, the official stated that anything that threatens GPS, such as alternative PNT technologies, faces pushback. When asked, another DOD official agreed there is an impression that the GPS program has a lot of political clout within DOD, and that those trying to develop alternative PNT technologies may face political challenges. Another DOD official made a related statement, saying that there does not appear to be motivation for a large-scale alternative PNT solution.

[34] The Office of the Secretary of Defense develops and maintains the PNT Roadmap and coordinates with other DOD groups. Each military service has its own group responsible for PNT. For example, the Army and Air Force have Cross Functional Teams for the development of alternative PNT while PNT-related development in the Navy is managed by the Navigator of the U.S. Navy.

[35] Department of Defense, *Positioning, Navigation, and Timing Management,* DOD Instruction (DoDI) 4650.06 (July 30, 2020).

[36] The PNT Oversight Council produced annual reports, which are classified. We did not review the classified reports from the PNT Oversight Council.

[37] Six out of fourteen experts said there was a lack of leadership within DOD, and no experts at the meeting we convened disagreed with that opinion.

[38] 10 U.S.C. § 2281(a) provides for the sustainment and operation of GPS for military use but that there is not a comparable statutory requirement to provide for the sustainment and operation of alternative PNT.

However, other DOD officials said PNT prioritization is occurring at the military-service level. For example, according to Navy officials, the Navy is currently developing and integrating a PNT system for ships that will implement MOSA. Similarly, the Air Force is maturing a MOSA PNT solution for aircraft.[39] Another official said that the Army created its Assured PNT Cross Function Team in 2018 to prioritize alternative PNT and to take actions such as assisting with transitioning technology to programs of record and interfacing with industry to mitigate issues. Another official said there are good examples of strategies and initiatives on the military service level that could be incorporated into plans in the future.

The National Defense Authorization Act for Fiscal Year 2021 has a section directing the Secretary of Defense to mature, test, and produce prioritized elements needed to generate resilient alternative PNT.[40] One DOD official stated this law will help in prioritizing alternative PNT.

4.1.2 Over-reliance on GPS

Both experts and DOD officials said that the vulnerabilities of relying on GPS are well known, but DOD's response may not be sufficient to address the threat. GPS remains the primary source of PNT for the foreseeable future in the DOD. Experts at the meeting that we convened questioned the resiliency of relying on GPS as the core of the military PNT solution. For example, one expert told us that DOD uses GPS even when it is not needed, and given the threats to GPS, this over-reliance introduces vulnerabilities.

A MITRE report found the same issues that experts discussed with us, stating "widespread dependence on current GPS is a serious problem."[41] MITRE's proposed strategy includes moving the core PNT source from GPS to precision clocks and inertial sensors (relative PNT sensors), which are very difficult to spoof or jam. This approach could result in a more resilient overall PNT solution.

4.1.3 Unclear performance requirements

Officials from DOD's science and technology community as well as experts from outside of DOD said challenges related to PNT requirements hinder developing technologies.[42] First, officials told us that there are no centrally defined requirements for alternative PNT, because PNT requirements are specific for each platform or mission. This is an issue for R&D, as new technologies then must meet a range of requirements. While discussing the unclear performance requirements, one expert cited past examples where clear requirements from DOD prompted industry to create solutions.

Second, DOD officials stated PNT requirements are not well defined and default

[39]Both the Navy program (GPS-Based Positioning, Navigation and Timing Service) and the Air Force program (Resilient Embedded GPS/Inertial Navigation System) are programs of record. These programs were out of scope for our review, as we focused on technologies within the research portfolio.

[40]William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021, Pub. L. No. 116-283, § 1611, 134 Stat. 3388, 4048-49.

[41]John Betz, PhD, *Achieving Robust and Resilient Navigation and Timing for Defense Applications* (The MITRE Corporation, 2019).

[42]We did not interview DOD officials responsible for creating requirements, as it was out of scope for this technology assessment. One official stated that one of the military services has performed analysis on PNT requirements for its missions.

to GPS capabilities, even if that level of performance is not needed to perform a mission. According to the PNT Roadmap, program managers routinely demand performance levels that match those of GPS. However, in many cases, a mission may not need GPS-level performance.[43] For example, a ship may be able to successfully navigate a route with location data less precise than those provided by GPS.[44] Another DOD official stated that in addition to performance, the size, weight, and power requirements for a PNT system also default to GPS. For example, when making weight trade-offs between subcomponents, the PNT system's allocation is often reduced based on the assumption that GPS will be used. By relying on GPS as the default PNT technology rather than defining actual needs and requirements, DOD programs could be excluding potential technologies that may meet mission needs with greater resilience than GPS. One expert noted that there may be PNT technologies commercially available now that meet the true mission requirements (i.e., the actual precision and accuracy of PNT data needed to successfully carry out a mission).

4.1.4 Limited incentives for industry

According to experts, another challenge to developing PNT solutions is a lack of incentive for industry. One expert stated that the proposed DOD PNT solution of an array of several different PNT technologies divides an already small market, creating less incentive for companies. One DOD official had the same concern, stating that having multiple parallel PNT solutions might lead to a fractured industrial base. According to one expert, the DOD market for alternative PNT technology is not big enough to achieve economies of scale like those seen with GPS.[45]

Another expert stated that there is a lot of money going into commercial R&D—specifically navigation—and that the commercial market has the potential to outpace DOD, unless DOD finds a way to take advantage of the gains in the commercial sector. This expert stated that a MOSA could provide DOD with an easy way to implement new technologies. A DOD official said that the department relies on the military services to be aware of developments in the commercial sector.

4.1.5 Complex and costly integration

As discussed earlier, integration is both expensive and time consuming, resulting in platforms using outdated PNT technology. One DOD official stated that integration is often addressed on a case-by-case basis due to the number of platforms that require PNT. Another DOD official stated that customized integration drives up costs. Two officials from different military services cited increased costs associated with integrating a new technology into a legacy system. Another DOD official said there was a lack of economies of scale for platforms such as aircraft; for example, one expert said that it could cost billions to modify the F-35 aircraft

[43] GPS performance includes many attributes such as accuracy, availability, and update frequency.

[44] However, one DOD official noted that ships may have other combat related missions with more stringent PNT requirements.

[45] This same expert mentioned that one way to mitigate this could be increased collaboration between military and civilian PNT communities in the United States.

fleet. The PNT Roadmap also discusses this consideration and includes questions about how alternative PNT technology is integrated into the platform's navigation system, the cost of that integration, and how to ensure the technology is compatible with a MOSA.

In response to the integration challenge, DOD is providing funding of $17 million to the Army for the period of fiscal years 2020-2024 to create a MOSA for the entire DOD. This effort is intended to support the integration of different alternative PNT sources into platforms. One DOD official stated this is a small amount of money to cover the initiative. In comparison, the entire DOD science and technology investment in PNT totaled $783 million over the same time period. One expert said they would like to see the MOSA initiative funding increased in order to bring more focus onto the initiative. Another expert stated that, without additional long term funding, the initiative will likely "peter out."

4.1.6 Limited transfer of new technologies to operational systems

Experts said that transitioning alternative PNT technology from R&D to a program of record is a challenge. According to the PNT Roadmap, new technologies can be demonstrated to show that they work, but few successfully transition to operational systems. The PNT Roadmap cites multiple reasons, including some of the challenges described above such as unclear performance requirements and complex and costly integration.

In addition, one DOD official said vendor lock-in on the platform level (where the program is dependent on the vendor, making it costly to switch to a new technology) is a challenge. Another official talked about the related issue of proprietary systems that cannot be upgraded. A DOD official further stated that PNT systems bought today are closed systems because one prime contractor is responsible for developing, procuring, packaging, and delivering an entire system. The official stated that, because of this proprietary nature, there are few opportunities to integrate alternative PNT technologies.

4.1.7 Potential vulnerabilities in alternative PNT technologies

Experts said there was a gap in knowledge about vulnerabilities in alternative PNT technologies. Experts stated that, given the diverse and evolving nature of the threats to GPS, alternative PNT technologies should also be rigorously examined for their effectiveness under potential future threats. According to the PNT Roadmap, some considerations include considering how adversaries could interfere with data sets or models used by alternative PNT technologies. Also, many alternative PNT technologies rely on communications links, which may not be available in a degraded environment. One DOD official said the focus for alternative PNT technologies is to fill currently known gaps with GPS spoofing and jamming. However, this official said more attention should be given to determine threats to PNT.

4.2 Several options may help address challenges

As discussed above, DOD faces a number of challenges with the development of alternative PNT technologies if the status quo continues. We identified policy options that may help address these challenges. The policy options identify possible new actions by policymakers, which may include Congress, federal agencies, and industry groups.

4.2.1 Increase collaboration

Policymakers could consider mechanisms to coordinate across DOD to clarify responsibilities and authorities in prioritizing the need for alternative PNT technologies.

- Description: Coordination is needed since PNT enables many DOD functions, from training to delivering supplies. Given the number of programs involved across the military services, prioritizing the need to develop alternative PNT technologies depends on all involved having clear responsibilities and authorities. One such mechanism could be through the PNT Oversight Council. The PNT Oversight Council is responsible for ensuring DOD PNT capabilities are available and interoperable across DOD.[46] However, according to DOD officials, the PNT Oversight Council primarily focuses on GPS. Potential approaches to increasing coordination could incorporate best practices, such as defining a common outcome to increase the visibility of alternative PNT technologies across DOD, establishing joint strategies, and leveraging resources.

- Opportunities: Increased coordination could allow the military services to leverage one another's R&D advancements. If DOD coordinates in prioritizing the need for alternative PNT, this could increase the technology's visibility within DOD, giving officials overseeing programs and platforms a better understanding of the types of alternative PNT technology available.

- Considerations: PNT solutions for a particular mission or platform may still need significant customization, offsetting the potential benefits from centralized coordination. Current mechanisms, such as the PNT Oversight Council, may not have the capacity to manage alternative PNT coordination.

4.2.2 Focus on resiliency

Policymakers could consider selecting the most resilient technologies as the cornerstone of the PNT suite for military missions, rather than defaulting to GPS.

- *Description*: Overreliance on GPS may introduce unnecessary vulnerabilities. For this reason, other countries, such as China and Russia, have alternative PNT systems. Instead of assuming GPS remains the cornerstone of a PNT suite of technologies, other technologies could be considered for their resiliency to ensure continued operation in a threat environment. For example, on-board inertial systems and clocks are generally harder to spoof or jam. GPS could still be used in the PNT suite as a complement to a more robust and resilient PNT technology. In some cases, GPS may still be the most resilient PNT source, especially considering ongoing

[46] Department of Defense, *Positioning, Navigation, and Timing Management,* DOD Instruction (DoDI) 4650.06 (July 30, 2020).

investments to increase the resiliency of GPS.

- *Opportunities*: Under this mindset, technologies that add to resilient PNT could receive higher priority for development, even if they are not full replacements for GPS. For example, one expert said with a shift in thinking, many technologies, such as low Earth orbit satellites, would be considered promising when used with an inertial/clock system on a platform.

- *Considerations*: A PNT solution will need multiple technologies to meet full PNT requirements, because no single alternative PNT technology is currently able to provide all of the required information. Additionally, most alternative PNT technologies do not provide the same level of performance as GPS. Finally, DOD will need to continue maintaining GPS, as it will remain a part of the PNT solution.[47]

4.2.3 Clarify requirements

Policymakers could consider opportunities for DOD to clarify what level of PNT performance is actually needed for missions, rather than defaulting to requirements that match GPS performance.

- *Description*: Without requirements that reflect the mission needs, past practices would indicate that PNT requirements will continue to default to GPS. According to the PNT Roadmap, programs often demand GPS-level performance, even when it is not needed. At the same time, GPS is often smaller, lower weight, and cheaper than alternative technologies. Programs may not plan for the added space or cost needed for alternative solutions. This then pushes platforms towards a GPS solution over an alternative PNT solution that may better match performance and resiliency requirements. Requirements could also better consider vulnerabilities introduced by relying on a single PNT source such as GPS. Such requirements, created to reduce vulnerabilities, would better prepare DOD to be more resilient to threats against PNT.

- *Opportunities*: With performance requirements that better reflect actual mission needs, DOD could make more informed decisions in developing viable alternative technologies that will meet the actual mission needs, but not necessarily have GPS level of performance. For example, there could be tradeoffs where an alternative PNT solution may be cheaper or quicker to integrate then GPS, but may not have performance precision on GPS. If the mission requirements do not need a GPS level of performance precision, this alternative PNT solution may meet mission needs, and result in cost or schedule savings.

- *Considerations*: Creating requirements involves appropriately skilled personnel. For example, we previously reported that program managers and other acquisition officials often lack experience and

[47] DOD also must maintain GPS for civilian uses. See 10 U.S.C. § 2281(b).

expertise to manage requirements and acquisitions, and rely too much on contractors to determine what is needed to develop a weapon system.[48] In addition, for PNT, programs may still want GPS-level performance, because more precise PNT information is desired, even when it goes beyond what is needed to complete a specific mission.

4.2.4 Coordinate with industry

Policymakers could consider ensuring that DOD and the commercial industry coordinate so that industry is prepared to meet DOD's needs, and so that DOD can leverage industry advances.

- *Description*: DOD needs the commercial industrial base to manufacture PNT solutions. Thus, ensuring the industrial base is prepared to manufacture PNT solutions is in DOD's best interest. At the same time, commercial sectors may have invested in R&D of PNT technologies that DOD could leverage such as navigation algorithms used in autonomous vehicles.

- *Opportunities*: Industry may be better positioned to meet DOD's needs if those needs are clearly communicated. Collaboration between DOD and industry on alternative PNT solutions can also help ensure a large enough customer base to support commercial interest in DOD as a customer. Similarly, commercially available alternative PNT technologies may meet DOD's needs more quickly and at a lower cost than a new technology that would be funded by DOD.

- *Considerations*: Commercial industry may not be incentivized to develop and manufacture alternative PNT technologies if the market is too small. The DOD lifecycle of a technology is much longer than a typical commercial lifecycle, which could cause issues. Experts also have concerns that lack of transparency into proprietary commercial technology may mask vulnerabilities.

4.2.5 Institutionalize open architecture

Policymakers could consider making the open architecture initiative more permanent, including providing funding.

- *Description*: Costly and complex integration of alternative PNT technology is a roadblock to getting the technology into operation. The open architecture initiative intends to standardize many of the interfaces and define different modules, with the goal of being able to quickly add new alternative PNT technologies.

- *Opportunities*: With appropriate resources, DOD's open architecture initiative has the potential to greatly reduce integration costs and time for all PNT technologies. This could make it easier to bring new alternative PNT technology to DOD, which could assist in staying ahead of evolving threats to PNT.

[48] GAO, *Defense Acquisition Process: Military Service Chiefs' Concerns Reflect Need to Better Define Requirements before Programs Start,* GAO-15-469 (Washington, D.C.: June 11, 2015).

- *Considerations*: The open architecture initiative will need buy-in across the military services, as well as with commercial industry partners, which may be difficult to achieve. Once implemented, the open architecture initiative could need continued resources and governance, as the architecture will likely evolve.

4.2.6 Analyze vulnerabilities

Policymakers could consider having DOD conduct ongoing analysis of vulnerabilities of different PNT systems, comprised of different combinations of PNT technologies.

- *Description*: Threats to PNT technology are diverse, from spoofing and jamming signals to attacking infrastructure supplying PNT information. As threats evolve, ongoing analysis of each PNT technology's strengths and weaknesses would be needed. For example, PNT systems could undergo red team testing, where an independent team of developers attempts to mimic an adversary's actions to expose weaknesses. Effective modeling and simulation could also provide information on how different PNT technologies work together in threat environments. Combined with an open architecture approach, future PNT systems could more effectively match a technology's strengths with mission threats.
- *Opportunities*: Given a future solution will likely require a PNT system comprised of a combination of different technologies, users could be better informed about each combination's overall vulnerabilities. This could allow users to better match PNT solutions to the mission and threat.
- *Considerations*: The complexity of having a unique PNT system for each mission and platform could make vulnerability analysis for such systems difficult. Also, if DOD relies more on alternative PNT, the threats will evolve in response to that strategy--just as the threats are in response to DOD's reliance on GPS—which may mean the vulnerability analysis needs to be regularly updated.

5 Agency and Expert Comments

We provided a draft of this product to the Department of Defense with a request for comments. DOD provided us with technical comments, which we incorporated as appropriate.

We invited the participants from our meeting of experts to review our draft report. Among those participants, six experts provided technical comments, which we incorporated as appropriate.

If you or your staff have any questions about this report, please contact Karen Howard at 202-512-6888 or HowardK@gao.gov or Jon Ludwigson at 202-512-4841 or LudwigsonJ@gao.gov. GAO staff who made key contributions to this report are listed in appendix III.

Karen L. Howard

Karen L. Howard, PhD
Director
Science, Technology Assessment, and Analytics

Jon Ludwigson

Jon Ludwigson
Director
Contracting and National Security Acquisitions

Appendix I: Objectives, Scope, and Methodology

Objectives

We were asked to assess the positioning, navigation, and timing (PNT) technologies DOD is developing to complement GPS. This report discusses:

1. how DOD plans to meet future PNT needs and the capabilities and limitations of alternative PNT technologies;
2. how alternative PNT technologies integrate with one another and with current PNT capabilities; and
3. challenges with the development and integration of alternative technologies, and policy options.

Scope

We scoped this technology assessment to PNT technologies in development for defense applications. We excluded (1) GPS or similar foreign-based Global Navigation Satellite Systems, (2) any technology that would enhance GPS, such as anti-jam antennas, and (3) technologies intended to be a follow-on to GPS. We also excluded non-DOD uses of PNT. The focus of this assessment is on technology, and we did not include non-technological solutions such as changes to training, tactics, techniques, or procedures.

Methodology

For all the objectives, we reviewed relevant literature for background material. We identified relevant literature, such as peer reviewed material, conference papers, industry articles, and other publications, by searching on different databases, including the Defense Technical Information Center.[49] We also asked officials we interviewed for relevant literature. Further, we reviewed DOD documentation, such as the PNT Science and Technology Roadmap issued by the Office of the Under Secretary of Defense for Research and Engineering. We also interviewed officials from the Office of the Under Secretary of Defense for Research and Engineering, the Navigator of the U.S. Navy's office, the Army's Assured PNT cross functional team, the Air Force's PNT cross functional team, and the Defense Advanced Research Projects Agency, among others.

Additionally, we convened an expert meeting with the assistance of the National Academies of Sciences, Engineering, and Medicine to provide their insights on complementary PNT technologies, integration, overall challenges, and policy options.[50] The meeting was held over three days with 14 experts, listed in Appendix II. We identified experts from a range of stakeholder groups including federal agencies, academia, and industry, with expertise covering significant areas of our review. We asked experts at our meeting to

[49]The Defense Technical Information Center is DOD's repository of government funded scientific, technical, engineering and business related information.

[50]This meeting of experts was planned and convened with the assistance of the National Academies of Sciences, Engineering, and Medicine to better ensure that a breadth of expertise was brought to bear in its preparation. However, all final decisions regarding meeting substance and expert participation were the responsibility of GAO. Any conclusions and policy options in GAO technology assessments are solely those of GAO.

identify any potential conflicts of interest, which were considered to be any current financial or other interest that might conflict with the service of an individual because it could impair objectivity. The group of experts as a whole was judged to have no inappropriate biases. We used the meeting's discussion to add greater depth to our sections on technologies, integration, challenges, and policy options, among other areas. Following the meeting, we continued to draw on the expertise of those individuals who agreed to work with us during the rest of our study.

To address the first objective, we selected nine PNT development programs to further examine based on the agency or military service responsible for the program, and each program's technological approach, funding, and intended platforms. These nine programs were selected from approximately 70 programs identified from DOD documentation, of which approximately 45 programs were within the scope of this report. We conducted semi-structured interviews with officials from those nine selected programs. The selected programs provide illustrative examples of alternative PNT science and technology efforts and are not generalizable to all of DOD's efforts.

To address the second objective, we reviewed DOD documentation, such as the Army PNT reference architecture and an interim annual report on PNT modeling and simulation. We also interviewed DOD officials working on the PNT open architecture initiative and modeling and simulation initiative.

To address the third objective, we identified common challenges from interviews with DOD and participants in the expert meeting. To develop policy options, we first identified policy ideas that may address challenges to the development and integration of alternative PNT technologies within DOD. We then synthesized these ideas to develop policy options for addressing these challenges. We assessed policy ideas from literature, interviews with DOD, and participants in the expert meeting. We analyzed each policy option by identifying and discussing potential benefits and considerations of implementing them.

We conducted our work from March 2020 to May 2021 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

Appendix II: Expert Participation

With the assistance of the National Academies of Sciences, Engineering, and Medicine, we convened a meeting of experts to inform our work on complementary PNT technologies. The meeting was held virtually on September 14, 16, and 18, 2020.

The experts who participated in this meeting are listed below, along with their title at the time of the meeting. These experts gave us additional assistance throughout our work, including six experts who reviewed our draft report for accuracy and provided technical comment.

John W. Betz
Fellow
The MITRE Corporation

Bill Bollwerk
Consultant
United States Naval Observatory

Alison K. Brown
President and Chief Executive Officer
NAVSYS Corporation

Joseph Broz
Executive Director and Chair of the Governing Board
The Quantum Economic Development Consortium
Senior Advisor for Quantum
Air Force Research Laboratory

Kevin Coggins
Vice President
Booz Allen Hamilton

Elizabeth Donley
Chief; Time and Frequency Division
National Institute of Standards and Technology

Demoz Gebre-Egziabher
Professor; Department of Aerospace Engineering and Mechanics
University of Minnesota
Director
Minnesota Space Grant Consortium

Dana A. Goward
President
Resilient Navigation and Timing Foundation

Ralph E. Hopkins
Distinguished Member of the Technical Staff and Group Leader; Positioning, Navigation, and Timing Division
The Charles Stark Draper Laboratory, Inc.

Robert Leishman
Director
Autonomy and Navigation Technology Center
Research Assistant Professor
Air Force Institute of Technology

Paul Massatt
Senior Project Leader
The Aerospace Corporation

John F. Raquet
Director; Dayton Office
Integrated Solutions for Systems, Inc.

Logan Scott
Consultant
LS Consulting

Stefanie Tompkins
Vice President for Research and Technology Transfer
Colorado School of Mines

Appendix III: GAO Contacts and Staff Acknowledgments

GAO contacts

Karen L. Howard at (202) 512-6888 or HowardK@gao.gov

Jon Ludwigson at (202) 512-4841 or LudwigsonJ@gao.gov

Staff acknowledgments

In addition to the contacts named above, R. Scott Fletcher (Assistant Director), Jenn Beddor (Analyst-in-Charge), Will Bauder, Chi Mai, Sean Seales, and Jay Tallon made key contributions to this report. David Blanding, Jenny Chanley, Louise Fickel, Patrick Harner, Nacole King, Summer Lingard-Smith, Anika McMillon, Matt Metz, and Edith Yuh also contributed to this report.

(104209)

GAO's Mission

The Government Accountability Office, the audit, evaluation, and investigative arm of Congress, exists to support Congress in meeting its constitutional responsibilities and to help improve the performance and accountability of the federal government for the American people. GAO examines the use of public funds; evaluates federal programs and policies; and provides analyses, recommendations, and other assistance to help Congress make informed oversight, policy, and funding decisions. GAO's commitment to good government is reflected in its core values of accountability, integrity, and reliability.

Obtaining Copies of GAO Reports and Testimony

The fastest and easiest way to obtain copies of GAO documents at no cost is through GAO's website (https://www.gao.gov). Each weekday afternoon, GAO posts on its website newly released reports, testimony, and correspondence. To have GAO e-mail you a list of newly posted products, go to https://www.gao.gov and select "E-mail Updates."

Order by Phone

The price of each GAO publication reflects GAO's actual cost of production and distribution and depends on the number of pages in the publication and whether the publication is printed in color or black and white. Pricing and ordering information is posted on GAO's website, https://www.gao.gov/ordering.htm.

Place orders by calling (202) 512-6000, toll free (866) 801-7077, or
TDD (202) 512-2537.

Orders may be paid for using American Express, Discover Card, MasterCard, Visa, check, or money order. Call for additional information.

Connect with GAO

Connect with GAO on Facebook, Flickr, Twitter, and YouTube.
Subscribe to our RSS Feeds or E-mail Updates.
Listen to our Podcasts and read The Watchblog.
Visit GAO on the web at https://www.gao.gov.

To Report Fraud, Waste, and Abuse in Federal Programs

Contact: Website: https://www.gao.gov/fraudnet/fraudnet.htm
Automated answering system: (800) 424-5454 or (202) 512-7470

Congressional Relations

Orice Williams Brown, Managing Director, WilliamsO@gao.gov, (202) 512-4400,
U.S. Government Accountability Office, 441 G Street NW, Room 7125, Washington, DC 20548

Public Affairs

Chuck Young, Managing Director, YoungC1@gao.gov, (202) 512-4800
U.S. Government Accountability Office, 441 G Street NW, Room 7149, Washington, DC 20548

Strategic Planning and External Liaison

Stephen Sanford, Acting Managing Director, spel@gao.gov, (202) 512-9715
U.S. Government Accountability Office, 441 G Street NW, Room 7B37N, Washington, DC 20548