Position, Navigation, and Timing Control

Executive Summary

May 2024

DEFENSE SCIENCE BOARD

OFFICE OF THE UNDER SECRETARY OF DEFENSE FOR RESEARCH AND ENGINEERING

OFFICE OF THE SECRETARY OF DEFENSE
3140 DEFENSE PENTAGON
WASHINGTON, DC 20301–3140

DEFENSE SCIENCE
BOARD

MEMORANDUM FOR UNDER SECRETARY OF DEFENSE FOR RESEARCH AND ENGINEERING

SUBJECT: Defense Science Board (DSB) Report on Position, Navigation, and Timing Control

I am pleased to forward the final report of the DSB study on *Position, Navigation, and Timing Control*, co-chaired by Dr. Daniel Hastings and Mr. James Shields. The Global Positioning System (GPS) remains the gold standard in worldwide distribution of position and timing information, and precision based off this capability has become a cornerstone of both global and domestic economies, as well as American military power. GPS enables telecommunications, banking, transportation, and weather tracking in addition to its use in precision guided munitions. However, the availability and accuracy of GPS and Global Navigation Satellite Systems (GNSS) may not be guaranteed at all places and times. As a result, the Department of Defense (DoD) has an ongoing interest in identifying, developing, and implementing alternative means of obtaining and distributing position and timing information, as well as navigating accordingly.

There is no one-size-fits-all alternative to GNSS for DoD. Different missions and systems have different requirements, which can be met in part or in full by combinations of alternative navigation technologies. Vision-based navigation, celestial navigation, signals of opportunity, and various types of map-matching are all viable means to this end. Extensive GPS jamming in Syria and Ukraine indicate that, at a minimum, warfighters must be trained and equipped to operate in settings where GNSS is not consistently available.

To provide actionable recommendations to the Department, the DSB examined a variety of alternative navigation systems, space-based and otherwise, and considered warfighter needs and future opportunities for meeting them. I fully endorse all the study's recommendations and urge their careful consideration and adoption.

Dr. Eric D. Evans
Chair, Defense Science Board

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DEFENSE SCIENCE BOARD

OFFICE OF THE SECRETARY OF DEFENSE
3140 DEFENSE PENTAGON
WASHINGTON, DC 20301–3140

MEMORANDUM FOR THE CHAIR, DEFENSE SCIENCE BOARD

SUBJECT: Report of the Defense Science Board (DSB) Task Force on Position, Navigation, and Timing Control

Attached is the final report of the DSB Task Force on *Position, Navigation, and Timing Control.* The Task Force was charged with several objectives related to the Global Positioning System (GPS), including identifying current limits, necessary enhancements, and future challenges, and evaluating alternative satellite navigation (SATNAV) architectures and non-SATNAV means of obtaining and distributing position and timing information. Significant shifts in technology have occurred since this tasking was signed, including most notably a reduction in launch costs that has spurred on domestic and foreign commercial space industries, providing the opportunity to rapidly deploy purpose-built, low-cost medium Earth orbit satellites to address well-known, long-standing GPS challenges. To fulfill its mission, the Task Force received briefings from individuals in the defense and commercial sectors, as well as academia and federally funded research and development centers.

Although there is no silver bullet to solve the Department's reliance on GPS, there are concrete actions that senior leaders can take in the near- and mid-term to improve its posture. These include programs to develop and productize promising technology for use in future systems, as well as policy actions to identify mission-specific PNT needs and prepare warfighters for challenging environments. Having observed extensive use of jammers in Syria and Ukraine, we find it likely that the United States will face similar challenges in any major conflict. As such, the Department of Defense must learn what lessons it can now and prepare accordingly.

There are many ongoing efforts within the Department to bolster PNT capabilities. The Task Force observed that many PNT challenges could be solved, or at least ameliorated, with consistent funding and high-level recognition of the problem. As precision is critical to the Department from both technological and cultural perspectives, ensuring its availability should be treated as a serious matter.

J. D. Shields

Daniel Hastings

Mr. James D. Shields
Co-chair

Dr. Daniel E. Hastings
Co-chair

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Executive Summary

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Task Force Background and Approach

On December 6, 2019, the Under Secretary of Defense for Research and Engineering (USD(R&E)) tasked the Defense Science Board (DSB) to undertake a study on the future of position, navigation, and timing (PNT) control. Technological and geopolitical developments since the 2005 *DSB Task Force on the Future of the Global Positioning System* (GPS) have broadened the possibility space in terms of potential risks to overreliance on GPS, as well as opportunities to acquire and provide PNT via other means. Key questions in the terms of reference (Appendix A) cover the resilience of current GPS systems, benefits and risks of using commercial systems, and the potential for alternative PNT paradigms.

To conduct this study, the DSB stood up a task force of subject matter experts from public and private sectors, federally funded research and development centers, national laboratories, and relevant Department of Defense (DoD) stakeholders. The Task Force received briefings and reviewed material that covered developing technologies, program delays, acquisition policy, and obstacles to information management and dissemination.

GPS as the Gold Standard

GPS is a space-based, dual-use PNT system developed by the DoD in the 1970s, which is now managed through an interagency process. It consists of space, control, and user segments, which have been updated and modernized at various paces and to varying degrees of success. The distribution of highly accurate position and timing information is now of great value for global finance, telecommunications, commercial aviation, autonomous vehicles, and even relatively esoteric uses such as monitoring for earthquake precursors. Its impact on the U.S. economy is now estimated at $1.4 trillion, and it remains a key driver of economies worldwide despite development of alternative global navigation satellite systems (GNSS).

In the national security arena, DoD force structures and modern warfighting methods depend on high-level precision. The low cost of GPS receiver chips has enabled the capability to be embedded in many military systems, and it remains the gold standard for military PNT.

Overview of Study Areas

The Task Force assessed five areas over the course of the study:

- Hardening GPS
- Alternate Satellite Navigation (SATNAV)
- Alternative Positioning and Navigation
- Precision Timing for DoD Missions
- Operational Navigation Warfare

Study Area: Hardening GPS

The DoD has sought to guarantee GPS availability during peer conflict for many years due to the importance of precision in modern warfighting. The 2005 *DSB Task Force on the Future of the Global*

Positioning System assessed then-current vulnerabilities and made recommendations to address them. Specifically, it found that:

- improvements are needed, implementation is lacking;
- serious delays are affecting military signals and equipment;
- raising anti-jam margins is essential to future operations; and
- anti-jam solutions are known (increased satellite power and improved user equipment) but implementation lags need.

The Task Force now calls for bold action using the practices which have revolutionized the commercial space world to acquire new proliferated low-cost spot beam satellites (which the Task Force refers to as GPS IIIF-Lite) for launch into medium Earth orbit. If this recommendation is adopted, the GPS constellation will be meaningfully proliferated beyond current numbers, offer much needed capabilities faster, and remain postured for better integration of new technologies.

Military GPS User Equipment (MGUE) programs also face setbacks for a variety of reasons that are described and evaluated in the report. These issues must be addressed in tandem to achieve the desired results.

Study Area: Alternate Satellite Navigation (SATNAV)

Relative to the 2005 DSB study, much has changed in the PNT field beyond GPS. Several alternative GNSS are now operational, including those from Europe (Galileo), Russia (GLONASS), and China (BeiDou); Japan and India have also launched their own regionally focused systems. Commercial receivers are widely available that process different combinations of these GNSS signals in addition to GPS.

Proliferated systems in low Earth orbit such as Iridium and Starlink have demonstrated the ability to provide navigation solutions, and companies now produce far cheaper satellites through new commercial practices. SpaceX has also shown that frequent use of partially reusable vehicles can substantially lower the cost of launch. Finally, low-cost atomic clocks and terrestrial over-the-air transfer of time through these systems increases the options for distributing precision time to users.

Study Area: Alternative Positioning and Navigation

Using multiple sensors to obtain position and navigation data is often necessary when SATNAV sources are unavailable, although even optimal combinations cannot retain GPS-level accuracy on their own. The core of these integrated multi-sensor systems is an inertial navigation system (INS) of the greatest accuracy consistent with mission/platform size, weight, power, and cost (SWaP-C) constraints. However, no matter the cost, INS cannot provide high-precision positioning data indefinitely. Inertial sensors (gyros and accelerometers) experience errors that cause uncertainty to grow over time. As such, the INS must be augmented by one or more aiding sensors whose outputs are combined with INS data via software algorithm.

The Task Force identified two compelling INS product opportunities that appear to be technically ready for transition. The 2019 *DSB Task Force on Applications of Quantum Technologies* concluded that quantum inertial sensor technology is technically feasible, and that a DoD investment to productize a quantum accelerometer would provide a previously unavailable solid-state strategic-grade instrument.[1] Advances in fiber optic gyro technology are such that it should also be possible to develop a navigation-grade INS at tactical SWaP-C.

There are significant software requirements to integrate aiding sensors and INS data into a single position/navigation solution. This development has historically been repeated for each individual platform or weapon. Despite multiple DoD investments in creating government-owned modular open systems approaches, there has been limited success reusing integration software across platforms. Section 805 of the National Defense Authorization Act for Fiscal Year 2017 established a requirement for MOSA and government ownership of integration software.

Study Area: Precision Timing for DoD Missions

Today, globally coordinated time is available to anyone with a GPS receiver. GPS-provided timing is valuable to domestic critical infrastructure such as financial services, telecommunications, and electric utilities, as well as DoD users that do not typically require precision positioning data, including fixed site command and control centers. Mature clock technology provides performance options ranging from inexpensive quartz clocks that offer only short periods of quality time holdover to laboratory grade atomic clocks like those that set the international time standard.

Study Area: Operational Navigation Warfare

The Task Force focused on protecting U.S. PNT capabilities through hardening GPS, identifying alternative PN technologies, and securing timing; it also reviewed other aspects of navigation warfare which include operationalizing U.S. PNT and denying adversaries' PNT-enabled capabilities. Learning lessons from ongoing conflicts has taken on new urgency in this regard.

Task Force Recommendations

The Task Force recommendations, if implemented, will provide a proliferated PNT constellation with capability to meet current and near-future needs. Action on MGUE will speed production on the equipment necessary to use these signals. Policy leeway on the use of alternative SATNAV signals will offer additional options in the field, when necessary, as will development of fieldable alternative positioning and timing equipment. Finally, use of these systems and policies must be tested and exercised in realistic environments to achieve meaningful results.

[1] "Defense Science Board Report on Applications of Quantum Technologies," Defense Science Board, November 1, 2019. 32-33.

Appendix A. Terms of Reference

RESEARCH AND ENGINEERING

THE UNDER SECRETARY OF DEFENSE
3030 DEFENSE PENTAGON
WASHINGTON, DC 20301-3030

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For Open Publication
Dec 16, 2019
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DEC - 6 2019

MEMORANDUM FOR CHAIRMAN, DEFENSE SCIENCE BOARD

SUBJECT: Terms of Reference – Defense Science Board Task Force on Position, Navigation, and Timing Control

The United States Global Positioning System (GPS) has led the world in the development and applications of global precision position, navigation, and timing (PNT). The U.S. Air Force (USAF) developed the system in the 1970s after a successful technology demonstration that the U.S. Naval Research Laboratory (NRL) originally developed in the late 1960s as an alternative to Transit, the first space-based navigation system developed by the then-Advanced Research Projects Agency and John Hopkins University Applied Physics Laboratory. Transit was successfully fielded in the 1960s in support of the U.S. Navy submarine Polaris Ballistic Missile System (SSBN). The Transit system provided accurate SSBN location for the launching of Polaris missiles from arbitrary ocean locations around the world. The system was based on a constellation of Low Earth Orbit (LEO) satellites broadcasting very high frequency and ultra high frequency signals and exploiting the physics of frequency difference of arrival (FDOA) for providing time and location. The NRL GPS technology was based on using time difference of arrival from four satellites in Medium Earth Orbit (MEO), each flying precision quantum clocks. It was chosen over the Transit FDOA approach due to superior dynamic PNT potential.

Today, the USAF GPS system is the world's premier PNT system, providing users with single meter positioning and 10s of nanosecond timing accuracy to support a myriad of defense and commercial applications. The system has undergone a sequence of development and production upgrades on both the space and ground segments (control system and terminals) leading to the current generation of GPS-3A satellites and the emerging Next Generation Operational Control System ground control segment with the associated M-code user segment enhancements. While performance and resilience continue to improve, the system has matured to the point that these changes have resulted in incremental improvement to overall system performance. Of greater benefit for consumers has been the integration of the many foreign GPS-like systems—i.e., European Union Galileo, Russian Global Navigation Satellite System, and the Chinese BeiDou systems—as can be seen in the modern iPhone and Galaxy cell phones using multiple Global Navigation Satellite Systems plus cellular network data augmentation to get responsive and accurate positioning information. The current system has less susceptibility to jamming and spoofing, but challenges remain, including the slow fielding of user M-code capability, cyber, and kinetic threats. System performance in clear line-of-sight situations is good, but degradation can occur in canyons, cities, and high-signal, multipath environments. The cost of the system and ongoing upgrades have undergone significant growth making it hard to increase the density of satellites to address the more challenging environments.

At the same time, the commercial world and new space communication providers are now beginning to populate the LEO and MEO regimes with proliferated constellations whose plans include hundreds to thousands of satellites in these orbital regimes with the promise of providing high bandwidth and high connectivity in the most restrictive terrain and city environments using radio frequency (RF) signals from 1 gigahertz (GHz) to 40 GHz. Opportunities abound with enabling technology of software defined receivers and RF waveform generators, active phased array antennas in both the space and the user segments for multi-mission systems that can provide communications, PNT broadcast, and electronic warfare functions. In addition, with the large-scale production required, it offers the promise of low cost by taking advantage of production learning curves and economies of scale. A future multi-mission constellation that can transmit and receive RF signal across a broad spectrum will allow both the ability provide and deny communications and PNT globally and will provide support to all essential warfighting missions.

Given these opportunities, I am establishing a Task Force under the Defense Science Board (DSB) that will study the issue and send its advice and recommendation to the DSB for it, through discussion and deliberation in a properly noticed and open meeting. This study will identify and recommend specific architectures and operational approaches to enhance current PNT and support communications missions as well as provide ability to deny and confound other space based PNT systems over the next 10 years. Also, the Task Force will consider what synergy and dual use opportunities are possible for both PNT and communication missions across military, government infrastructure, and commercial applications. Key questions to be address include:

- What are the performance and resilience limits of the current GPS systems, and how is this expected to change over the next decade?

- What are the benefits and risks associated with employing military PNT systems that rely upon new commercial space communication systems to provide terrestrial and space PNT?

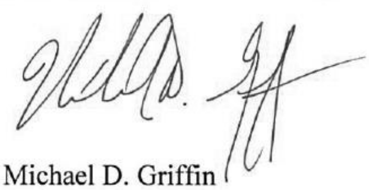
- What are the benefits and risks associated with utilizing architectures that rely upon RF array technology to provide PNT, along with advanced communication abilities? Consider the impact of RF frequency and waveform diversity on navigation, time distribution, and communication.

- What are the performance and resilience benefits of incorporating alternative means to acquire and update PNT information to accomplish military missions? These can include portable atomic clocks, imaged-based navigation, quantum sensors, or terrestrial-based navigation and timing distribution.

I will sponsor the study. I am recommending to the Chief Management Officer that Dr. William LaPlante and Mr. James Shields serve as the co-Chairmen of this study. Col Brent Grimes will serve as the Executive Secretary. Mr. Kevin Doxey will serve as the DSB Secretariat and Designated Federal Officer.

The Task Force members are granted access to those Department of Defense (DoD) officials and data necessary for the appropriate conduct of their study. I, as the Under Secretary of Defense for Research and Engineering, will serve as the DoD decision-maker for the matter under consideration and will coordinate decision-making as appropriate with other stakeholders identified by the study's findings and recommendations. The nominal start date of the study period will be within 3 months of signing this Terms of Reference, and the study period will be between 9–12 months. The final report will be completed within 6 months from the end of the study period. Extensions for unforeseen circumstances will be handled accordingly.

The Task Force will operate in accordance with the provisions of the Federal Advisory Committee Act (Title 5 United States Code (U.S.C), Appendix), the Government in the Sunshine Act (Title 5 U.S.C., Section 552b), and Title 41 Code of Federal Regulations, Sections 102-3.140 and 102-3.150, DoD Instruction 5105.04, and the Deputy Secretary of Defense memo "DoD Federal Advisory Committee Management Program," dated 6 August 2007. The Task Force does not have the authority to make decisions or recommendations on behalf of the DSB nor may it report directly to any Federal representative. DSB discussion and deliberation will be properly noticed and open, subject to the Government in the Sunshine Act. It is not anticipated that this study will need to go into any "particular matters" within the meaning of title 18, U.S.C., section 208, nor will it cause any members to be placed in the position of action as a procurement official.



Michael D. Griffin

Appendix B. Task Force Membership

Co-Chairs	
Mr. James Shields	Dr. Daniel Hastings

Task Force Members	
Dr. John Betz	Mr. George Klaus
Mr. D. Marshall Brenizer	Mr. Tony Kourepenis
Dr. Willem de Vries	Mr. Edward Powers
Dr. Brent Grime	Dr. J. Scott Stadler
Dr. Thomas Karr	Ms. Mandy Vaughn
Dr. Paul Kaminski	

Executive Secretary
Col Rojan Robotham, *USAF*

Government Advisors	
Dr. Tom Blenk, *JPEO AA*	Mr. Brian Stutz, *JNWC*
Mr. Ivan Franklin, *USA*	Mr. Michael Trzeciak, *USA*
Col Matthew Garvin, *USAF*	COL Jason Tussey, *USA*
Dr. Jeffrey Hebert, *USAF*	Maj Gen Steven Whitney, *USSF*
Mr. Paul Manz, *JPEO AA*	

DSB Secretariat
Ms. Elizabeth Kowalski, DSB Executive Director / Designated Federal Officer

SAIC Study Support	
Mr. Paul Normolle	Ms. Brenda Poole

Task Force Members (Prior to Secretary of Defense Zero-Based Review)[2]	
Dr. William LaPlante	Mr. Christopher Day
Mr. William Delany	Mr. Robert Nichols
Mr. David Van Buren	Mr. Vincent Vitto
Dr. Robert Wisnieff	

[2] This Task Force was originally chaired by Dr. William LaPlante and Mr. James Shields. A zero-based review of DoD advisory committees in February 2021 paused work and changed overall DSB membership. When the Task Force restarted in late 2022, Dr. LaPlante had joined the government as USD(A&S), and Dr. Daniel Hastings was asked to step in as co-chair. Several new members also joined the Task Force during this restart process.

Appendix C. Briefings Received

Meeting 1 (21-22 October 2020)

Threat Briefing
National Ground Intelligence Center

GPS Programmatic Overview
Office of the Asst. Sec. of the Air Force for Acquisition, Technology and Logistics

Meeting 2 (9-10 November 2020)

Global GNSS Technical and Business Status
Task Force Member

Timing and Transfer Alternatives to GPS
Task Force Member

OSD and Service PNT Open Architectures
Task Force Member

PNT / Navigation Warfare Policy
C3/C4 Directorates, DoD CIO

DSB Space Resiliency Study
Space Security and Defense Program

Meeting 3 (24 November 2020)

Joint Program Executive Office (Armaments and Ammunition) PNT Efforts
Task Force Member

U.S. Army PNT Efforts
Task Force Member

U.S. Air Force PNT Efforts
Task Force Member

Meeting 4 (13-14 January 2021)

System Level and Enabling Technologies
Draper Laboratory

Integrated PNT and GPS Integrity Monitor, Time Transfer and Ranging Over Alternative Physical Layers, and Gravity-Aided Inertial Navigation
Task Force Member

Anti-Jam / Anti-Spoof
MITRE

High Accuracy Location Determination Using Precision Astronomy and Earth Orientation Parameters
Task Force Member

Janus Software Defined Radio
MITRE

Use of Foreign SATNAV Signals in Military Terminals
Task Force Member

Department of the Navy PNT Efforts
U.S. Navy OPNAV N2/N6E4

Meeting 5 (1-2 December 2022)

Lessons Learned from Ukraine
National Ground Intelligence Center

Joint Program Executive Office (Armaments and Ammunition) PNT Update

Task Force Member

Office of the Under Secretary for Research and Engineering PNT Efforts
Task Force Member

U.S. Army PNT Update
Task Force Member

Department of the Navy - PNT Update
U.S. Navy OPNAV N2/N6E4

Meeting 6 (4-5 January 2023)

U.S. Air Force - PNT Update
Task Force Member

JANUS Software Defined Receiver Update
MITRE

Threat Briefing
National Space Intelligence Center

GPS Enterprise Update
U.S. Space Force Space Systems Command

Meeting 7 (9-10 February 2023)

Johns Hopkins University Applied Physics Laboratory PNT Programs
Task Force Member

PNT Programs Update
Draper Laboratory

Update on Timekeeping and Distribution
Task Force Member

Cybersecurity in Space
MIT Lincoln Laboratory

PNT Programs
DARPA

SDA Proliferated LEO
Task Force Member

SATNAV Situational Awareness
MITRE

Meeting 8 (23-24 March 2023)

PNT as a Service: Leveraging SATCOM for PNT
NAVSYS

Lessons Learned from Syria
USSOCOM

GNSS Operational Awareness Tool
Naval Research Laboratory

Quantum PNT Applications
OUSD(R&E)

PNT in the Cislunar Environment
NASA

MGUE Fielding Priorities
DoD CIO

Additional PNT Programs
DARPA

Meeting 9 (27-28 April 2023)

M-Code Keying and Contingency Recovery
GPS SE&I

Meeting 11 (9 June 2023)

Lightweight SATNAV Architecture
Air Force Research Laboratory

Appendix D. Acronym List

CSAC	Chip Scale Atomic Clock
DoD	Department of Defense
DSB	Defense Science Board
FY	fiscal year
GNSS	global navigation satellite systems
GPS	global positioning system
INS	inertial navigation system
MGUE	military GPS user equipment
MOSAs	modular open systems approaches
NAVWAR	navigation warfare
NDAA	National Defense Authorization Act
PN	position and navigation
PNT	position, navigation, and timing
SATNAV	satellite navigation
SWaP-C	size, weight, power, and cost
USD(R&E)	Under Secretary of Defense for Research and Engineering
USG	United States Government

Defense Science Board

DSB

Department of Defense