United States Government Accountability Office

Report to Congressional Committees

June 2023

GPS MODERNIZATION

Space Force Should Reassess Requirements for Satellites and Handheld Devices

Accessible Version

GAO-23-106018

GAO Highlights

Highlights of GAO-23-106018, a report to congressional committees

June 2023

GPS MODERNIZATION

Space Force Should Reassess Requirements for Satellites and Handheld Devices

Why GAO Did This Study

The Air Force launched the first GPS satellite capable of broadcasting the jam-resistant M-code signal in 2005. However, continued delays to the ground and user equipment segments prevent widespread use of the technology.

Congress included a provision for GAO to assess the cost, schedule and performance of GPS acquisition programs. This report assesses (1) risks and challenges to transitioning to a planned next-generation ground control system and how Space Force is mitigating them; (2) the extent to which Space Force identified and addressed risks affecting the space segment and delivery of M-Code capability; and (3) the progress DOD made in developing and integrating the M-code user equipment.

To conduct this work, GAO reviewed DOD's plans for GPS, its data on satellite reliability and launch schedules, and interviewed DOD officials.

What GAO Recommends

GAO is making two recommendations to DOD: (1) assess the number of satellites necessary to meet operational needs, and (2) either develop a sound business case for the M-code capable Increment 2 handheld, or do not initiate the effort. DOD concurred with both recommendations.

View GAO-23-106018. For more information, contact Jon Ludwigson at (202) 512-4841 or ludwigsonj@gao.gov.

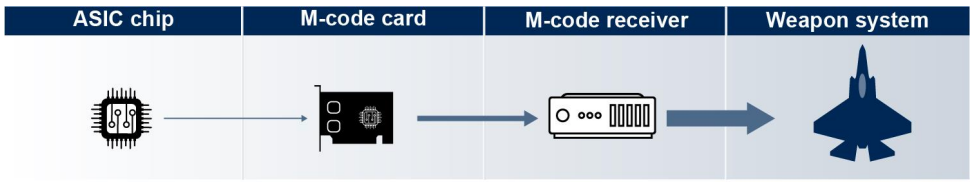
What GAO Found

GPS is the principal source of positioning, navigation, and timing information for the U.S. military and its partners. The Department of Defense (DOD) has worked for more than 2 decades to modernize GPS with a more jam-resistant, military-specific signal known as M-code. Space Force, part of the Department of the Air Force, is responsible for GPS modernization.

The GPS system consists of three segments that cooperate to provide M-code: a ground control segment, a space segment, and user equipment.

- **Ground.** In 2022, Space Force further delayed delivery of the ground control segment due to development challenges. This delay pushes delivery until December 2023 at a minimum. Space Force officials have not finalized a new schedule and acknowledged that remaining risks could lead to additional delays. GAO will continue to monitor Space Force's progress in adhering to its new schedule.
- **Space.** Space Force met its approved requirement for 24 M-code-capable satellites on orbit, but determined that it needs at least three more to meet certain user requirements for accuracy. Building and maintaining this larger constellation presents a challenge. GAO's analysis indicates it is not likely that 27 satellites will be available on a consistent basis over the next decade. Unless the Air Force assesses its operational need for satellites to establish a firm requirement for a 27-satellite constellation, other DOD efforts could take priority, leaving the warfighter with GPS user equipment performing below the required capability levels.
- **User equipment.** MGUE Increment 1 development progressed to the point where the military departments are ready to commence activities in support of testing and fielding it on the lead weapon systems. Delays and unexpected challenges could affect the fielding of capability for some systems. The figure below illustrates the integration process.

GPS User Equipment Integration



ASIC Application-Specific Integrated Circuit **M-code** Military code

Source: GAO analysis and representation of Department of Defense documentation. | GAO-23-106018

Space Force seeks to expand the use of M-code technology by developing a second increment consisting of an improved M-code chip and card, as well as a handheld receiver. Space Force lacks a major committed customer for the handheld receiver. The Army, the largest potential user of such a device, has its own plans for handheld receivers, and Marine Corps officials say the service is still considering its options. Without a sound business case for its proposed handheld product, Space Force risks expending significant resources without providing a benefit to military users.

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Abbreviations

ASIC	application-specific integrated circuit
DAPS	Dismounted Assured Positioning, Navigation, and Timing System
DOD	Department of Defense
EGI-M	Embedded GPS Inertial Navigation System – Modernized
GPNTS	GPS-based Positioning, Navigation, and Timing Service
GPS III	Global Positioning System III
GPS IIIF	Global Positioning System III Follow-on
JLTV	Joint Light Tactical Vehicle
MAGR-2K-M	Miniature Airborne GPS Receiver 2000 – Modernized
MAPS	Mounted Assured Positioning, Navigation, and Timing System
M-code	military code
MGUE	Military GPS User Equipment
MTA	middle tier of acquisition
NDAA	National Defense Authorization Act
OCS	Operational Control Segment
OCX	Next Generation Operational Control System

PNT	positioning, navigation, and timing
R-EGI	Resilient-Embedded GPS/Inertial Navigation System
SSC	Space Systems Command

U.S. GOVERNMENT ACCOUNTABILITY OFFICE
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June 5, 2023

Congressional Committees

The Department of Defense's (DOD) GPS remains the principal source of positioning, navigation, and timing (PNT) information for the U.S. military and North Atlantic Treaty Organization partners. DOD has been working for more than 2 decades to modernize DOD's use of GPS with a more jam-resistant, military-specific signal, referred to as military code (M-code), which is critical to maintaining the system's effectiveness in the face of adversary threats. While the Air Force launched the first GPS satellite capable of broadcasting the M-code signal in 2005, efforts led by the U.S. Space Force to develop modernized elements of GPS to use M-code are ongoing.

Space Force's GPS modernization efforts include the development of upgraded satellites, a modernized ground control system called the Next Generation Operational Control System, and user equipment, called M-code cards. Once Space Force's GPS development effort produces the M-code cards, the military departments are responsible for integrating these cards into specialized GPS receivers for use in military aircraft, ships, vehicles, and other weapon systems. Together, these cards and receivers will be capable of receiving and using the M-code signals broadcast by the GPS satellites. Since 2009, we have reported on the challenges DOD has experienced developing these systems.[1]

Section 1621 of the National Defense Authorization Act (NDAA) for Fiscal Year 2016 included a provision for GAO to report on, among other things, the cost, schedule, and performance of the GPS acquisition programs

[1]GAO, *GPS Modernization: Better Information and Detailed Test Plans Needed for Timely Fielding of Military User Equipment*, GAO-22-105086 (Washington, D.C.: May 9, 2022); ; 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); *Global Positioning System: Better Planning and Coordination Needed to Improve Prospects for Fielding Modernized Capability*, GAO-18-74 (Washington, D.C.: Dec. 12, 2017); *GPS: Actions Needed to Address Ground System Development Problems and User Equipment Production Readiness*, GAO-15-657 (Washington, D.C.: Sept. 9, 2015); *Global Positioning System: Challenges in Sustaining and Upgrading Capabilities Persist*, GAO-10-636 (Washington, D.C.: Sept. 15, 2010); and *Global Positioning System: Significant Challenges in Sustaining and Upgrading Widely Used Capabilities*, GAO-09-325 (Washington, D.C.: Apr. 30, 2009).

until they reach initial operational capability.[2] This report assesses (1) the risks and challenges Space Force identified to transitioning the ground control segment to the Next Generation Operational Control System and how it is mitigating them; (2) the extent to which Space Force identified and addressed risks affecting the space segment and delivery of M-code capability; (3) the progress DOD made in developing and integrating the first increment of M-code user equipment; and (4) the extent to which Space Force is managing risk in development of the second increment of M-code user equipment.

To conduct our work, we analyzed the GPS satellite constellation based on GPS reliability data provided by Space Force. We also reviewed pertinent documentation, such as cost, schedule, performance, and risk reports; and conducted interviews with relevant officials from DOD, the Army, Navy, Marine Corps, Air Force, and Space Force. For additional details on our scope and methodology, see appendix I.

We conducted this performance audit from April 2022 to June 2023 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Background

GPS consists of three segments—space, ground control, and user equipment. The space segment is a constellation of continuously broadcasting, orbiting satellites. The ground control segment commands and controls the satellites. The user equipment segment includes cards and receivers used by the military in aircraft, ships, land vehicles, munitions, and handheld devices that derive PNT data from the satellite signals. Since 2000, the Air Force (and later Space Force) have pursued a multi-billion dollar effort to modernize the three segments of GPS to provide new signals, enhance cybersecurity, and counter known threats. In August 2021, day-to-day responsibility for modernizing and sustaining

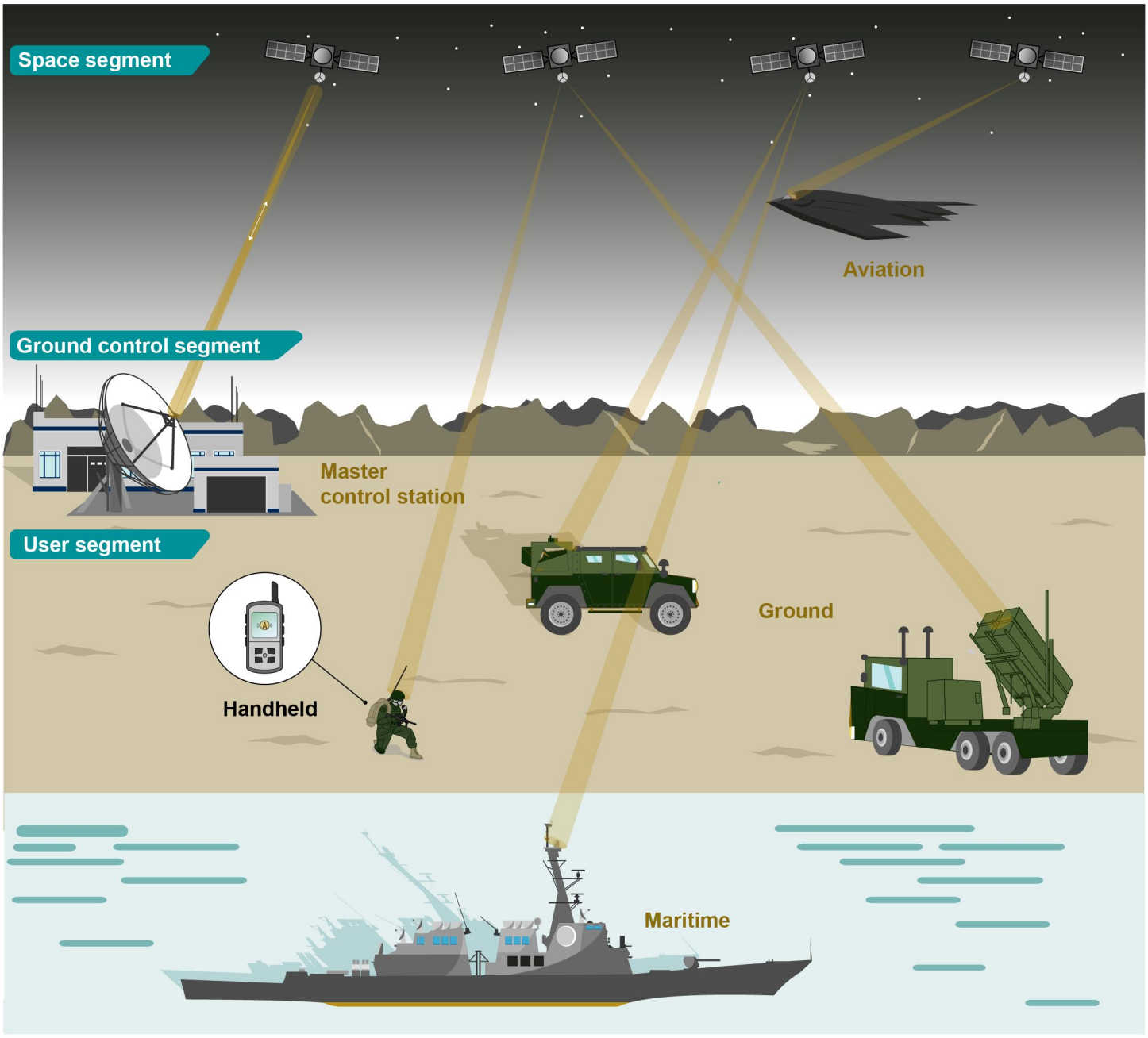
[2]Pub. L. No. 114-92, § 1621 (10 U.S.C. § 2281 note).

GPS transitioned from the Air Force to Space Force's Space Systems Command (SSC).

GPS Modernization

Collectively, the ongoing GPS acquisition efforts aim to sustain the existing GPS capability and enhance the current system by adding M-code capability. M-code is a stronger, encrypted, military-specific GPS signal designed to meet military PNT information needs. M-code will help military users overcome attempts to block the GPS signal, known as jamming, by using a more powerful signal with a broader radio frequency range. It will also protect against false GPS signals, known as spoofing, by encrypting the signal. Figure 1 shows the GPS satellite, ground control, and user equipment segments that function together as an operational system.

Figure 1: GPS Segments and Platform Types

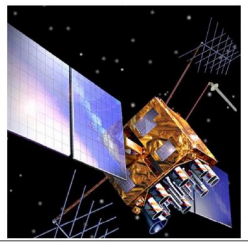
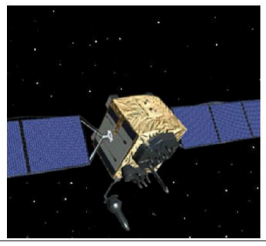


Source: GAO analysis and representation of Department of Defense documentation. | GAO-23-106018

M-code Space and Ground Segment

The GPS satellite constellation is composed of four generations of satellites with varying capabilities and design lives. The first satellite able to transmit the M-code signal entered orbit in 2005 and 25 of the 31 satellites in the GPS constellation are M-code capable. Ensuring that the constellation maintains and expands this M-code capability requires launching additional M-code capable satellites. SSC manages the acquisition of the space segment portion of this effort through two programs known as the GPS III and GPS III Follow-On (GPS IIIF) satellite programs. These programs are replacing existing satellites as they near the end of their intended operational life. Figure 2 describes the evolution of M-code-capable GPS satellite generations, including capabilities and life-span estimates.

Figure 2: Active and Future M-code GPS Satellites

	GPS IIR-M	GPS IIF	GPS III	GPS IIIF
				
Number	7 operational	12 operational	6 operational; 4 not yet launched	Up to 22
Design life[a]	7.5 years	12 years	15 years	15 years
Mean life estimate[b]	21.6 years	24.6 years	16.7 years	16.2 years
Launch	2005 - 2009	2010 - 2016	2018 - 2025	Planned to begin from late 2026
Capabilities	• Second civilian signal • Second military signal (M-code) for enhanced jam resistance • Ability to increase signal power to improve resistance to jamming	**IIR-M capabilities, plus:** • Third civilian signal for transportation safety requirements • Improved accuracy, signal strength, and quality • Advanced atomic clocks	**IIF capabilities, plus:** • Fourth civilian signal to enable GPS interoperability with foreign satellite navigation systems • Enhanced signal reliability, accuracy, and integrity • Stronger military signal to improve jamming resistance	**III capabilities, plus:** • Steerable, high power M-code signal, known as Regional Military Protection • Search and rescue capability for detection and location of emergency beacons

Source: GAO analysis of Department of Defense information (data); U.S. government (images). | GAO-23-106018

Note: In addition to the M-code capable satellites depicted in this table, the space segment also contains 6 non-M-code GPS IIR satellites.

[a]Design life is the period of time during which the satellite is expected to meet its mission objectives.

[b]Mean life estimate figures reflect the average of the predicted lifespans for the satellites of a given GPS satellite generation.

Modernizing the GPS constellation also requires the development of a ground control system that can enable the launch and control of both existing and new, more powerful satellites. DOD has been working to develop the modernized ground control segment since 2010. In 2020, SSC provided two modifications to the current GPS ground control system – the Operational Control Segment (OCS) –to enable, among other things, some operational control of a subset of M-code capabilities, and thereby support the testing and fielding of M-code user equipment. SSC has since continued to develop the system it eventually expects to

provide the full M-code capability. These efforts to modernize the ground segment are managed through the GPS Next Generation Operational Control System (OCX) program, which plans to enable full M-code capabilities, as well as provide improved cybersecurity. SSC's OCX efforts are structured through a series of block upgrades, and are primarily software-based, but they also include new hardware and upgrades to monitoring stations throughout the world. Raytheon Technologies, the prime contractor for OCX, is developing OCX in a series of blocks. See Table 1 for a description of these efforts.

Table 1: Current GPS Ground Control Modernization Program

Program	Description	Total program costs as of January 2023
Next Generation Operational Control System (OCX) Blocks 0, 1 and 2	**Block 0**—provides the launch and checkout system and supports initial testing of GPS III satellites. GPS III satellites cannot launch without OCX Block 0. It also provides modern cybersecurity capabilities, a key advancement in securing the system. The contractor delivered Block 0 in October 2017. Space Force has used Block 0 to launch six GPS III satellites as of January 2023. **Blocks 1 and 2**—will provide command and control for previous generations of satellites and GPS III satellites, monitoring and control for both current and modernized signals, and full M-code broadcast capability.	**$7 billion**
OCX Block 3F	**Block 3F**—will build on OCX Blocks 1 and 2 software to add capabilities to control and use the GPS IIIF space segment and future user equipment capabilities. Space Force awarded a development contract for OCX Block 3F to Raytheon in April 2021.	**$469 million**

Source: GAO analysis of Department of Defense Data. | GAO-23-106018

Note: All dollar amounts are in fiscal year 2023 dollars.

The users of OCX are satellite operators from Space Force's 2nd and 19th Space Operations Squadrons. The operators will assist with developmental testing of OCX after receiving training from Raytheon. The operators are also responsible for transitioning the GPS satellite constellation from OCS to OCX.

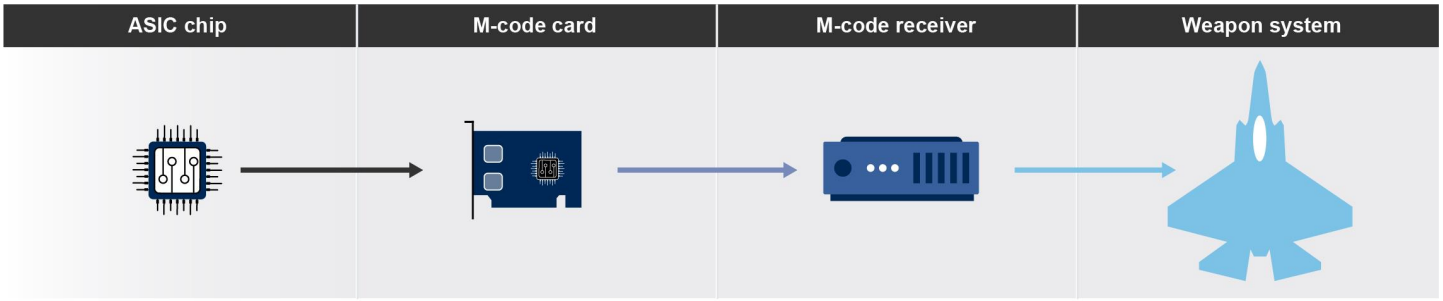
M-code User Equipment Segment

In order for warfighters to use the M-code signal transmitted by the space segment and controlled by the ground segment, the military departments will need to upgrade existing weapon systems and platforms with M-code capable user equipment. As we have previously reported, approximately 700 different types of weapon systems such as aircraft, ground vehicles, ships, and other equipment will ultimately require M-code capable user

equipment. [3] The military departments will outfit this wide range of systems with modernized, M-code capable GPS receivers. Eventually, the total number of GPS receivers purchased by the DOD could number up to 1 million.[4]

GPS user equipment consists of three key components: a microelectronic circuit chip, a card that uses the chip, and a receiver that provides the ability to use the card. The development and manufacture of each component is a key part of the overall modernization effort. One key element in GPS modernization has been the development of an application-specific integrated circuit (ASIC), a type of microelectronic component specifically designed to process and execute M-code functions. These chips are then integrated into a card that processes M-code signals to provide PNT information. The military departments will then integrate each specialized M-code card into a receiver that provides an interface with the host weapon system. See Figure 3 for a simplified depiction of GPS user equipment integration for one system.

Figure 3: GPS User Equipment Integration



ASIC Application-Specific Integrated Circuit
M-code Military code

Source: GAO analysis and representation of Department of Defense documentation. | GAO-23-106018

[3]GAO-22-105086.

[4]The Ike Skelton National Defense Authorization Act for Fiscal Year 2011, Pub. L. No. 111-383, § 913 (10 U.S.C. 2281 note). provides that none of the funds authorized to be appropriated or otherwise made available under the act or any other act for DOD may be obligated or expended to purchase GPS user equipment after Fiscal Year 2017 unless the equipment is capable of receiving M-code. The Secretary of Defense may waive this limitation under certain circumstances or certain exceptions may apply. Concurrent with M-code card development delays, DOD has issued waivers for this requirement for the hundreds of types of weapon systems that will eventually integrate M-code cards.

Military GPS User Equipment Increment 1

Space Force's Military GPS User Equipment (MGUE) program is developing the first generation of M-code capable user equipment. In January 2017, DOD approved the MGUE Increment 1 program to begin development of an ASIC chip and receiver cards that the military departments could then integrate into receivers developed for this purpose. SSC initially awarded contracts to three different contractors—L3Harris, Raytheon, and Rockwell Collins (later BAE Systems)—to develop Increment 1 M-code cards.

Critical to the development of MGUE Increment 1 is the production of the ASIC chip. GlobalFoundries, the sole manufacturer of these chips, is in the process of phasing out production of these chips because more advanced technologies now dominate the commercial microelectronics market. M-code cards developed under the MGUE Increment 1 program, as well as derivative versions of these cards, all require increment 1 ASICs specially designed for them, with no potential for an off-the-shelf replacement. Beginning in 2019, the Defense Logistics Agency and officials from the Office of the Under Secretary of Defense for Acquisition and Sustainment developed plans for a bulk buy of nearly 1 million chips. They estimated that this would provide for DOD's needs through approximately 2028. DOD awarded contracts for this bulk buy in 2021-2022.

The MGUE Increment 1 program is developing two card types—one for use in ground-based weapons systems such as combat vehicles, which we refer to as the ground card, and another for use in aviation and maritime weapons systems, which we refer to as the aviation/maritime card. The program initially included five card development efforts through three contractors. But, over time the scope of the program narrowed and contractors limited their involvement in aspects of the development effort. Today, the program primarily consists of the L3Harris-designed ground card, and the Raytheon-designed aviation/maritime card.

Each of the initial contractors for the MGUE Increment 1 program, including those who are no longer participating, is also developing derivative cards. Derivative cards use the same ASIC as their Increment 1 parent cards, as well as much of the same software. Contractors' derivative cards can vary in size and technical capability, however, allowing them to meet specific needs of different receivers and specific uses. Derivative cards must still have their designs certified and authorized by the Air Force and Space Force, however.

The MGUE Increment 1 program office initially defined completion based on four exit criteria that required operational testing approved by the Director, Operational Test and Evaluation for each card across multiple platforms. Development delays, rising program costs, and changes to the contractors' marketing and production plans forced changes to these criteria. In August 2020, the Air Force reduced the exit criteria. Changes included:

- For the Raytheon-designed aviation/maritime card, the program requires operational testing, with oversight by the Director, Operational Test and Evaluation, only for the two lead platforms testing the card. The Air Force will test this card on its B-2 Spirit bomber and the Navy will test the card on an *Arleigh Burke* class destroyer.
- For the L3Harris-designed ground card, the program now requires only a field user evaluation with no Director, Operational Test and Evaluation oversight. The Increment 1 program initially planned to conduct evaluations on the Army's Stryker and the Marine Corps' Joint Light Tactical Vehicle (JLTV). In March 2021, however, Space Force and Army agreed that the JLTV field user evaluation would meet the Army's test objectives for the Stryker and elected to conduct only the JLTV evaluation.

As a result of the various types of cards that have been developed within the MGUE program and as derivatives, the military departments have options as they proceed with receiver development. For each weapon system, when the military departments upgrade to M-code, they can select an Increment 1 card, a derivative card based on one of the Increment 1 cards, or pursue additional development of a different card at their own expense.

Military GPS User Equipment Increment 2

Space Force is executing the MGUE Increment 2 effort to develop a smaller, more power efficient ASIC that is based on a manufacturing process that will have sufficient commercial interest to avoid the scarcity issues that led to the Increment 1 bulk buy. The Increment 2 ASIC combines a series of commercial off-the-shelf designs with sensitive military functions added to the programming later.[5] SSC plans to use these size and power advantages to develop a card specifically for

[5]GAO-21-145.

handheld devices and precision-guided munitions. The Air Force approved the acquisition strategy for MGUE Increment 2 in November 2018. The effort's acquisition strategy is to pursue two middle tier of acquisition (MTA) rapid prototyping efforts.[6]

The first MTA effort, estimated to cost approximately $1.4 billion, involves developing the Next-Generation ASIC and integrating it with a smaller M-code card. Raytheon, BAE, and L3Harris are each developing an Increment 2 card. The effort completed preliminary design reviews for each vendor's chip in mid-2021 and conducted preliminary design reviews on the cards in 2022. Though the effort only seeks to develop a chip and card, it specifically tailored its requirements to meet certain performance parameters for subsequently developed handheld receivers and munitions.

The second MTA effort, estimated at $149.2 million in 2020, will build off the chip and card to develop a handheld, M-code capable receiver. Following a risk reduction phase, SSC plans to initiate this effort shortly after the chip-and-card effort complete its critical design review in the second half of fiscal year 2023.

M-code Receiver Development

The military departments are procuring or developing several different models of M-code capable receivers for use with either Increment 1 cards or a derivative card. The military departments are tailoring these receivers to meet the varying needs of systems that operate in the ground, aviation, and maritime domains. In addition, the military departments developed some receivers to process both M-code and alternate PNT information derived from other sensors or equipment, which we refer to as multi-PNT

[6]Section 804 of the National Defense Authorization Act for Fiscal Year 2016, Pub. L. No. 114-92 (2015) (10 U.S.C. §2302 note) required DOD to issue guidance establishing two new streamlined acquisition pathways for DOD—rapid prototyping and rapid fielding—under the broader term "middle tier of acquisitions." The objective of a rapid prototyping program is to field a prototype that can be demonstrated in an operational environment and provide for a residual operational capability within 5 years of the program start date. These acquisition pathways are distinct from the traditional acquisition system for major defense acquisition programs in that they allow for programs to be exempted from certain acquisition and requirements processes normally followed for such acquisitions. GAO, *Middle-Tier Defense Acquisitions: Rapid Prototyping and Fielding Requires Changes to Oversight and Development Approaches*, GAO-23-105008 (Washington, D.C.: February 7, 2023).

receivers.[7] We have previously reported on development of alternate PNT systems and receivers.[8]

Some receiver development efforts for weapon systems are dependent on Space Force providing fully functional M-code cards in order to conduct developmental and operational testing. This is true for the receivers associated with the Air Force and the Navy's lead platforms, known as the Miniature Airborne GPS Receiver 2000 – Modernized (MAGR-2K-M) and the GPS-based Position, Navigation, and Timing Service (GPNTS), respectively. Both departments also have other receivers under development using derivative cards but must complete integration and testing of the receivers on the lead platforms.

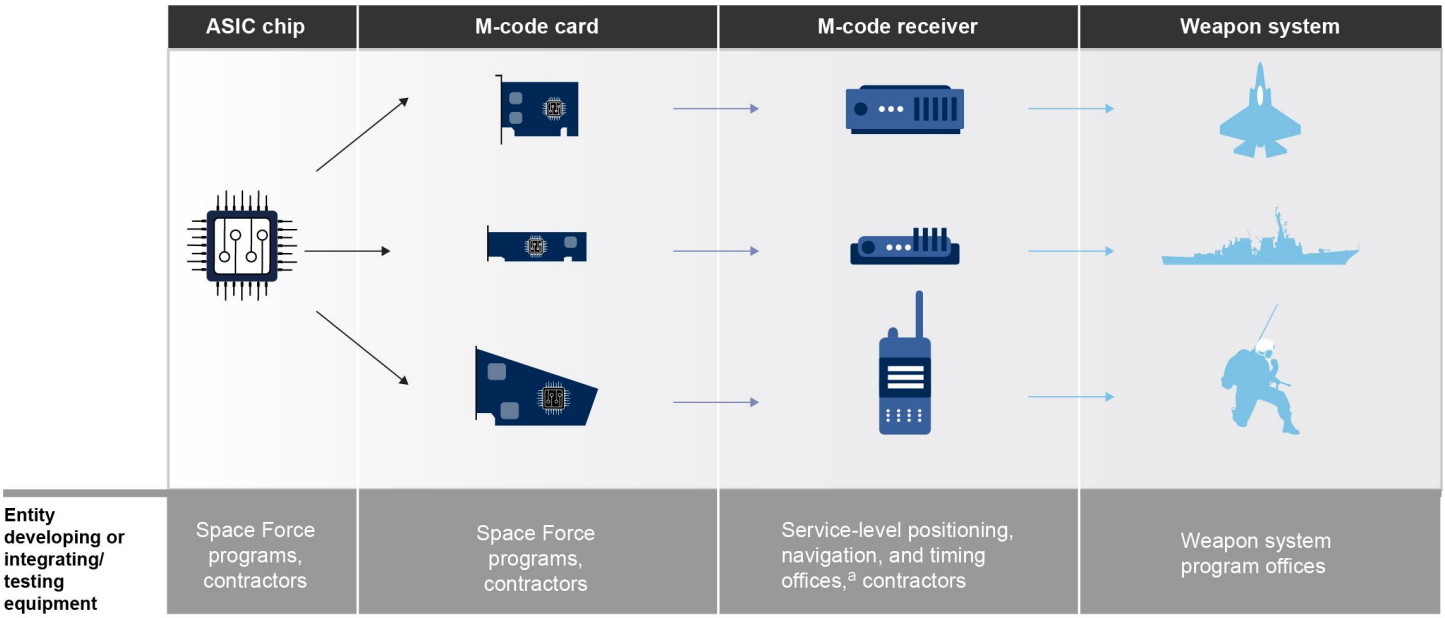
Army receiver efforts have been less dependent on Space Force. Since 2020, the Army has developed a family of mounted and dismounted receivers using a derivative card. BAE developed this card based on its work developing a ground card under the MGUE Increment 1 program before it ceased participating in that portion of the program.

See figure 4 for a simplified depiction of entities involved with receiver development.

[7]It is possible to deliver this capability at the card level as well, as some derivative cards do and the Increment 2 card also plans to do.

[8]GAO, *GPS Alternatives: DOD is Developing Navigation Systems but Is Not Measuring Overall Progress.* GAO-22-106010 (Washington, D.C.: August 5, 2022).

Figure 4: GPS User Equipment Integration and Receiver Development Authorities



ASIC Application-Specific Integrated Circuit
M-code Military code

Source: GAO analysis and representation of Department of Defense documentation. | GAO-23-106018

[a]Includes offices such as: Air Force Positioning, Navigation, and Timing (PNT) Program Office, Navy Communications and GPS Navigation Program Office, Army Assured Airspace Access Systems, and Army Project Manager for Positioning, Navigation, and Timing.

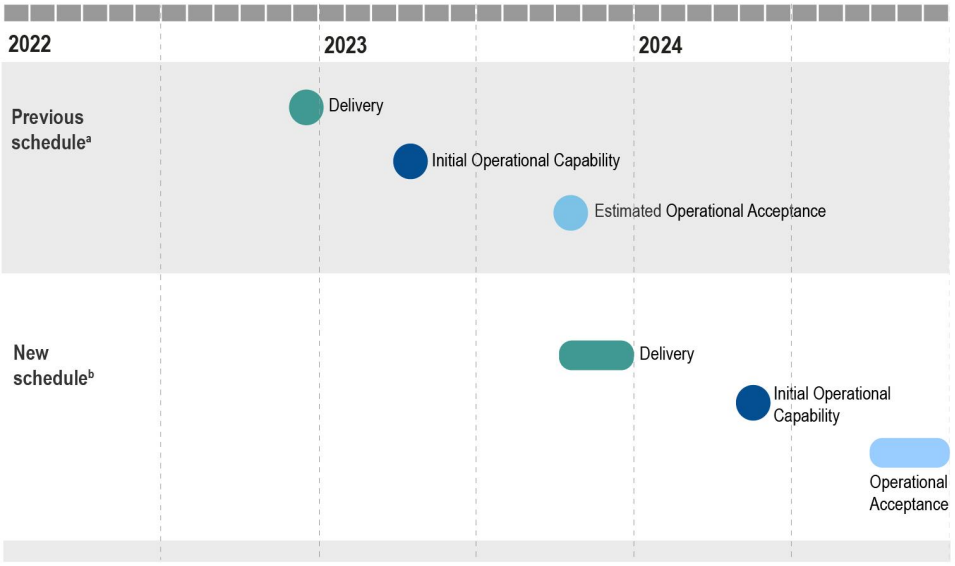
Space Force Delayed Delivery of OCX Ground System to Address Challenges

Space Force Further Delayed Delivery of OCX Due to Multiple Challenges

In December 2022, Space Force estimated that Raytheon would deliver OCX Blocks 1 and 2 from October to December 2023, a 10- to 12-month delay from a previous goal of December 2022.[9] This most recent delay is due to challenges with software development, schedule compression, and training. As a result, these delays will push the system's initial operational capability milestone from April 2023 to May 2024. Figure 5 shows the previous schedule and the current revised schedule.

[9]We previously reported that the OCX program had three major schedule revisions prior to 2022. These revisions occurred due to issues with program management and technical challenges and the need to address a cybersecurity risk. In the latter case, IBM sold the server product line used by the program to Lenovo, a Chinese corporation, which DOD determined created a cybersecurity risk. Consequently, in March 2020, the OCX program modified an existing contract with Raytheon to replace the IBM hardware. According to program documentation at the time, this $359 million contract modification added 10 months to the development schedule. GAO, *Weapon Systems Annual Assessment: Updated Program Oversight Approach Needed,* GAO-21-222 (Washington, D.C.: June 8, 2021); and *Global Positioning System: Updated Schedule Assessment Could Help Decision Makers Address Likely Delays Related to New Ground Control System,* GAO-19-250 (Washington, D.C.: May 21, 2019).

Figure 5. Next Generation GPS Operational Control System (OCX) Schedule Comparison



Source: GAO representation of Department of Defense information. | GAO-23-106018

[a]The previous schedule is as of August 2022

[b]The new schedule is as of February 2023

Space Force delayed delivery of OCX Blocks 1 and 2 due to the need for additional time to address several challenges.

- **Software development producing more deficiencies than expected.** The contractor, Raytheon, faced unanticipated challenges during the software qualification testing of OCX in 2022. The purpose of this testing is to ensure the system works as intended and meets the requirements before proceeding to developmental testing. The GPS System Simulator, which Raytheon uses for this phase of testing, also experienced a technical issue that caused the system to malfunction when run for long periods. According to program officials, Raytheon paused testing for 2 months to fix this issue.

  Once the issue was resolved, Raytheon discovered more deficiencies than anticipated during subsequent software qualification testing. These deficiencies included errors uploading navigation data to satellites in a simulated environment. The ability to upload this data is an essential function of the ground control system. As of September 2022, approximately 50 percent of software passed testing, lower than the program's goal of 80 percent. This low pass rate and the need to fix critical software deficiencies posed a risk to the delivery of OCX.

Raytheon attempted to resolve these challenges by increasing the resources for software testing in 2022. In addition to the GPS System Simulator, Raytheon used additional computer systems for software development. These systems included the Near Ops Environment, which is a duplicate of the OCX Blocks 1 and 2 system meant for the nascent OCX Block 3F program to use for Block 3F development. Raytheon also used a portion of the Alternate Master Control Station, which is the backup OCX system meant for installation at Vandenberg Space Force Base.

Raytheon also increased the number of staff for software testing in preparation for and during the software qualification testing. Raytheon had decreased staff on the program in the months prior to this test event. According to program officials, this was part of the original plan. As testing began and additional deficiencies were discovered, however, Raytheon began to increase staffing again. Program officials also told us Raytheon added additional shifts to increase the pace of testing.

In addition, Raytheon and the program office stated that they focused on fixing only those software deficiencies that relate directly to contract requirements, which we refer to as critical deficiencies. As of December 2022, program office officials told us there were 116 critical software deficiencies that relate to 219 requirements. These critical deficiencies are a subset of the about 6,000 deficiencies in the backlog. Raytheon representatives said many of the deficiencies in the backlog were not related to issues with requirements and may be duplicates or related to documentation. Program officials said that Raytheon would address additional deficiencies under the follow-on contract modification for interim contractor support after delivery.

- **Schedule compression leading to increased concurrency.** As development took longer than planned due to software challenges, the program compressed the schedule in an attempt to meet previously established milestone dates, which introduced significant concurrency between development and testing. This compression left no margin to manage software development issues, as testing overlapped with development. For example, the program scheduled several events to run at the same time, including conducting software qualification testing, training satellite operators on the system so they can conduct testing, and preparing for the constellation transition.

  The concurrency posed risks to the program. Test officials expressed concern about parallel testing, which could lead the program to reduce the scope of testing or skip some tests. For example, the program scheduled cybersecurity testing to occur concurrently with

developmental testing. Test officials said it is challenging to test for cyber vulnerabilities at the same time as testing for functionality of the system because cybersecurity testing creates instability in the system. Test officials told us they were also concerned that the program might reduce test procedures due to lack of time or the need to address functionality issues during this test event.

- **Technical manuals not meeting operator needs.** Additional delays occurred due to the need for Raytheon to revise the technical orders, which function as operators' manuals for OCX. The operators from 2nd Space Operations Squadron use these technical manuals to run and maintain the system and for operator training material. The operators deemed Raytheon's original drafts insufficient because, according to the operators, these manuals did not include routine satellite procedures or information on how to handle anomalous satellite activity, essential components of satellite operations. Space Force determined that the technical manual changes that the operators requested were outside the scope of the current contract with Raytheon. The program office is currently negotiating a contract modification to revise the manuals, which Raytheon expects to complete in March 2023.

  As a result of delays in finalizing these manuals, Space Force delayed training the first cadre of operators. According to Space Force officials, Raytheon will train this cadre, which will then train the rest of the unit. Trained operators from the first cadre will also support developmental testing of OCX and begin the constellation's transition to the new system. Operators told us they are concerned about the time it will take to develop a training program and train a full crew of operators, as performing these duties must occur in addition to managing the existing system. Operators also told us that, even upon receipt of revised manuals, training a full crew to operate OCX would not be possible until 5 months after the delivery date, in part, due to competing priorities.

  To mitigate these challenges, the operators are training staff on an OCX simulator, which operators believe will prepare them for full OCX training. Operators said that they also communicate with the OCX program office about providing more notice of scheduled events so that the operators can plan for and manage their workload.

The 10- to 12-month delay recognizes that Raytheon requires more time to address the challenges associated with software deficiencies, concurrency of development and testing efforts, and revising the technical manuals. In addition to the challenges described above, according to

program officials, a 2023 budget shortfall of $74.3 million will further complicate the schedule for development.

Delaying Delivery Does Not Resolve All Risks for OCX Schedule

While Space Force has not finalized a new schedule for the program, officials acknowledged that the expected delays reflect slower-than-expected progress, and there are still risks to the program. If testing reveals additional deficiencies or any other unexpected issues arise, the program may delay the delivery further because little margin remains in the proposed schedule. In prior work, we found that software development is often challenging for DOD weapon system programs, including challenges completing software development in time for developmental testing and integrating software with hardware.[10] Given that these aspects are necessary for OCX Blocks 1 and 2, software development may continue to pose risks to OCX.

The schedule delays extend the time in which Space Force must rely on the current control system, which cannot use the full capability of M-code. Prior modifications to the current ground system enable basic use of M-code, but full use of M-code is not possible until the transition to OCX. The delay increases the already significant misalignment of OCX with the space and user equipment segments, as GPS III satellites and M-code-capable user equipment are in place but cannot use the full capabilities of M-code.

Because further development of OCX is intended to be integrated with and, effectively, built on top of the work in Blocks 1 and 2, the delays to Block 1 and 2 add risk to development of Block 3F. OCX Block 3F is the enhanced ground system required to launch and control GPS IIIF satellites. However, since Blocks 1 and 2 are not yet complete, they do not provide a stable baseline for Block 3F development. OCX Block 3F program officials told us that the program plans to adjust its schedule based on OCX Block 1 and 2 schedule changes. According to officials from OSD's Office of the Director for Developmental Test, Evaluation, and Assessments, there have already been multiple changes to the OCX

[10]GAO, *Weapon Systems Annual Assessment: Challenges to Fielding Capabilities Faster Persist,* GAO-22-105230 (Washington, D.C.: Jun. 8, 2022); and *Weapon Systems Annual Assessment: Updated Program Oversight Approach Needed,* GAO-21-222 (Washington, D.C.: June 8, 2021).

Blocks 1 and 2 software. Further changes could result in additional work for the OCX Block 3F development effort to adapt to the changes being made to Blocks 1 and 2. OCX Block 3F program officials stated that the program regularly meets with the OCX Blocks 1 and 2 program to reduce risk through cooperative effort. Program officials noted that the lead contractor, Raytheon, plays a large role in synchronizing the two programs' efforts.

The delay in delivery of Blocks 1 and 2 also delayed the transition of contractor personnel and other resources from Blocks 1 and 2 to the Block 3F effort. Raytheon had to retain personnel on OCX Blocks 1 and 2 that it planned to transition to Block 3F. Defense Contract Management Agency officials reported that they expect staff availability to continue to affect the OCX Block 3F program at least until the point at which OCX Blocks 1 and 2 are delivered to Space Force. Delays in the completion of OCX Blocks 1 and 2 also resulted in interruptions to the OCX Block 3F program's access to the Near Ops Environment.

The OCX Block 3F program is working to mitigate schedule risks by delivering capabilities incrementally. Incremental development allows the program to focus on discrete portions of capability, which assists in delivering capabilities more quickly. From its beginning, the OCX Block 3F program planned to deliver its capabilities in three sequential capability releases, prioritizing the first release, which delivers the ability to launch GPS IIIF satellites. This capability is currently scheduled to deliver in the second quarter of fiscal year 2024. Space Force intends this delivery to enable pre-launch preparations and exercises for GPS IIIF satellites, while the program continues to develop the control software. The second and third capability releases deliver a boosted M-code signal, called Regional Military Protection, and other modernized capabilities. The program intends all three increments to complete before the first GPS IIIF satellite launch in fiscal year 2027. We will continue to monitor Space Force's progress adhering to its new schedule.

Space Force Took Steps to Mitigate Some Space Segment Risks, but Current

Requirements and Future Needs Are Not Aligned

Space Force satisfied the requirement for full operational capability that the GPS space segment include at least 24 M-code capable GPS satellites. At the same time, however, Space Force identified an approved requirement for M-Code user equipment that would need 27 M-code satellites. Projections indicate that Space Force can provide an active constellation of 24 M-code capable satellites with reasonably high confidence, contingent on Space Force successfully mitigating risk to ongoing acquisition programs. Launching and preserving an active constellation of 27 M-code capable GPS satellites, however, presents a greater challenge. While Space Force identified shortfalls to the 27 M-code capable satellite GPS constellation as a risk, this preferred operational capability is not an approved requirement and would require additional, potentially costly, measures to allow for such capabilities over time.

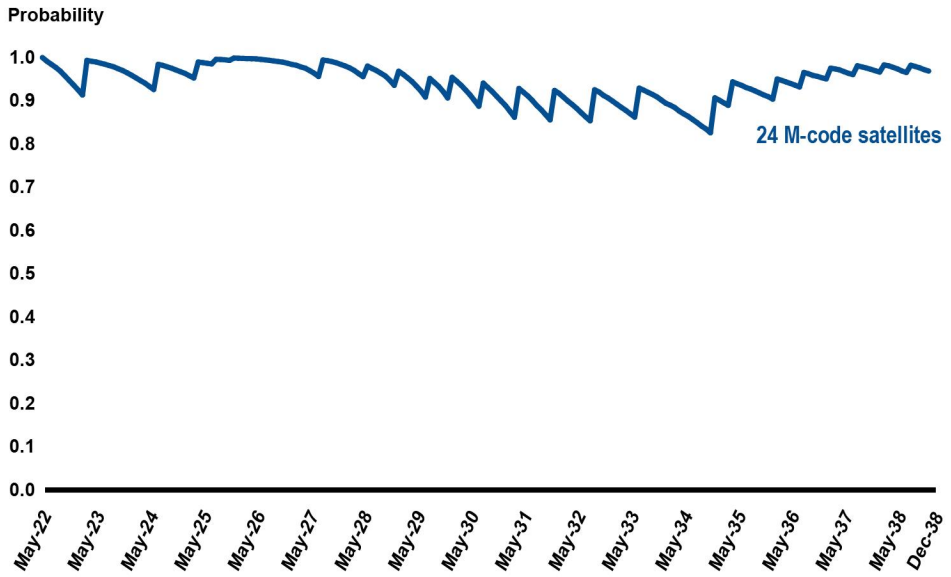
Space Force Is Addressing Risks to Preserving 24 Satellites on Orbit

Space Force successfully met the full operational requirement for the GPS space segment of at least 24 operational M-code capable satellites on orbit in 2022. Projections indicate a high probability that Space Force will continue to meet this requirement at least through the end of the 2020s. To meet this minimum number, Space Force must continuously produce and launch new satellites to replace older ones as they reach the end of their operational lives.

Projections based on Space Force's most recent GPS satellite reliability data and future satellite launch schedules indicate that the GPS constellation should maintain at least a 95 percent probability of 24 operational M-code capable satellites for most of the remainder of the

2020s.[11] These projections also indicate that, from early 2030 through 2036, this probability will decline, but will remain above 80 percent. During this time, increasing numbers of older satellites—most particularly of the IIR-M series—will reach the end of their projected operational life spans. Figure 6 below illustrates this probability over time.

Figure 6: Probability of Preserving a 24-satellite M-code Capable GPS Constellation



Source: GAO analysis of Department of Defense data. I GAO-23-106018

[11]Prior GAO reporting on GPS constellation availability assessed the constellation against a 95 percent probability of 24 GPS satellites because this is DOD-established standard to which the US government is committed for the operational availability of 24 satellites for the civilian and pre-M-code military positioning service. However, DOD has not established a probability standard for the GPS space segment's full operational capability of 24 M-Code capable satellites. It remains a useful benchmark for a reasonably high level of confidence in achieving a particular level of performance. GAO-18-74; GAO-15-657; GAO-10-636; GAO-09-325

Accessible Data for Figure 6: Probability of Preserving a 24-satellite M-code Capable GPS Constellation

Date	May 2022 - 24 PNT - M-Code
5/1/2022	1
6/1/2022	0.9909
7/1/2022	0.9826
8/1/2022	0.9737
9/1/2022	0.9665
10/1/2022	0.9587
11/1/2022	0.9475
12/1/2022	0.9371
1/1/2023	0.923
2/1/2023	0.9085
3/1/2023	0.9924
4/1/2023	0.9899
5/1/2023	0.9874
6/1/2023	0.9855
7/1/2023	0.9833
8/1/2023	0.9809
9/1/2023	0.9778
10/1/2023	0.9742
11/1/2023	0.9686
12/1/2023	0.9635
1/1/2024	0.9589
2/1/2024	0.954
3/1/2024	0.9488
4/1/2024	0.9424
5/1/2024	0.9345
6/1/2024	0.9253
7/1/2024	0.9848
8/1/2024	0.9831
9/1/2024	0.9813
10/1/2024	0.9781
11/1/2024	0.9736
12/1/2024	0.9705
1/1/2025	0.9661

Date	May 2022 - 24 PNT - M-Code
2/1/2025	0.9623
3/1/2025	0.9583
4/1/2025	0.9892
5/1/2025	0.9878
6/1/2025	0.9859
7/1/2025	0.9837
8/1/2025	0.9961
9/1/2025	0.9957
10/1/2025	0.9952
11/1/2025	0.9943
12/1/2025	0.9987
1/1/2026	0.9984
2/1/2026	0.9979
3/1/2026	0.9975
4/1/2026	0.9971
5/1/2026	0.9961
6/1/2026	0.9954
7/1/2026	0.9946
8/1/2026	0.994
9/1/2026	0.9923
10/1/2026	0.9905
11/1/2026	0.9882
12/1/2026	0.9847
1/1/2027	0.9821
2/1/2027	0.9794
3/1/2027	0.9756
4/1/2027	0.9709
5/1/2027	0.9659
6/1/2027	0.9593
7/1/2027	0.9501
8/1/2027	0.9944
9/1/2027	0.993
10/1/2027	0.9916
11/1/2027	0.9896
12/1/2027	0.9866
1/1/2028	0.9829

Date	May 2022 - 24 PNT - M-Code
2/1/2028	0.9791
3/1/2028	0.9741
4/1/2028	0.9673
5/1/2028	0.959
6/1/2028	0.9823
7/1/2028	0.9771
8/1/2028	0.9721
9/1/2028	0.9658
10/1/2028	0.957
11/1/2028	0.9471
12/1/2028	0.9368
1/1/2029	0.9708
2/1/2029	0.9637
3/1/2029	0.9549
4/1/2029	0.9459
5/1/2029	0.9369
6/1/2029	0.9243
7/1/2029	0.9116
8/1/2029	0.9544
9/1/2029	0.9458
10/1/2029	0.9362
11/1/2029	0.9239
12/1/2029	0.9116
1/1/2030	0.9558
2/1/2030	0.9479
3/1/2030	0.9385
4/1/2030	0.9294
5/1/2030	0.9173
6/1/2030	0.9041
7/1/2030	0.8935
8/1/2030	0.9439
9/1/2030	0.9375
10/1/2030	0.9293
11/1/2030	0.9192
12/1/2030	0.9087
1/1/2031	0.8953

Date	May 2022 - 24 PNT - M-Code
2/1/2031	0.8833
3/1/2031	0.8691
4/1/2031	0.9336
5/1/2031	0.9256
6/1/2031	0.9162
7/1/2031	0.9063
8/1/2031	0.8964
9/1/2031	0.886
10/1/2031	0.8745
11/1/2031	0.8635
12/1/2031	0.9288
1/1/2032	0.9209
2/1/2032	0.9136
3/1/2032	0.9074
4/1/2032	0.8999
5/1/2032	0.8916
6/1/2032	0.881
7/1/2032	0.8734
8/1/2032	0.8642
9/1/2032	0.9286
10/1/2032	0.922
11/1/2032	0.9163
12/1/2032	0.9097
1/1/2033	0.9035
2/1/2033	0.8966
3/1/2033	0.8893
4/1/2033	0.8815
5/1/2033	0.8735
6/1/2033	0.8666
7/1/2033	0.9274
8/1/2033	0.922
9/1/2033	0.917
10/1/2033	0.9122
11/1/2033	0.9067
12/1/2033	0.902
1/1/2034	0.8959

Date	May 2022 - 24 PNT - M-Code
2/1/2034	0.8915
3/1/2034	0.8844
4/1/2034	0.8791
5/1/2034	0.8715
6/1/2034	0.8628
7/1/2034	0.8564
8/1/2034	0.8473
9/1/2034	0.8408
10/1/2034	0.8346
11/1/2034	0.8277
12/1/2034	0.9014
1/1/2035	0.8957
2/1/2035	0.8899
3/1/2035	0.8838
4/1/2035	0.9398
5/1/2035	0.9356
6/1/2035	0.9315
7/1/2035	0.9273
8/1/2035	0.922
9/1/2035	0.9175
10/1/2035	0.9117
11/1/2035	0.9072
12/1/2035	0.9036
1/1/2036	0.8993
2/1/2036	0.9475
3/1/2036	0.9439
4/1/2036	0.9412
5/1/2036	0.9368
6/1/2036	0.9319
7/1/2036	0.9284
8/1/2036	0.9636
9/1/2036	0.9606
10/1/2036	0.9575
11/1/2036	0.9551
12/1/2036	0.9527
1/1/2037	0.9493

Date	May 2022 - 24 PNT - M-Code
2/1/2037	0.9735
3/1/2037	0.9718
4/1/2037	0.9689
5/1/2037	0.9657
6/1/2037	0.9624
7/1/2037	0.9582
8/1/2037	0.9793
9/1/2037	0.977
10/1/2037	0.9745
11/1/2037	0.9707
12/1/2037	0.9674
1/1/2038	0.9639
2/1/2038	0.982
3/1/2038	0.9797
4/1/2038	0.977
5/1/2038	0.974
6/1/2038	0.9699
7/1/2038	0.9661
8/1/2038	0.9825
9/1/2038	0.9797
10/1/2038	0.9758
11/1/2038	0.9733
12/1/2038	0.9701

Space Force is currently working to mitigate identified risks to its plans to replenish the GPS constellation with GPS IIIF satellites, which will follow the projected launch of the last GPS III satellite in 2025. As previously stated, Space Force is working to address risks to the OCX Block 3F ground control program that is required to launch and operate the GPS IIIF satellites. In parallel with these efforts, Space Force is currently working to mitigate technical risks within the GPS IIIF program.

- In 2022, the program encountered and worked to resolve technical challenges in the development of the satellite's mission data unit, which is effectively the "brain" of the satellite's navigation mission. For instance, the program implemented a redesign to a board on the frequency synthesizer to address a shortcoming in the mission data

unit's digital waveform generator—a new technology for the GPS IIIF satellites.

- In addition, the GPS IIIF program also implemented a mitigation strategy to address delays to the program's linearized traveling wave tube amplifier—a component needed to enable a high-powered, steerable M-code signal from the GPS IIIF satellite. In 2022, the program encountered manufacturing and technical challenges in constructing this amplifier. To address this challenge, the prime contractor, Lockheed Martin, plans to subcontract the construction of amplifiers for the fifth GPS IIIF satellite onward. Despite these challenges, the GPS IIIF program maintained its projected February 2026 delivery date for the first GPS IIIF satellite. However, the program consumed some of its schedule margin in accommodating delays to component deliveries.

Space Force Assessed the Need for Additional Satellites to Meet Warfighter Requirements

Space Force's approved accuracy requirement for M-code user equipment cannot be met without more than 24 M-code capable satellites, but achieving and sustaining a larger constellation size presents challenges. Space Force indicated that the preferred full operational capability for the GPS space segment is 27 M-code capable GPS satellites. Space Force is projected to launch the 27th M-code capable GPS satellite in February 2025. In addition to the need to launch more satellites to reach 27 on orbit, it could be more challenging to preserve that larger number of satellites in operation. In particular, maintaining the constellation at that level would then—at a minimum—require launching new satellites at a rate that keeps pace with the rate at which older satellites wear out or otherwise reach end of life. The projected launch rate for GPS IIIF satellites is less than the projected rate at which older-generation M-Code capable GPS satellites will begin reaching their end of life. Most immediately, the IIR-M satellites are projected to reach the end of their operational lives over a span between 2027 and 2032. This end of life for the IIR-M satellites is projected to occur due to age-related declines in the ability of the solar arrays to sufficiently recharge the satellites' batteries.

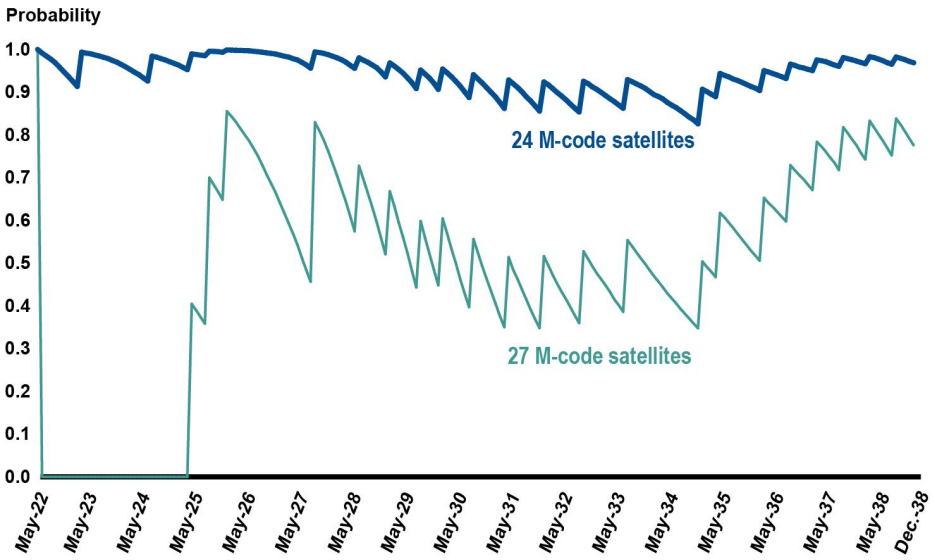
Our analysis of Space Force-provided satellite data and launch projections found that Space Force's current launch schedule for the GPS IIIF satellites does not replenish the constellation at a pace that provides confidence of preserving an active constellation of 27 M-code capable

satellites. According to our analysis, the constellation shows recurrent dips below a 50-percent probability of providing 27 active satellites beginning in mid-2029. According to our projections, the constellation will not achieve a consistent probability above 50 percent before April 2035. Additionally, Space Force's projected launch schedule for the IIIF satellites is based on an optimistic scenario for the first GPS IIIF launch. The launch schedule for the IIIF is predicated on the contractor delivering the satellite in February 2026—nearly 2 years in advance of the program's objective delivery date of January 2028. The projected February 2026 delivery is less than 7.5 years from the program's September 2018 development start. The prior GPS IIF and GPS III satellite programs took 9.5 and 9.3 years, respectively, from development start to first delivery.

Our analysis found that delivery delays to either the GPS IIIF or OCX Block 3F programs could result in marked declines in the likelihood of maintaining a 27 M-code capable satellite constellation. For instance, if the first GPS IIIF satellite were to deliver in February 2027—rather than February 2026—and launch 6 months after delivery, the probability of 27 M-code satellites in the constellation drops to less than 50 percent from mid-2027 through early 2037. [12] Figure 7 below compares the 27-satellite constellation's probability with that of a 24-satellite constellation.

[12]For this scenario our analysis assumed the pace of subsequent IIIF launches would remain unchanged and each launch would shift forward correspondingly to the delay of the first IIIF launch.

Figure 7: Probability of Preserving a 27-satellite M-code Capable GPS Constellation



Source: GAO analysis of Department of Defense data. I GAO-23-106018

Accessible Data for Figure 7: Probability of Preserving a 27-satellite M-code Capable GPS Constellation

Date	May 2022 - 24 PNT - M-Code	May 2022 - 27 PNT - M-Code
5/1/2022	1	1
6/1/2022	0.9909	0
7/1/2022	0.9826	0
8/1/2022	0.9737	0
9/1/2022	0.9665	0
10/1/2022	0.9587	0
11/1/2022	0.9475	0
12/1/2022	0.9371	0
1/1/2023	0.923	0
2/1/2023	0.9085	0
3/1/2023	0.9924	0
4/1/2023	0.9899	0
5/1/2023	0.9874	0
6/1/2023	0.9855	0
7/1/2023	0.9833	0
8/1/2023	0.9809	0

Date	May 2022 - 24 PNT - M-Code	May 2022 - 27 PNT - M-Code
9/1/2023	0.9778	0
10/1/2023	0.9742	0
11/1/2023	0.9686	0
12/1/2023	0.9635	0
1/1/2024	0.9589	0
2/1/2024	0.954	0
3/1/2024	0.9488	0
4/1/2024	0.9424	0
5/1/2024	0.9345	0
6/1/2024	0.9253	0
7/1/2024	0.9848	0
8/1/2024	0.9831	0
9/1/2024	0.9813	0
10/1/2024	0.9781	0
11/1/2024	0.9736	0
12/1/2024	0.9705	0
1/1/2025	0.9661	0
2/1/2025	0.9623	0
3/1/2025	0.9583	0
4/1/2025	0.9892	0.4094
5/1/2025	0.9878	0.3946
6/1/2025	0.9859	0.379
7/1/2025	0.9837	0.3652
8/1/2025	0.9961	0.6979
9/1/2025	0.9957	0.6825
10/1/2025	0.9952	0.6684
11/1/2025	0.9943	0.6505
12/1/2025	0.9987	0.8523
1/1/2026	0.9984	0.84
2/1/2026	0.9979	0.8276
3/1/2026	0.9975	0.8154
4/1/2026	0.9971	0.803
5/1/2026	0.9961	0.7868
6/1/2026	0.9954	0.7703
7/1/2026	0.9946	0.7535
8/1/2026	0.994	0.7353

Date	May 2022 - 24 PNT - M-Code	May 2022 - 27 PNT - M-Code
9/1/2026	0.9923	0.7142
10/1/2026	0.9905	0.6947
11/1/2026	0.9882	0.6725
12/1/2026	0.9847	0.6495
1/1/2027	0.9821	0.6239
2/1/2027	0.9794	0.596
3/1/2027	0.9756	0.5698
4/1/2027	0.9709	0.5429
5/1/2027	0.9659	0.5133
6/1/2027	0.9593	0.483
7/1/2027	0.9501	0.4513
8/1/2027	0.9944	0.829
9/1/2027	0.993	0.8082
10/1/2027	0.9916	0.7865
11/1/2027	0.9896	0.7615
12/1/2027	0.9866	0.7354
1/1/2028	0.9829	0.7078
2/1/2028	0.9791	0.6753
3/1/2028	0.9741	0.6442
4/1/2028	0.9673	0.6101
5/1/2028	0.959	0.5717
6/1/2028	0.9823	0.7263
7/1/2028	0.9771	0.6932
8/1/2028	0.9721	0.6577
9/1/2028	0.9658	0.6243
10/1/2028	0.957	0.5894
11/1/2028	0.9471	0.5519
12/1/2028	0.9368	0.5124
1/1/2029	0.9708	0.6699
2/1/2029	0.9637	0.6339
3/1/2029	0.9549	0.5935
4/1/2029	0.9459	0.558
5/1/2029	0.9369	0.5175
6/1/2029	0.9243	0.4762
7/1/2029	0.9116	0.4361
8/1/2029	0.9544	0.5964

Date	May 2022 - 24 PNT - M-Code	May 2022 - 27 PNT - M-Code
9/1/2029	0.9458	0.559
10/1/2029	0.9362	0.5185
11/1/2029	0.9239	0.48
12/1/2029	0.9116	0.4434
1/1/2030	0.9558	0.6019
2/1/2030	0.9479	0.5659
3/1/2030	0.9385	0.5319
4/1/2030	0.9294	0.4964
5/1/2030	0.9173	0.4633
6/1/2030	0.9041	0.4303
7/1/2030	0.8935	0.395
8/1/2030	0.9439	0.559
9/1/2030	0.9375	0.5277
10/1/2030	0.9293	0.4943
11/1/2030	0.9192	0.4652
12/1/2030	0.9087	0.4349
1/1/2031	0.8953	0.4065
2/1/2031	0.8833	0.3758
3/1/2031	0.8691	0.3516
4/1/2031	0.9336	0.5175
5/1/2031	0.9256	0.4912
6/1/2031	0.9162	0.4653
7/1/2031	0.9063	0.4414
8/1/2031	0.8964	0.4183
9/1/2031	0.886	0.3929
10/1/2031	0.8745	0.3718
11/1/2031	0.8635	0.3505
12/1/2031	0.9288	0.5178
1/1/2032	0.9209	0.4956
2/1/2032	0.9136	0.4738
3/1/2032	0.9074	0.454
4/1/2032	0.8999	0.4347
5/1/2032	0.8916	0.4141
6/1/2032	0.881	0.3968
7/1/2032	0.8734	0.3782
8/1/2032	0.8642	0.3579

Date	May 2022 - 24 PNT - M-Code	May 2022 - 27 PNT - M-Code
9/1/2032	0.9286	0.5237
10/1/2032	0.922	0.51
11/1/2032	0.9163	0.4931
12/1/2032	0.9097	0.4768
1/1/2033	0.9035	0.4609
2/1/2033	0.8966	0.4458
3/1/2033	0.8893	0.4323
4/1/2033	0.8815	0.4157
5/1/2033	0.8735	0.401
6/1/2033	0.8666	0.3867
7/1/2033	0.9274	0.5469
8/1/2033	0.922	0.5318
9/1/2033	0.917	0.5174
10/1/2033	0.9122	0.5047
11/1/2033	0.9067	0.4916
12/1/2033	0.902	0.478
1/1/2034	0.8959	0.4642
2/1/2034	0.8915	0.4511
3/1/2034	0.8844	0.4385
4/1/2034	0.8791	0.4253
5/1/2034	0.8715	0.4144
6/1/2034	0.8628	0.4028
7/1/2034	0.8564	0.3914
8/1/2034	0.8473	0.3794
9/1/2034	0.8408	0.3673
10/1/2034	0.8346	0.3561
11/1/2034	0.8277	0.3456
12/1/2034	0.9014	0.4989
1/1/2035	0.8957	0.4884
2/1/2035	0.8899	0.4767
3/1/2035	0.8838	0.4649
4/1/2035	0.9398	0.6174
5/1/2035	0.9356	0.6075
6/1/2035	0.9315	0.5953
7/1/2035	0.9273	0.5849
8/1/2035	0.922	0.5741

Date	May 2022 - 24 PNT - M-Code	May 2022 - 27 PNT - M-Code
9/1/2035	0.9175	0.5624
10/1/2035	0.9117	0.5495
11/1/2035	0.9072	0.5371
12/1/2035	0.9036	0.5231
1/1/2036	0.8993	0.5097
2/1/2036	0.9475	0.6576
3/1/2036	0.9439	0.6467
4/1/2036	0.9412	0.6348
5/1/2036	0.9368	0.6242
6/1/2036	0.9319	0.6127
7/1/2036	0.9284	0.6001
8/1/2036	0.9636	0.7295
9/1/2036	0.9606	0.7198
10/1/2036	0.9575	0.7089
11/1/2036	0.9551	0.6969
12/1/2036	0.9527	0.6857
1/1/2037	0.9493	0.6732
2/1/2037	0.9735	0.7833
3/1/2037	0.9718	0.7706
4/1/2037	0.9689	0.7585
5/1/2037	0.9657	0.7455
6/1/2037	0.9624	0.7337
7/1/2037	0.9582	0.7202
8/1/2037	0.9793	0.8139
9/1/2037	0.977	0.8006
10/1/2037	0.9745	0.7875
11/1/2037	0.9707	0.7707
12/1/2037	0.9674	0.7538
1/1/2038	0.9639	0.7379
2/1/2038	0.982	0.827
3/1/2038	0.9797	0.8149
4/1/2038	0.977	0.7998
5/1/2038	0.974	0.7847
6/1/2038	0.9699	0.7684
7/1/2038	0.9661	0.7495
8/1/2038	0.9825	0.8367

Date	May 2022 - 24 PNT - M-Code	May 2022 - 27 PNT - M-Code
9/1/2038	0.9797	0.8244
10/1/2038	0.9758	0.809
11/1/2038	0.9733	0.7923
12/1/2038	0.9701	0.7748

Space Force recognizes the risks to achieving a 27 M-code satellite constellation and is pursuing several mitigation strategies. The potential strategies under consideration include implementing new power management techniques to derive additional service life from the IIR-M and, potentially later, from the IIF satellites. Space Force indicated that the employment of power management techniques for IIR-M satellites could potentially extend these satellites' M-code broadcast and service life up to 10 years.[13] GAO analysis indicates that, even with a 2.5 year increase to the projected lives of each IIR-M satellite, the GPS constellation's probability of having 27 operational M-Code capable GPS satellites would increase to a level consistently above 60 percent from late 2025 through early 2034, exceeding 95 percent at multiple junctures between 2029 and 2031.[14] Space Force was exploring this mitigation, and has not yet made a determination as to how and when to implement such techniques, according to SSC officials in December 2022.

Space Force additionally plans to monitor the pace at which satellites need to be replenished to determine the risks of shortfalls to the preferred 27 M-code satellite GPS constellation. Space Force conducts annual assessments of the GPS constellation's health to determine when new satellites will be needed to replenish older satellites and adjusts launches, as appropriate. Space Force officials further stated that Space Operations Command established a GPS constellation sustainment assessment team in late 2021 to analyze future constellation replenishment needs and

[13]Such power management techniques would involve reducing the battery discharge during periods in which the satellite is not in the presence of sunlight—that is, during periods in which the earth is between the sun and the satellite. During such eclipse periods, which are less than an hour in duration, the satellites would reduce the signal types broadcast as a means of preserving the capacity of the power subsystem.

[14]This analysis was conducted by modifying one of the two Space Force-provided parameters for satellite wear-out reliability for each IIR-M satellite. This parameter was adjusted to provide exactly 2.5 additional years to each IIR-M satellite's projected lifespan. All other Space Force provided data (e.g., other satellite reliability parameters and launch dates) were kept constant.

to make recommendations on where new satellites should be placed within the constellation so as to provide optimized performance for the warfighter.

Launch vehicles, however, are expensive, require advanced planning, and are subject to competing priorities. Space Force launches GPS satellites on launch vehicles provided by the National Security Space Launch program, which procures launch services for multiple programs, including GPS, the Space Development Agency, and other DOD and national security customers. Space Force plans launches 2 to 3 years in advance of the actual launch. If Space Force chooses to accelerate the launches of GPS satellites in the future in order to support a 27 M-code satellite constellation, it may have difficulty doing so if the space segment is currently meeting its approved requirement.

As recently as 2021, Space Force affirmed the approved requirement of 24 M-code satellites needed for full operational M-code capability. Studies from as early as 2019 indicated the need for a larger constellation to provide the coverage needed for M-code user equipment, according to officials from OSD's Office of the Director for Developmental Test, Evaluation, and Assessments. These officials stated that an Institute for Defense Analyses study—subsequently confirmed by Space Force's own analysis—determined that a minimum of 27 operational M-code capable GPS satellites was necessary to meet MGUE Increment 1's approved requirements. These requirements included, for example, vertical position and time accuracy. These systems, thus, have conflicting approved requirements: a 24-satellite constellation is the approved requirement of the space segment, but 27 satellites are, in fact, necessary to meet user equipment approved requirements.

According to Space Force officials, Space Force does not have an approved requirement for a 27 M-code satellite constellation. According to these officials and program documentation, even upon achieving the 24-satellite requirement, they plan to continue adding to the constellation. Space Force officials said that this is in keeping with past practice, for previous iterations of the GPS space segment.

The GPS program's current situation is different, in that in prior years the Air Force and, then, Space Force have been able to exceed 27 satellites, at times fielding up to 31 operational satellites. However, M-code capable user equipment is now nearing a state of readiness for the warfighter, and the number of M-code satellites is less than the constellation's overall total. Ensuring that 27 M-code satellites remain active in the future—

particularly as older M-code satellites begin reaching end of life from 2027—will likely be more difficult for Space Force. While Space Force identified some steps to mitigate these challenges, officials from the Office of Developmental Test, Evaluation, and Assessment stated that Space Force has also considered delaying the user equipment requirements that cannot be met with fewer than 27 M-code satellites.

We have noted, in prior reporting, the importance of programs establishing well-defined requirements.[15] In addition, GAO's *Standards for Internal Control in the Federal Government* stipulates that management should identify and respond to risks to achieve defined objectives.[16] If a constellation of 27 M-code capable GPS satellites is necessary to meet approved user equipment requirements and warfighter needs, the lack of an approved requirement for that number could result in other DOD efforts taking priority, leaving the warfighter with GPS user equipment performing below the required capability levels. By establishing a well-defined requirement for the number of satellites required for the M-code constellation, Space Force could ensure that decisions on resource allocation are based on a clear understanding of operational need, thereby mitigating risk to the warfighter.

Progress Made on User Equipment, but Receiver Delays Could Result In Capability Gaps

M-code Increment 1 Development Nearly Complete

After years of delays, the MGUE Increment 1 development efforts have progressed, bringing them closer to transition to the military departments for testing, integration, and fielding. For example, Space Force completed development of the ground card in 2022. In addition, in March 2023, the contractor delivered the aviation/maritime card to the government in support of testing and integration.

[15]GAO, *Acquisition Reform: DOD Should Streamline Its Decision-Making Process for Weapon Systems to Reduce Inefficiencies*, GAO-15-192 (Washington, D.C.: Feb. 24, 2015).

[16]GAO, *Standards for Internal Controls in the Federal Government*, GAO-14-704G (Washington, D.C.: Sept. 10, 2014).

The Marine Corps Operational Test and Evaluation Activity completed the MGUE Increment 1 field user evaluation in September 2021 at White Sands Missile Range, New Mexico. This evaluation assessed multiple M-code cards by integrating each of them with a receiver on a Marine Corps' Joint Light Tactical Vehicle. The purpose of the evaluation, in part, was to demonstrate the capability of the Increment 1 ground card manufactured by L3Harris and fulfill one of the critical exit criteria for the program. According to these officials, the evaluation also assessed several other cards as a "target of opportunity," such as a BAE-manufactured derivative card. The evaluation was limited to demonstrating the receiver cards' ability to provide assured PNT data while operating in GPS-constrained environments.

The evaluation showed that the L3Harris ground card did not perform as expected. Following the evaluation, Marine Corps test officials provided their results to SSC via a test report and related analyses. SSC subsequently analyzed the test data and concluded that the L3Harris card did not connect to an M-code signal and relied instead on legacy signals. According to Space Force officials, this failure was due to the use of an expired encryption key. Marine Corps officials stated that the test design included multiple checks to preclude this error and explained that the failure occurred due to hardware and software issues with the card.

SSC officials also stated that subsequent updates to the ground card software had corrected the issue and would prevent the error from re-occurring. Despite the outcome of the evaluation, SSC officials stated that developmental testing already performed on the L3Harris card verified the issue had been corrected and satisfied the program's exit criteria. According to Army officials, derivatives of the L3Harris ground card are planned or under consideration for several systems.

SSC also reported progress on the development of the aviation/maritime card. In October 2022, Raytheon delivered software to support integration testing by the Air Force and Navy. In December 2022, SSC determined that issues with this software required further modifications before final integration testing could begin. SSC now plans to release a corrected version of this software that will satisfy the Technical Requirements Verification milestone by April 2023. According to MGUE program office, the Air Force and Navy are updating their test plans accordingly. Once the corrected version is received, the Air Force plans to conduct a combined developmental and operational test with the Air Force's MAGR-2K-M receiver and its lead platform, the B-2 Spirit. This testing is expected to conclude in fiscal year 2024. The Navy will integrate the card

with its GPS-Based Positioning, Navigation and Timing Service (GPNTS) Receiver and conduct testing on the Navy's lead platform, an *Arleigh Burke* class destroyer. Follow-on testing is scheduled for the latter half of fiscal year 2025, according to the MGUE program office.

Army Beginning to Field User Equipment, which the Marine Corps Is Considering

The Army has also made progress developing and fielding M-code technologies. According to Army officials, delays to Space Force's MGUE Increment 1 program resulted in the schedule lagging behind the Army's needs. According to these officials, the Army chose to develop and field a family of GPS receivers tailored to the Army's requirements based on a derivative M-code receiver card. This card is manufactured by BAE and derived from work the contractor performed under the MGUE Increment 1 program. The Air Force also reviewed and approved the card and chip in the BAE derivative design to ensure it conforms to appropriate standards. As a result of using this derivative card, Army officials stated that working in parallel with the Increment 1 program's efforts allowed them to field user equipment more quickly than if they had waited for the conclusion of the program.

The Army's receiver development efforts include the Mounted Assured Positioning, Navigation, and Timing System (MAPS), the Dismounted Assured Positioning, Navigation, and Timing System (DAPS), and select missiles and munitions. The Army authorized rapid prototyping for MAPS and DAPS using the urgent capability acquisition pathway.[17] The Army plans to eventually transition these two efforts to the major capability acquisition pathway. MAPS and DAPS consist of several planned phases, which the Army refers to as generations, with some provisions for incremental improvements within generations. MAPS and DAPS Generation I have both completed testing and are currently being fielded. Figures 8 and 9 show timelines for MAPS and DAPS Generation II.

[17]The Urgent Capability Acquisition pathway is used to field capabilities that meet urgent existing and/or emerging operational needs in less than 2 years. See Department of Defense Instruction 5000.81 – *Urgent Capability Acquisition* and Department of Defense Directive 5000.71 – *Rapid Fulfillment of Combatant Commander Urgent Operational Needs.*

Figure 8: Mounted Assured Positioning, Navigation, and Timing System, Generation II Schedule

Source: GAO analysis of Department of Defense information. | GAO-23-106018

Figure 9: Dismounted Assured Positioning, Navigation and Timing System Schedule, Generation II Schedule

Source: GAO analysis of Department of Defense information. | GAO-23-106018

MAPS Generation II, as well as DAPS and its variants, are all M-code-enabled systems.

- MAPS Generation II will replace the existing GPS receivers and antennas in most of the Army's ground vehicle variants and as of July 2022 is expected to reach initial operational capability in the second quarter of fiscal year 2024.
- The Army is acquiring the first two variants of DAPS Generation I in response to an urgent operational need for deployed Army forces. The effort will result in the limited equipping of two Infantry Brigade Combat Teams. Both variants operate with the existing Nett Warrior system, a suite of communications and sensor equipment currently deployed with Army soldiers. The first variant of DAPS cannot operate independently of the Nett Warrior system's common battery, but the second variant contains its own battery. The Army expects DAPS Generation II to have additional capabilities, including hardening against chemical, biological, and nuclear environments, and reduced energy consumption.

The Army also plans to use a variety of Increment 1 derivative cards in missile and munitions systems. According to Army officials, the Army has already fielded a BAE-manufactured derivative card with select weapon systems, such as the Patriot missile system. While the bulk buy of Increment 1 ASICs imposes limits on the number of available M-code cards, Army officials said they weighed these factors when deciding to place them in expendable munitions. They noted that the Army's allocation of ASICs was the highest of all of the military departments.

Marine Corps officials have stated that they are open to adopting some Army solutions for ground systems, should they meet their needs. In

some cases, they said, the Marine Corps was reluctant to sign on to certain Army receivers due to concerns about weight or unit costs. In November 2022, the Marine Corps directed its Mounted Assured Resilient Navigation program to field vehicle-based M-code receivers in two phases. In the first phase, the Marine Corps would purchase at least 110 MAPS Generation II receivers and its related supporting equipment through the planned Army production contract. In the second phase, the program would work with industry to develop a Marine Corps-specific solution at a potentially significantly reduced cost from MAPS Generation II. For dismounted applications, the Marine Corps had been working with Space Force, but is monitoring the Army's progress in developing and fielding DAPS.

Air Force and Navy Efforts to Integrate M-code Hampered by Delays

As development on the MGUE Increment 1 aviation/maritime card nears completion, Air Force and Navy receiver efforts are preparing to integrate and test it with their lead weapon systems, the B-2 Bomber and *Arleigh Burke* class destroyer. Despite this progress, delays in delivery of one Air Force developed receiver could result in a capability gap for the Navy starting in 2025.

The Navy's GPNTS is designed to act as a multi-PNT receiver, with the ability to integrate PNT information from different sensors, and with space for multiple receiver cards. The Navy is currently fielding this receiver on the *Arleigh Burke* class destroyer with a non-M-code GPS card, which will be replaced when the M-code card becomes available following operational test and evaluation in November 2024 and release of the final report results by April 2025.

The Air Force is developing three receivers for use with the aviation/maritime card:

- The **Miniature Airborne GPS Receiver 2000 – Modernized (MAGR-2K-M)** is the lead Air Force receiver associated with the MGUE Increment 1 program. Although it will eventually integrate with several aircraft, the Air Force plans to first test and integrate it with the B-2 Spirit Bomber. The program plans to conduct a combined developmental and operational test program in the first quarter of fiscal year 2024, and expects to issue its final report by the end of that quarter.

- The **Resilient Embedded GPS/Inertial Navigation System (R-EGI) receiver** is a middle tier of acquisition rapid prototyping program, hat seeks to integrate an M-code receiver with Air Force F-16s within 5 years. According to Air Force officials, R-EGI began because the Air Force recognized that the proprietary nature of existing receivers limited their ability to respond to future threats or challenges. As a result, the Air Force is designing R-EGI using an open-systems approach, and employing a design agent to ensure that the Air Force will retain rights to key resulting intellectual property. R-EGI will use a receiver card derived from the aviation-maritime card. Air Force officials also said they chose the F-16 as the lead platform for R-EGI because the space available allowed for a larger and less technically challenging receiver. The program experienced delays in fiscal year 2022, due in part to supply chain issues and parts availability. The R-EGI program now has a prototype of the receiver under development and expects to enter flight-testing by 2024. According to a program official, they are developing plans to include R-EGI on F-15 and F-15 EX platforms as well.
- **The Embedded GPS Inertial Navigation System – Modernized (EGI-M) receiver** is an Air Force program to replace a family of legacy receivers used across multiple Air Force and Navy air platforms. The receivers the Air Force is replacing are manufactured by two different contractors: Honeywell and Northrup Grumman. Each contractor is developing replacements for its own legacy hardware. According to documentation from DOD, both contractors have experienced significant delays and cost overruns, including breaches of key schedule milestones by as much as 15 months. According to an Air Force program official, over the course of fiscal year 2022, it became clear that neither contractor would be able to meet its revised schedule baseline. The Air Force is currently working with the contractors to prepare a new schedule. Though the schedule is still under development, Air Force officials stated they cannot deliver EGI-M to support initial fielding before fiscal year 2025.

The EGI-M program delays pose a particular problem for the Navy. According to a November 2018 Memorandum of Agreement between the Air Force and Navy, the Air Force is the primary developer for EGI-M prior to Milestone C, while the Navy is responsible for communicating platform-specific requirements and specifications. According to Navy officials, at least some legacy EGI receivers for Navy air platforms will reach the end of their operational lives in 2025, and the receivers and the cards that

support them are no longer in production. As a result, the Navy faces a potential capability gap starting in 2025.

Navy officials stated that they have warned DOD leadership of this scenario for several years through discussions before the PNT Oversight Council, a DOD-wide interagency body dedicated to PNT issues. In 2021, budget constraints resulted in a significant slowdown of EGI-M, which resulted in a major breach of its schedule milestones. Air Force and other Navy platforms face similar end-of-life issues with other legacy receivers. Partly in response to these issues, Air Force leadership has shifted its focus to emphasize R-EGI as its receiver of choice for future programs. According to Navy officials, R-EGI cannot meet the needs of Navy air platforms due to size and power requirements and, as a result, they are reliant on the timely delivery of EGI-M. In September 2022, Air Force documentation stated that the contractors would no longer be able to meet the initial revised schedule. Air Force program officials have since been working with the contractors on a new schedule.

According to Navy officials, coordination with the Air Force on EGI-M has typically occurred through the DOD PNT Oversight Council. This interagency body meets regularly, and covers a broad range of issues. In the latter half of 2022, the PNT Oversight Council convened a working group to report on the capability gap and address possible mitigations. Partly in response to this, Navy officials said they are working on identifying measures that could mitigate the future capability gap. They also said that senior DOD leadership is now reaching out to Northrop Grumman and Honeywell leadership to convey the seriousness of the problem and encourage them to work to accelerate the EGI-M development schedule. If the legacy receiver's end-of-life occurs beginning in 2025, as expected, and EGI-M is not yet available for integration, Navy officials told us they might have to ground select aircraft. We will continue to monitor the Air Force's progress in adhering to its new schedule.

Efforts to Develop Next Generation User Equipment Have Technical Risks, and Business Case for Handheld Receiver Is Flawed

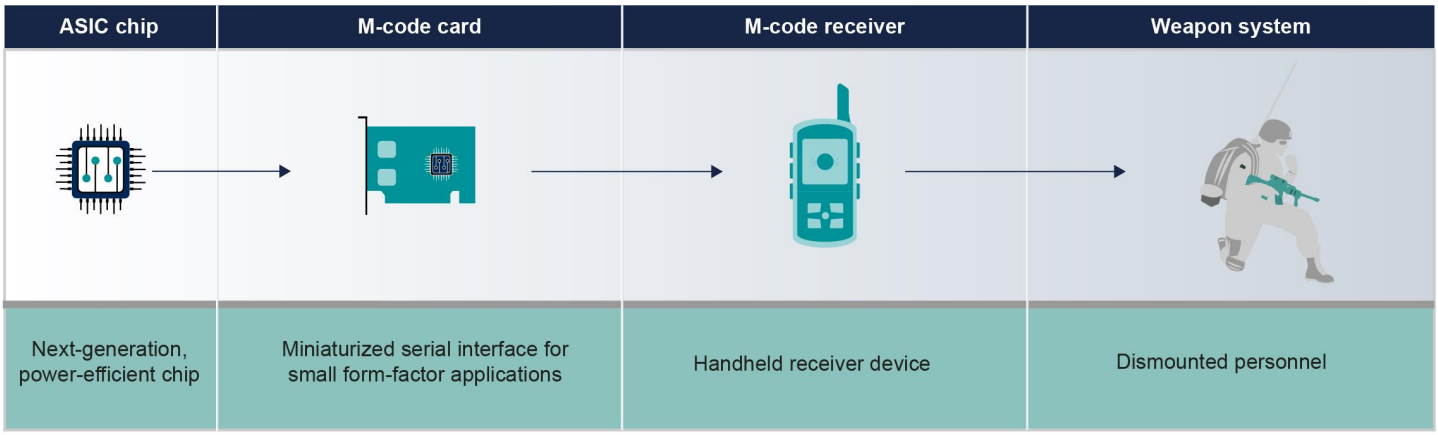
Increment 2 Efforts Struggling to Meet Performance Requirements

The MGUE Increment 2 effort seeks to improve upon the capabilities in MGUE Increment 1. To date, several contractors developing the chips and cards have not met performance requirements, with consequences for cost, schedule, and performance. Development for the Increment 2 chip and card is a 5-year middle tier of acquisition rapid prototyping effort with a cost of approximately $1.4 billion. The effort seeks to develop a next-generation ASIC and smaller receiver card by the first quarter of fiscal year 2026. According to program documentation prepared at the inception of this effort, this chip and card combination was primarily designed for applications such as handheld devices and munitions. These applications require a chip and card combination that is both smaller than Increment 1, more power efficient, and for which there is a robust enough industrial base to avoid the supply challenges associated with Increment 1 chips.

To do so, the program moved away from the typical DOD approach of using “trusted” manufacturers, and instead assembled the Increment 2 ASIC using commercial design elements, programming in militarily sensitive information later.[18] The program awarded three contracts in November 2020. Space Force retained three contractors through the entire prototype development phase, in order to develop a competitive commercial base for the manufacture of the card, as well as for future variants. Space Force officials also envision quickly transitioning the technology to follow-on efforts. Program officials developed specific requirements for performance, which are necessary to facilitate these future efforts. Figure 10 illustrates the development process envisioned by Increment 2.

[18]With respect to microelectronics, a so-called “trusted” environment is required to secure national security systems by assessing the integrity of the people and processes used to design, generate, manufacture, and distribute national security critical components, and include fabrication of classified designs.

Figure 10: Military GPS User Equipment Increment 2 Development Pathway



ASIC Application-Specific Integrated Circuit
M-code Military code
MGUE Military GPS User Equipment

Source: GAO analysis and representation of Department of Defense documentation. | GAO-23-106018

Since the November 2020 contract award, two of the three contractors stated they are unable to meet several requirements within existing program plans. This prompted the program office to request that the Joint Requirements Oversight Council provide relief from these requirements. In support of that process, the program also solicited feedback on the proposed changes from other DOD stakeholders.

Program officials stated that relieving some requirements would have minimal effects on performance.

- In one case, a requirement exists directing Increment 2 to detect a rare, misleading GPS signal and to disregard it. The technique the program used for this requirement tended to produce too many false positives, causing the system to disregard accurate data. Filtering out these signals forced the system to rely on fewer correct signals, leading to degraded accuracy for the system overall. The GPS ground control segment already monitors for, and seeks to correct, this type of misleading signal. Program officials suggested they stop trying to monitor for this signal on the user device and rely on the control segment instead.
- Another requirement seeks to have MGUE Increment 2 function in the presence of both friendly and enemy GPS jammers. The program noted that the requirement seeks a specific level of performance when the jammers are located immediately next to each other, an unlikely

scenario. Furthermore, the program noted that it was not aware of any U.S. capability to perform this specific kind of jamming, limiting the operational effect of reducing or eliminating the requirement. The Joint Navigation Warfare Center had no objection to reducing the requirement for filtering friendly GPS jamming.

Two further requirements directly affect aspects of the performance of systems relying on the Increment 2 chip and card: (1) a requirement for the time necessary to fix one's location when first powered on (known as time to first fix) in the presence of enemy jamming, and (2) overall battery life.

According to program officials and Defense Contract Management Agency documents, the inability to meet these requirements is due to the chip consuming far more power than the program originally expected.[19] As a result, the device overheats. When this occurs, the device must make trade-offs between heat and processing power, resulting in an overall degradation in performance. Overall battery life is an extension of the same problem as, according to program officials, the space and weight budgets for the intended systems limit the ability to increase the battery size.

Defense Contract Management Agency and program officials projected that surmounting the power-efficiency problems for Increment 2 could be costly in terms of time and schedule as they necessitate significant re-engineering of the designs. The Increment 2 program estimated that it would require an additional $300 million and an additional 48 months to meet existing requirements. At the time of our review, documentation indicated that one contractor met both requirements. But, according to defense contractor oversight officials that same contractor experienced significant cost and schedule overruns over the previous 2 years.

Instead of incurring these significant re-engineering costs, program officials requested a reduction in the amount of presumed jamming associated with the time to first fix requirement. The Joint Navigation Warfare Center and U.S. Space Command preferred to keep this requirement unchanged unless they had evidence from users that the reduced performance would be acceptable.

[19]The Defense Contract Management Agency is a DOD organization which provides contract management services as well as independent oversight of the execution of defense contracts.

Program officials also suggested meeting the battery life requirement by making adjustments to assumptions about how devices incorporating the chip and card would work, such as the length of the time a display would stay on, the amount of time spent in a standby mode, and limiting the number of satellites that a device could track. In response to these proposed adjustments, Space Force staff's requirements office wanted more options presented to the military departments for how to handle the energy limitations before changing the requirement. As of December 2022 the Joint Requirements Oversight Council has yet to make a decision on the requests for relief from these four requirements.

Current Business Case for Handheld Receiver Is Flawed, and Continued Investment Risks Unnecessary Spending

SSC plans to develop a handheld M-code GPS device from the Increment 2 card. However, in addition to the technical challenges discussed above, the business case for this effort suffers from the lack of a major, committed customer. SSC intends the Increment 2 handheld program to be a second, 5-year, rapid prototyping middle tier of acquisition program, and intends to start the effort in the fourth quarter of fiscal year 2023. In 2020 the Air Force estimated the effort would cost $149.2 million. Unlike Increment 1, where the military departments are responsible for developing the receivers, Space Force intends to develop the Increment 2 handheld receiver for use by other military departments.

The acquisition strategy for the Increment 2 effort noted that the Army, the largest potential customer, stated it has no plans to procure the handheld, a fact that poses a significant risk for the program's business case. Army officials subsequently confirmed to us that the Army has no plans to acquire the handheld. The program sought to make up for the Army's lack of interest with other potential customers, such as foreign military sales, but still considered the issue a top risk.

In March 2022, we found that leading companies employ several key principles that help to ensure successful product development.[20] One of these principles is to attain a sound business case informed by research and collaboration with customers. In developing a sound business case, we identified several sub-principles, including:

[20]GAO, *Leading Practices: Agency Acquisition Policies Could Better Implement Key Product Development Principles,* GAO-22-104513 (Washington, D.C.: Mar. 10, 2022).

- investing time to research a marketable product,
- soliciting early feedback from customers, and
- a willingness to end programs that no longer have a sound business case.

SSC projected the Increment 2 handheld would cost at least 60 percent more than the Army's current non-M-code handheld, and that the lower production quantities resulting from the Army decision to not acquire the handheld unfavorably affect this price. Because production quantities are so important to the product's development, knowledge of potential customers' needs, and the quantities they plan to procure, constitute important elements of the business case.

Army officials, who represent the largest potential customer, stated that, while they are interested in the Increment 2 chip and card, they are not interested in the SSC-developed, Increment 2 handheld receiver. The Army already has plans for developing its own M-code handheld equipment and some of these efforts are further along in development than the Increment 2 handheld. The portion of the Army's DAPS program using the urgent acquisition pathway provides a handheld M-code capability using MGUE Increment 1 technology. This program achieved initial operating capability, and, according to Army officials, equipped its first full unit in the first quarter of fiscal year 2023. Army officials also said that, if the Inc. 2 handheld effort succeeds, they may leverage the results in the future to help fulfill its own unique requirements.

The Marine Corps worked closely with SSC to develop requirements for the handheld receiver. According to Marine Corps officials, their current plans call for requesting funds for the procurement of a modernized handheld receiver starting in fiscal year 2027. These officials also said that they are working to update their requirements document for this capability, and that their market research identified the Army's DAPS solution as having the potential to fulfill these requirements as well. One Marine Corps official also said that the Marine Corps did not intend to commit to either DAPS or the SSC-developed handheld receiver prior to a full and open competition that evaluated both products against their requirements.

The Increment 2 acquisition strategy also proposed using Foreign Military Sales as a source of customers. SSC officials responsible for coordinating foreign sales stated that there is broad foreign interest in Increment 2 technology, but that foreign buyers often refrain from making

specific commitments to buy technologies that are not yet widely demonstrated.

In February 2022, the Air Force attempted to gauge the potential market for the handheld by requesting potential procurement quantities from the services. They found that the Navy's requirements had declined significantly to only a few thousand, while the Marine Corps and Air Force both indicated a potential quantity of about 50,000 units each. These figures were non-binding, however, and preceded the design reviews which demonstrated shortfalls in meeting requirements.

SSC plans to commence the Increment 2 handheld program in the fourth quarter of fiscal year 2023, just before the Critical Design Review for the chip and card program. Doing so means that SSC may not have fully addressed the issues that come from the lack of a major, committed customer. Furthermore, if the shortfalls with the Increment 2 chip and card are not resolved to the Marine Corps' satisfaction, there is a possibility that the program could lose the customer for nearly half of its potential procurement quantities. In that case, SSC will have invested finite development dollars and significant time without providing a benefit to military users in the form of greater capability.

Conclusions

DOD has been working for more than 2 decades on GPS modernization, but questions about key aspects of its approach remain. While Space Force seems well situated to achieve its approved requirement of keeping 24 M-code capable satellites in operation, Space Force's analysis indicates that 27 satellites are necessary to meet real-world warfighter needs.

In addition, SSC plans to develop a sophisticated handheld receiver for which the market may be limited. SSC is moving forward with a potentially unsound business case. Adhering to the current strategy without re-assessing the true scope of the market and the performance of their proposed solution risks investing years of effort as well as limited development funds.

Recommendations for Executive Action

We are making the following two recommendations to the Air Force:

The Secretary of the Air Force should ensure that the GPS program assesses whether an approved requirement for a 27-satellite M-code capable GPS satellite constellation is necessary to meet future operational needs. (Recommendation 1)

The Secretary of the Air Force should require that SSC produce a sound business case for the MGUE Increment 2 handheld prior to initiating the rapid prototyping phase of the middle tier of acquisition, or else not initiate the handheld rapid prototyping effort due to the absence of a sound business case. (Recommendation 2)

Agency Comments and Our Evaluation

We provided a draft of this report to DOD for review and comment. DOD provided an official comment letter (reproduced in appendix II) which concurred with our recommendations. They also provided technical comments which we incorporated as appropriate.

We are sending copies of this report to the appropriate congressional committees, the Secretary of Defense, the Secretary of the Air Force, the Secretary of the Army, the Secretary of the Navy, and other interested parties. In addition, the report is available at no charge on the GAO website at http://www.gao.gov.

If you or your staff have any questions concerning this report, please contact me at (202) 512-4841 or ludwigsonj@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. Key contributors to this report are listed in appendix III.

Jon Ludwigson
Director, Contracting and National Security Acquisitions

List of Committees

The Honorable Jack Reed
Chairman
The Honorable Roger Wicker
Ranking Member
Committee on Armed Services
United States Senate

The Honorable Jon Tester
Chairman
The Honorable Susan Collins
Ranking Member
Subcommittee on Defense
Committee on Appropriations
United States Senate

The Honorable Mike Rogers
Chairman
The Honorable Adam Smith
Ranking Member
Committee on Armed Services
House of Representatives

The Honorable Ken Calvert
Chair
The Honorable Betty McCollum
Ranking Member
Subcommittee on Defense
Committee on Appropriations
House of Representatives

Appendix I: Objectives, Scope, and Methodology

Section 1621 of the National Defense Authorization Act (NDAA) for Fiscal Year 2016 included a provision that the Air Force provide quarterly reports and supporting documentation to us on, among other things, next-generation GPS acquisition programs. The act also included a provision that GAO brief congressional defense committees on the first report and, at GAO's discretion, on subsequent reports. We published reports on the overall GPS enterprise, on schedule risks to the ground control segment of the GPS mission, and on progress and challenges delivering modernized GPS user equipment in December 2017, May 2019, January 2021, and May 2022, respectively. This report examines:

1. the risks that Space Force identified to transitioning the ground control segment to the Next Generation Operational Control System (OCX) and how it is mitigating them;
2. the extent to which Space Force identified and addressed risks affecting the space segment and delivery of M-code capability;
3. the progress that the Department of Defense (DOD) made in developing and integrating Military GPS User Equipment (MGUE)Increment 1; and
4. the extent to which Space Force is managing risk in MGUE Increment 2 development efforts.

To assess the risks that Space Force identified to transitioning the ground control segment to OCX and how it is mitigating them, we reviewed documents provided by Space Force's Space Systems Command (SSC). These include program schedules, monthly acquisition reports for OCX, and other reports describing program accomplishments and risks. We also reviewed program management documents produced by the contractor, Raytheon. In addition, we conducted interviews with officials from the Defense Contract Management Agency; Director of Operational Test and Evaluation; Office of Developmental Test, Evaluation, and Assessment; and Office of the Undersecretary of Defense for Acquisition and Sustainment. We also visited the GPS operational control center at Schriever Space Force Base and met with officials from Space Force 2nd and 19th Space Operations Squadrons.

To determine the extent to which Space Force identified and addressed risks affecting the space segment, we reviewed documents from SSC and the GPS III and GPS IIIF program offices and interviewed officials from the relevant DOD offices listed above. We also determined that GAO's leading practices for acquisition, which stipulate the need for well-defined requirements, are significant to this objective.[1] We also identified the control activities component of internal controls as significant to this objective; specifically, the underlying principles that management should identify and respond to risks to achieve defined objectives.[2]

To assess the projected health of the GPS constellation for both full operational capability of 24 M-code capable GPS satellites and the preferred operational capability of 27 M-code capable GPS satellites, we employed a methodology very similar to the one we used to assess constellation performance in 2009, 2010, 2015, and 2017.[3] We obtained information dated May 2022 from Space Force predicting the reliability for 61 GPS satellites—each of the 34 currently on-orbit (31 in operational status, three in non-operational reserve status) and 27 future GPS satellites—as a function of time. Each satellite's total reliability curve defines the probability that the satellite will still be operational at a given time in the future. The probability is generated from the product of two reliability curves—a wear-out reliability curve defined by the cumulative normal distribution, and a random reliability curve defined by the cumulative Weibull distribution.[4]

For our analysis, we excluded the 10 non-M-code capable GPS satellites, and included in our model only the 24 currently operational and 27 future M-code capable GPS satellites. For each of these 51 satellites, we

[1]GAO, *Acquisition Reform: DOD Should Streamline Its Decision-Making Process for Weapon Systems to Reduce Inefficiencies*, GAO-15-192 (Washington, D.C.: Feb. 24, 2015).

[2]GAO-14-704G.

[3]GAO, *Global Positioning System: Better Planning and Coordination Needed to Improve Prospects for Fielding Modernized Capability*, GAO-18-74 (Washington, D.C.: Dec. 12, 2017); *GPS: Actions Needed to Address Ground System Development Problems and User Equipment Production Readiness*, GAO-15-657 (Washington, D.C.: Sept. 9, 2015); *Global Positioning System: Challenges in Sustaining and Upgrading Capabilities Persist*, GAO-10-636 (Washington, D.C.: Sept. 15, 2010); and *Global Positioning System: Significant Challenges in Sustaining and Upgrading Widely Used Capabilities*, GAO-09-325 (Washington, D.C.: Apr. 30, 2009).

[4]The Weibull distribution is a common two-parameter continuous probability distribution; it is used to model the random failures of GPS satellites.

obtained the two parameters defining the cumulative normal distribution, and the two parameters defining the cumulative Weibull distribution. For each of the 27 unlaunched satellites that we included in our model, we also obtained a parameter defining its probability of successful launch, and its current scheduled launch date. The 27 unlaunched satellites include five GPS III satellites and 22 GPS IIIF satellites currently under contract; launch of the final GPS IIIF satellite that we included in our model is scheduled for January 2039.

Using this information, we generated overall reliability curves for each of the 51 M-code capable GPS satellites. We discussed with Space Force and Aerospace Corporation representatives, in general terms, how each satellite's normal and Weibull parameters were calculated. However, we did not analyze any of the data used to calculate these Space Force provided parameters. We found this data to be reliable for the purposes of supporting our analysis of the GPS constellation.

Using the reliability curves for each of the 51 M-code capable GPS satellites, we developed a Monte Carlo simulation to predict the probability that at least a given number of satellites would be operational as a function of time, based on the GPS launch schedule as of May 2022. We conducted several runs of our simulation—each run consisting of 10,000 trials—and generated saw-toothed curves depicting the probability that at least 24 and 27 M-code capable satellites would still be operational from May 2022 to December 2038.[5]

We then used our Monte Carlo simulation model to examine the effect of delays to the operational induction of the GPS III satellites into the constellation. We reran the model based on month and year delay scenarios, calculating new probabilities that at least 24 and 27 M-code capable satellites would still be operational from May 2022 to December 2038. To assess the potential effect of Space Force plans to extend the operational life span of IIR-M satellites through power management techniques, we modified, for each of the IIR-M satellites, one of the two Space Force provided Weibull parameters to provide an additional 2.5

[5]Monte Carlo simulation refers to a computer-based analysis that uses probability distributions for key variables, selects random values from each of the distributions simultaneously, and repeats the random selection over and over. Rather than presenting a single outcome—such as the mostly likely or average scenario—Monte Carlo simulations produce a distribution of outcomes that reflect the probability distributions of modeled uncertain variables.

years of life span for each IIR-M satellite for one scenario and an additional 5 years for a second scenario.

To assess the progress that DOD made in developing and integrating MGUE increment 1, we interviewed officials from the Office of the DOD Chief Information Officer and reviewed classified and unclassified briefing materials from the Position, Navigation, and Timing (PNT) Oversight Council. We also interviewed PNT offices in each military department to understand their roles in planning for M-code integration within their respective department. These included:

- the Office of the Deputy Chief of Naval Operations for Information Warfare;
- the Air Force's Resilient Positioning, Navigation, and Timing Cross-Functional Team and Position, Navigation, and Timing Program Office, Marine Corps Systems Command Communication Systems; and
- the Army's Cross-Functional Team for Assured Positioning, Navigation, and Timing and Space and the Army Program Manager for Position, Navigation, and Timing.

To examine the extent to which the military departments planned for the procurement, installation, and fielding of MGUE increment 1 user equipment, we reviewed the MGUE Increment 1 program monthly acquisitions reports and other briefings relevant to the program's progress delivering usable M-code cards. We interviewed MGUE Increment 1 program officials and M-code card contractors to obtain insight into progress and challenges in delivering M-code cards.

To determine the progress the military departments made in developing M-code receivers, selecting receiver solutions, and developing operational test plans for this equipment, we reviewed modernized receiver programs' baseline and schedule documents; and interviewed officials from service-level offices overseeing the development and integration of M-code receivers. To understand M-code user equipment operational testing plans, we interviewed officials from Director, Operational Test and Evaluation, Developmental Test Evaluation and Assessments, and military department's PNT offices. We also interviewed the Marine Corps Operational Test and Evaluation Activity to learn about the results of tests on the MGUE Increment 1 ground card.

To assess the extent to which Space Force is managing risk in MGUE Increment 2 development efforts, we interviewed officials and reviewed documentation from SSC, the MGUE Increment 2 program office, and military departments' PNT offices. These documents included program schedules, monthly acquisition reports for MGUE Increment 2, and other reports describing program accomplishments, setbacks, and risks. We reviewed documents produced by the contractors for MGUE Increment 2. We also interviewed officials from the Defense Contract Management Agency charged with overseeing these specific MGUE Increment 2 contractors, and reviewed documents relating to those contractors' performance. In addition, we determined that GAO-identified key principles for successful product development were significant to this objective.[6]

We conducted this performance audit from April 2022 to June 2023 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

[6]GAO, *Leading Practices: Agency Acquisition Policies Could Better Implement Key Product Development Principles,* GAO-22-104513 (Washington, D.C.: Mar. 10, 2022).

Appendix II: Comments from the Department of Defense

DEPARTMENT OF THE AIR FORCE
WASHINGTON DC

OFFICE OF THE ASSISTANT SECRETARY

18 May 2023

Mr. Jon Ludwigson
Director, Defense Capabilities and Management
U.S. Government Accountability Office
441 G Street, NW
Washington D.C., 20548

Dear Jon,

This is the Department of Defense response to the GAO Draft Report, GAO-23-106018, 'GPS MODERNIZATION: Space Force Should Re-assess Requirements for Satellites and Handheld Devices,' dated May, 2023 (GAO Code 106018).

The Department concurs with the GAO recommendations in the draft report and looks forward to receiving the final report. Thank you for allowing the department to review the draft report and we look forward to continuing collaboration with the GAO and other stakeholders to enhance GPS modernization for our warfighters and the nation.

Sincerely

FRANK CALVELLI
Assistant Secretary of the Air Force
(Space Acquisition & Integration)

GAO DRAFT REPORT DATED MARCH 27, 2023
GAO-23-106018 (GAO CODE 106018)

"GPS MODERNIZATION: SPACE FORCE SHOULD RE-ASSESS REQUIREMENTS FOR SATELLITES AND HANDHELD DEVICES"

DEPARTMENT OF DEFENSE COMMENTS TO THE GAO RECOMMENDATION

RECOMMENDATION 1: The GAO recommends that the Secretary of the Air Force should ensure that the GPS program assesses whether an approved requirement for a 27-satellite M-code capable GPS satellite constellation is necessary to meet future operational needs.

DoD RESPONSE: Concur.

RECOMMENDATION 2: The GAO recommends that the Secretary of the Air Force should require that SSC produce a sound business case for the MGUE Increment 2 handheld prior to initiating the rapid prototyping phase of the middle tier of acquisition, or else not initiate the handheld rapid prototyping effort due to the absence of a sound business case.

DoD RESPONSE: Concur.

Accessible Text for Appendix II: Comments from the Department of Defense

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U.S. Government Accountability Office
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Washington D.C., 20548

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FRANK CALVELLI
Assistant Secretary of the Air Force
(Space Acquisition & Integration)

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DoD RESPONSE: Concur.

Appendix III: GAO Contact and Staff Acknowledgments

GAO Contact

Jon Ludwigson, (202) 512-4841 or ludwigsonj@gao.gov

Staff Acknowledgments

In addition to the contact named above, the following staff members made key contributions to this report: J. Kristopher Keener (Assistant Director), Matthew J. Ambrose (Analyst-in-Charge), Pete Anderson, Susan C. Ditto, Michael Losacco, Jonathan Mulcare, Bonita Oden, Sylvia Schatz, Kimberly Schuster, and Robin Wilson.

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