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NASA's Development of Ground and Flight Application Software for the Artemis Program

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RESULTS IN BRIEF

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March 19, 2020 IG-20-014 (A-19-008-00)

WHY WE PERFORMED THIS AUDIT

NASA's plan to return astronauts to the Moon by late 2024 is dependent on three separately managed space flight development programs: a crew capsule called the Orion Multi-Purpose Crew Vehicle (Orion); a heavy-lift rocket known as the Space Launch System (SLS); and launch infrastructure at Kennedy Space Center (Kennedy) referred to as Exploration Ground Systems (EGS). Collectively, these three programs are integral to the first uncrewed test mission of the integrated Orion/SLS vehicle that, at the time of our review, was slated to launch in late 2020.

In support of NASA's lunar exploration efforts known as the Artemis Program, the EGS Program manages two major software development projects: (1) the Spaceport Command and Control System (SCCS), which will operate ground equipment such as pumps, motors, and valves, and monitor Orion and SLS during launch preparations, and (2) the Ground and Flight Application Software (GFAS), which will interface with flight systems and ground crews at Kennedy. In a March 2016 audit, we reported that SCCS had significantly exceeded its initial cost and schedule estimates with development costs increasing approximately 77 percent and release of a fully operational version of the software slipping 14 months. In this audit, we evaluated NASA's management of GFAS development, specifically whether NASA has taken appropriate steps in its software development and adequately managed the risks given the complexities of parallel hardware and software development. To conduct this audit, we identified key technical risks, reviewed project schedule status, analyzed financial data, reviewed relevant documentation used in GFAS development, and interviewed program officials, engineering staff, and contractors.

WHAT WE FOUND

To accomplish its mission, the EGS Program must move vehicles to launch pads, manage and operate the equipment required to integrate crew capsules with rockets, and launch the integrated vehicles into space. Importantly, GFAS—intended to provide computer console applications and displays for pre- and post-launch activities for Orion and SLS—was the third-most critical task in terms of schedule to meet the Artemis I launch date of November 2020.

> Falling within the EGS Program, GFAS is a set of computer console applications and displays supporting ground operations preparation of Orion and SLS; integrated movement, communications, and monitoring of Orion, SLS, and EGS operations at Kennedy Space Center; and launch and landing operations.

We found the EGS Program has taken appropriate steps to manage GFAS by implementing a flexible software development process and exercising appropriate oversight and risk management. However, we found that challenges from simultaneous hardware and software development efforts resulted in revisions to GFAS and contributed to increased development costs. In addition, NASA and Lockheed Martin—the contractor developing the Orion crew capsule—took 2 years to resolve information technology security issues that delayed the GFAS team from obtaining remote access to critical test equipment at the contractor's laboratory. Overall, as of October 2019 GFAS development has cost $51 million, about $14 million more than originally planned. Although EGS managers expect GFAS to be ready in time to launch Artemis I, it is essential that the Agency incorporate lessons learned from cross-program development, integration, and testing challenges to minimize risks to future software development.

What We Recommended

As NASA prepares for the Artemis I launch and matures techniques and testing across the SLS, Orion, and EGS Programs, we recommended the Associate Administrator for Human Exploration and Operations: (1) establish procedures for continually revising documentation and processes for efficient integration of flight software development and testing requirements to minimize the risks associated with parallel program development, and (2) document and implement lessons learned regarding the process of identifying, negotiating, and implementing information technology security mitigation steps to obtain remote access and functionality with contractor laboratories.

We provided a draft of this report to NASA management, who concurred with the recommendations and described planned actions to address them. We consider the proposed actions responsive and will close the recommendations upon completion and verification of the proposed actions.

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Acronyms

CUI	Compact Unique Identifier
EGS	Exploration Ground Systems
ESD	Exploration Systems Development
GAO	Government Accountability Office
GFAS	Ground and Flight Application Software
ITL	Integrated Test Laboratory
NPR	NASA Procedural Requirements
OIG	Office of Inspector General
OMRS	Operations and Maintenance Requirements and Specifications
SCCS	Spaceport Command and Control System
SIL	Systems Integration Laboratory
SLS	Space Launch System

INTRODUCTION

Humans have not travelled outside of low Earth orbit since the end of the Apollo program in 1972. NASA's Artemis program—driven by the Vice President's announcement that the administration was directing that the Agency return astronauts to the surface of the Moon by 2024—aims to change that, establishing a sustainable human presence on the Moon and providing a springboard for human travel to Mars.[1] NASA had slated the first test mission in this program, an uncrewed flight known as Artemis I, to launch in late 2020, but as of January 2020 the Agency was reviewing the date.

Artemis is NASA's path to the Moon and the next step in human exploration. All lunar activities, including robotic and human exploration, fall under the Artemis program, and are a part of the Agency's broader Moon to Mars exploration approach. The Orion Multi-Purpose Crew Vehicle (Orion); a heavy-lift rocket known as the Space Launch System (SLS); and the ground systems, known as the Exploration Ground Systems (EGS), are the backbone of the Artemis program.

In support of the Artemis program, EGS is modernizing and upgrading infrastructure at Kennedy Space Center (Kennedy) where the integrated Orion/SLS vehicles will launch. Vital to this effort are two major software development projects: (1) the Spaceport Command and Control System (SCCS), which will operate ground equipment such as pumps, motors, and valves, and will also monitor Orion and SLS during launch preparations, and (2) the Ground and Flight Application Software (GFAS), which will interface with flight systems and ground crews at Kennedy. Broadly speaking, SCCS is a computer operating system while GFAS is application software. GFAS software development remains on the critical path to support Artemis I, and is a high risk component of the EGS Program.[2]

In a March 2016 audit, we reported that SCCS had significantly exceeded its initial cost and schedule estimates.[3] We initiated this audit to review the second major software development project under EGS. Our overall objective was to evaluate NASA's management of GFAS development, specifically whether NASA has taken appropriate steps in its software development and adequately managed the risks given the complexities of a parallel hardware and software Artemis development environment. See Appendix A for details of the audit's scope and methodology.

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[1] NASA's fiscal year 2020 budget request envisioned returning U.S. astronauts to the Moon in 2028. However, in March 2019, the Vice President accelerated that timetable and announced 2024 as the goal for a Moon landing. In May 2019, NASA sent a $1.6 billion supplemental budget request to Congress primarily to support development of commercial human lunar landing systems and assist development of Orion and SLS in an effort to achieve that expedited goal.

[2] The "critical path" is the sequence of tasks that determines the longest duration of time needed to complete a project. It is important to identify the critical path and the resources needed to complete the critical tasks along the path if a project is to be completed on time and within its allocated resources.

[3] NASA Office of Inspector General (OIG), *Audit of the Spaceport Command and Control System* (IG-16-015, March 28, 2016).

Background

The Artemis program is managed by NASA's Human Exploration and Operations Mission Directorate and represents the largest development of space flight capabilities NASA has attempted since the first Space Shuttle was launched more than 38 years ago. Artemis missions to the Moon will expand the Agency's capabilities to transport crew and large amounts of cargo beyond low Earth orbit.

In March 2019, the administration announced that NASA's plans to land humans on the Moon would be accelerated by 4 years to 2024. However, the first launch of the integrated Orion/SLS capsule and rocket is significantly behind the schedule established by NASA in 2014. Originally designated as Exploration Mission-1, the 22- to 25-day uncrewed mission to orbit the Moon was initially planned for no later than November 2018 using EGS-designed software to test system readiness for future crewed operations. In June 2017, NASA notified Congress that the November 2018 launch date was not realistic and set a new launch date for December 2019 that included 6 months schedule reserve. NASA subsequently announced a new launch date of June 2020 and then again delayed the flight to November 2020 for the mission now known as Artemis I. As of January 2020, NASA was further reviewing and updating the Artemis I launch readiness date. Additional delays in the Artemis I launch date will likely impact the schedule for subsequent flights, in particular Artemis III—the mission that plans to return humans to the Moon's surface.

Orion, SLS, and EGS Management

The Orion, SLS, and EGS programs are assigned to Johnson Space Center, Marshall Space Flight Center, and Kennedy Space Center, respectively, as the lead Centers, and each program has shown significant cost increases and schedule slippage. In March 2015, we reported that interdependencies of the three programs resulted in substantial technical and programmatic challenges that had to be overcome for the ground system to meet the planned November 2018 launch date of the first integrated Orion/SLS system, in particular delays associated with development of command and control software.[4] In a March 2016 report, we found that the Agency's decision to integrate multiple products or, in some cases, parts of products, rather than developing SCCS software in-house or buying an off-the-shelf product caused a 77 percent increase in costs and delivery to be delayed by 14 months.[5] In a September 2016 report, we questioned the Agency's timeline for Orion due to late delivery of hardware and project development issues.[6] Likewise, an October 2018 report questioned the Agency's ability to complete SLS on the schedule planned due to hardware delivery and testing issues.[7]

The EGS Program is responsible for major infrastructure components supporting ground processing and launch preparations for the integrated Orion/SLS capsule and launch vehicle, including:

- *Multi-Payload Processing Facility*, where Orion will be fueled with propellants and other fluids the spacecraft and astronauts need to maneuver the capsule. The facility is also where

[4] NASA OIG, *NASA's Launch Support and Infrastructure Modernization: Assessment of the Ground Systems Needed to Launch SLS and Orion* (IG-15-012, March 18, 2015).

[5] IG-16-015.

[6] NASA OIG, *NASA's Management of the Orion Multi-Purpose Crew Vehicle Program* (IG-16-029, September 6, 2016).

[7] NASA OIG, *NASA's Management of the Space Launch System Stages Contract* (IG-19-001, October 10, 2018).

specialized equipment will remove unused hazardous propellants from Orion’s tanks during post-flight processing.

- *Vehicle Assembly Building*, at 525 feet tall and 518 feet wide, is one of the largest buildings in the world by area. Its four high bays with their extensible work platforms enables rockets and payloads to be stacked vertically and then transported to the launch pad.
- *Mobile launcher*, a ground structure used to assemble, process, and launch Orion and SLS, consists of a two-story base that serves as a platform for the rocket and a tower equipped with connection lines, called umbilicals, that will provide Orion and SLS with power, communications, coolant, and fuel prior to launch. The tower also contains a walkway for personnel and equipment entering the Orion crew module.
- *Crawler-transporter*, a tracked vehicle the size of a baseball infield that will transport the integrated Orion, SLS, and mobile launcher from the Vehicle Assembly Building to the launch pad.
- *Launch Pad 39B*, upgraded from Apollo and Space Shuttle-era missions to support launching the SLS, the pad provides electrical power, a water tower for the Ignition Overpressure and Sound Suppression System, flame trench and deflector to handle temperatures up to 2,200 degrees Fahrenheit during launch, and a safe launch area.

Crawler-transporter 2 at Kennedy

Source: NASA

- *Launch Control Center*, the hub of launch operations at Kennedy since the Apollo program, has played an integral role in NASA's human space flight programs for nearly 50 years.
- *Rotation, Processing, and Surge Facility*, about 90 feet tall, 190 feet long, and 90 feet wide, will be used to receive the solid rocket booster segments for the SLS rocket and prepare them to be integrated with other hardware in the Vehicle Assembly Building prior to launch.

Additionally, EGS is responsible for recovery of associated Orion elements and ground support equipment such as pressure vessels, pneumatic lines, valves, and gauges that interface with flight hardware.

EGS Software Development

To accomplish its mission, the EGS Program must move vehicles to launch pads, manage and operate the equipment required to integrate crew capsules with rockets, and launch the integrated vehicles into space. As part of this effort, EGS is developing a software system known as SCCS to control ground equipment, record and retrieve data, and monitor the health and status of spacecraft as they prepare for launch. EGS is also developing GFAS, a critical part of the program that will provide computer console applications and displays for pre- and post-launch activities for Orion and SLS.

The EGS Command, Control, and Communications Office is responsible for development of GFAS with support from Jacobs Technology, Inc. (Jacobs) under the existing Kennedy Test and Operations Support

Contract.[8] GFAS development is managed collaboratively by NASA and Jacobs project managers, as well as co-leads for the subsystems described in the following section. The GFAS component of the contract has a current estimated value of approximately $60 million through September 2020.

GFAS Functionality

GFAS is a set of computer console applications and displays supporting:

- ground operations preparation of Orion and SLS and their associated systems, such as the ground power systems that provide electrical power distribution and control between the ground processing facilities and the spacecraft
- integrated Orion, SLS, and EGS operations, movement, communications, and monitoring by ground operations personnel at Kennedy
- launch and landing operations

Orion service platform inside the Multi-Payload Processing Facility at Kennedy

Source: NASA

Prior to launch, NASA and the GFAS team will certify that personnel, hardware, software, procedures, and processes are ready to support normal and contingency operations for each of the following systems:

- *Avionics*, which provides the hardware and software to enable data exchange between Orion, SLS, and EGS.
- *Integration*, which provides control and monitoring of ground support equipment, spacecraft, and launch vehicle during ground operations, testing, and launch.
- *Communication*, which provides voice, photographic/video imaging, and data transmissions between Orion, SLS, and ground personnel in the launch control room and mission control.
- *Cryogenic Propulsion*, which provides storage, transfer, loading, and use of cryogenic propellants such as super-cooled hydrogen and oxygen.
- *Electrical*, which provides electrical power to the Orion, SLS, and launch site ground support equipment during all phases of vehicle integration, ground processing, and launch operations.
- *Environmental Control, Life Support, and Hypergolic Propulsion*, which provides handling and loading of hypergolic liquids and the Environmental Control, Life Support Systems necessary for servicing the vehicle and vehicle components.[9]

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[8] In December 2012, NASA awarded the Test Operations Support Contract to Jacobs for overall management and implementation of ground systems capabilities, flight hardware processing, and launch operations at Kennedy. The contract began in March 2013 and consists of a base period and options through September 2022. The original cost-plus-award-fee contract had a maximum potential value of $1.37 billion if NASA exercised all the options. GFAS development was added as a change request to the original contract.

[9] Hypergolic fluids are used in many different rocket and aircraft systems for propulsion and hydraulic power in satellites, manned spacecraft, military aircraft, and deep space probes.

- *Flight Control*, which provides electronic equipment and sensors related to the guidance, navigation (positioning), and controls (attitude and directional) of the Orion and SLS.
- *Auxiliary Power Unit and Hydraulic Operations*, which provides hydraulic pressure for performing thrust vector control testing on the solid rocket booster nozzles and Core Stage engines, as well as performing integrated testing for the Auxiliary Power Unit and launch countdown operations.[10]
- *Master*, which provides the ability to configure a Launch Control System set, control the hardware that makes up the set, and monitor the current condition of all hardware within the set.[11]
- *Mechanical*, which provides Environmental Control System purges to the integrated Orion and SLS vehicle, the launch pad sound suppression, and all launch accessories subsystems associated with the operation of the Mobile Launcher.

Cross-Program Integration

System integration for the Artemis Program is the process of bringing together the Orion, SLS, and EGS technical designs, hardware, and software to deliver a complete and functioning space flight system. Contrary to how NASA has organized previous space flight efforts with a single program manager and a contractor to support integration efforts, each program simultaneously manages its individual tasks while also participating in integration efforts in preparation for Artemis I. For example, Orion and SLS engineers are individually developing flight software unique to their respective programs—Orion is focused on the crew capsule, flight systems, and crew systems, while SLS is focused on the launch, ascent, and propulsion systems. At the same time, the GFAS team must integrate the Orion and SLS flight software with the ground control systems for vehicle assembly, launch readiness, and post-mission vehicle recovery and de-servicing. In 2017, the Government Accountability Office (GAO) reported that NASA's organizational approach for the programs' development provides greater cost efficiencies by requiring a smaller systems integration workforce size, minimizing chain-of-command decision makers, and allowing Orion, SLS, and EGS to proceed at their own pace. However, GAO also noted that this approach introduced oversight challenges and increased the likelihood that cross-program integration and testing challenges would develop.[12]

GFAS depends on both Orion and SLS to provide flight software, data products, emulators, and Operations and Maintenance Requirements and Specifications (OMRS) for cross-program integration and testing.[13] The Exploration Systems Development (ESD) office within NASA's Human Exploration and

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[10] During launch, the solid rocket booster nozzles direct the expanding gases via thrust vector control from the burning solid propellant downward, enabling the SLS to remain upright and on the correct trajectory. As planned, the SLS core stage would be the world's tallest and most powerful rocket stage. It will store cryogenic liquid hydrogen and liquid oxygen to power the stage's four RS-25 engines. It will also house the flight computers and much of the avionics needed to control the SLS's flight.

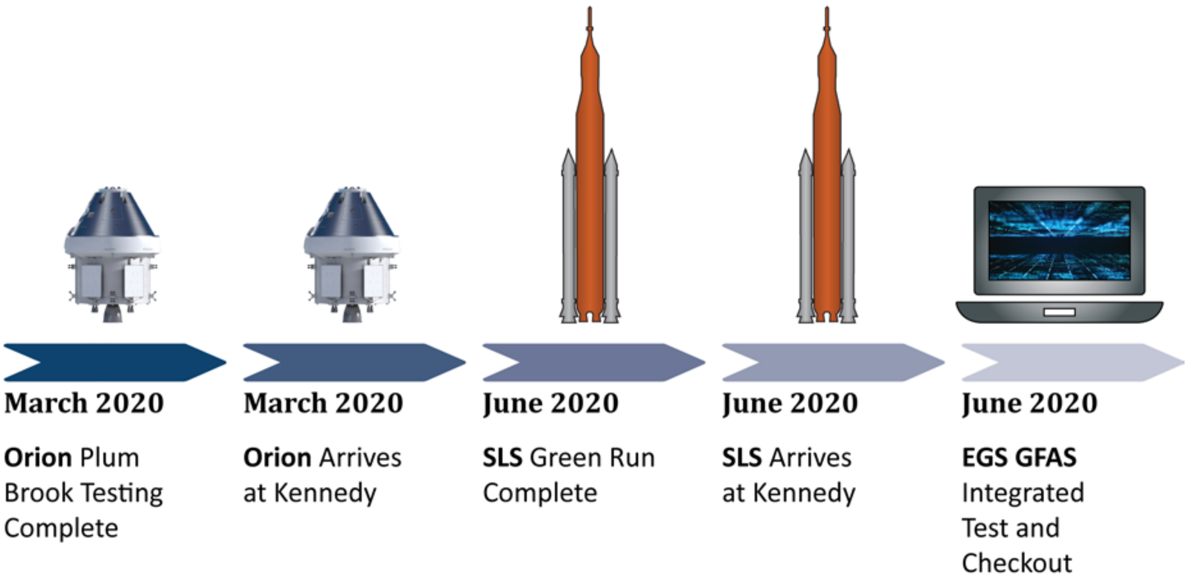
[11] A software set is composed of execution engines, control scripts, and displays that make up the user interface controlling the desired functionality.

[12] GAO, *NASA Human Space Exploration: Integration Approach Presents Challenges to Oversight and Independence* (GAO-18-28, October 19, 2017). Cross-program integration and testing refers to activities impacting more than one of the programs.

[13] Data products are the result of raw data processing into usable spacecraft, ground control, and communication data. An emulator is a hardware device or software program that enables one computer system to imitate the functions of another computer system.

Operations Mission Directorate is responsible for integrating the Orion, SLS, and the EGS programs. Specifically, the Cross-Program Systems Integration office is responsible for the development, management, and delivery of integrated technical requirements, interfaces, and data products through integration teams comprised of members from the Orion, SLS, and EGS programs. Although the integration teams are responsible for producing and managing cross-program integration technical products, the Orion, SLS, and EGS programs have the authority to jointly develop and control most cross-program data products needed to execute their respective programs and to meet the requirements of milestone reviews. Key cross-program integration milestones are shown in Figure 1.

Figure 1: GFAS Key Cross-Program Milestones



Source: NASA OIG presentation of NASA data.

OMRS are used to communicate to GFAS software developers (and the other programs) detailed requirements in support of launch processing activities such as integrated testing, servicing, and launch countdown. They define mandatory, unique configuration constraints or timed activities that are required to comply with the intent of a requirement. Ultimately, software developed within each of the programs has to link to OMRS and communicate with software developed in the other programs in order to support the launch and landing of the Artemis exploration mission.

Management and implementation of well-defined OMRS are integral to ground testing, launch, and recovery operations. OMRS are cross-program approved requirements levied upon EGS for implementation of ground processing operations, as well as for integration of the flight elements and ground support equipment needed to validate launch readiness of the integrated Orion and SLS vehicle. OMRS are driven primarily by safety, reliability, and operational analyses and provide the strategy, agreed to by all three space flight programs, for ground testing and operations. OMRS may include imaging support for safety-related hazard control and avoidance such as a video streaming capability to monitor the thermal protection systems on SLS components for ice formation.[14] In order for the overall program to be successful, OMRS must be timely and well defined.

ESD Integration Approach

The Cross-Program Systems Integration Office is responsible and accountable for technical integration across the ESD Enterprise. The ESD Enterprise is defined as the portfolio of capabilities under development, currently encompassing the Orion, SLS, and EGS programs as well as the necessary integration among the three programs to deliver the initial capabilities required for human space flight beyond low Earth orbit. Decision making is performed through various cross-program teams, boards, and panels with authority delegated from ESD. Examples include:

- *The Integrated Avionics and Software Integration Task Team* is responsible for ensuring that the integrated avionics and software assets developed, tested, and delivered by Orion, SLS, and EGS meet the technical requirements.
- *The Joint Integrated Control Board* controls the integrated Enterprise technical baseline and makes technical decisions needed to meet established milestones.
- *The OMRS Panel* approves new OMRS or changes to existing OMRS that do not impact the Enterprise overall cost, schedule, or technical baseline beyond the OMRS content itself. Unresolved OMRS technical issues or cost, schedule, or risk impacts are elevated to the Joint Integrated Control Board.
- *The Launch Commit Criteria Panel* oversees the development and management of launch commit criteria that ensure flight and ground systems are performing as required in launch countdown to support the safety of the flight and ground crew, public safety, integrated vehicle safety, and to ensure mission success.

Additional program-level boards involved in software integration include the Orion Flight Software Control Board, the SLS Avionics and Software Control Board, and the EGS Command, Control, and Communications Forum. Each of these program boards includes cross-program representation as well as Integrated Avionics and Software Integration Task Team representation. Disagreements between programs at the program boards are elevated to the Joint Integrated Control Board.

Cross-Program Testing for Flight Software

ESD is responsible for managing and integrating the parallel development of the Orion spacecraft, SLS launch vehicle, and EGS ground systems, including software such as GFAS. The GFAS development team relies on the Orion Program to provide flight software and data products for cross-program testing. The flight software runs on Orion computers and controls how the flight computers operate internally and how they communicate with other devices. The Orion Program provides the GFAS team flight software and data products through software releases about every 3 months; these releases include flight software, simulation software, data files, and reports to support operations.

In addition to the Orion flight software and data products, GFAS also relies on the SLS Program to provide flight software and data products for the core stage flight computers, RS-25 engines, and

[14] Spray-on foam insulation, along with other traditional insulation materials such as cork, provide thermal protection for every SLS part. Thermal protection is critical to enabling the cryogenic hydrogen and oxygen fuel to maintain its liquid state while SLS builds up tremendous amounts of heat as it accelerates through the atmosphere.

Interim Cryogenic Propulsion Stage. EGS uses flight software and data products from Orion and SLS to create software for development and integrated testing. Moreover, EGS may be required to update its ground systems software prior to launch per a change in OMRS. For example, the software for the Interim Cryogenic Propulsion Stage telemetry systems may need to be updated prior to launch due to a late hardware or flight telemetry change.

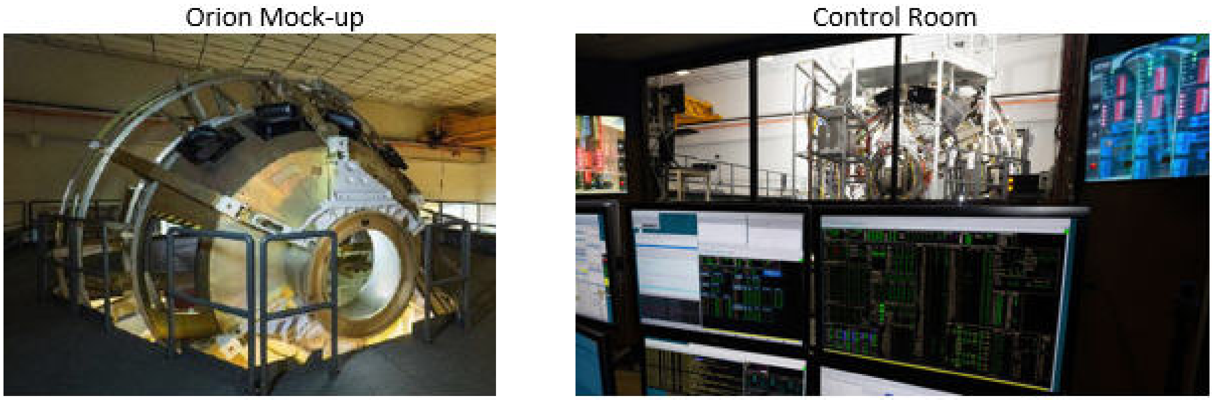
GFAS Testing

The complexity of human space flight requires significant time to develop and test components to ensure they are operating as designed—with the ultimate goal of ensuring the safety of the flight crew and success of the mission. The GFAS team performed preliminary testing of its software at Kennedy's Customer Avionics Interface Development and Analysis Laboratory using Orion and SLS equipment to simulate the behavior of flight and ground equipment. The simulations help demonstrate the capacity and capability of the different systems (i.e., avionics, propulsion, electrical) needed to keep, for example, a countdown progressing towards liftoff.

Additional GFAS integrated testing is accomplished in two off-site laboratories—the Integrated Test Laboratory (ITL) in Denver, Colorado, and the Systems Integration Laboratory (SIL) at Marshall Space Flight Center. A team of Kennedy engineers performs integrated testing at the laboratories and validates the software in a mock environment to ensure it performs as expected. These laboratories provide the most realistic test environment possible before the flight hardware and software are onboard the assembled spacecraft. Using laboratory emulators—some of which are provided by the EGS Program—software engineers are able to test systems, such as avionics, in a realistic configuration that can simulate the environmental and dynamic data as would be experienced in actual flight. Interactions with the natural environment and full vehicle dynamics, as well as system behaviors and various scenarios of equipment failures, environmental factors such as temperature and wind, and other performance profiles, are produced through these emulators, providing the GFAS team with the data needed to test software functionality.

Lockheed Martin's ITL was built to test Orion's computer systems. The laboratory's centerpiece is a structure mirroring the size, material, and shape of the Orion capsule (see Figure 2). The ITL is used to perform integration, verification, and validation testing of Orion avionics hardware and software, as well as the spacecraft's electrical power system. Over the past several years, ITL has run numerous simulations on Orion's computer, testing more than 1 million lines of software code to make sure the capsule and its sensors and controls will operate as expected.

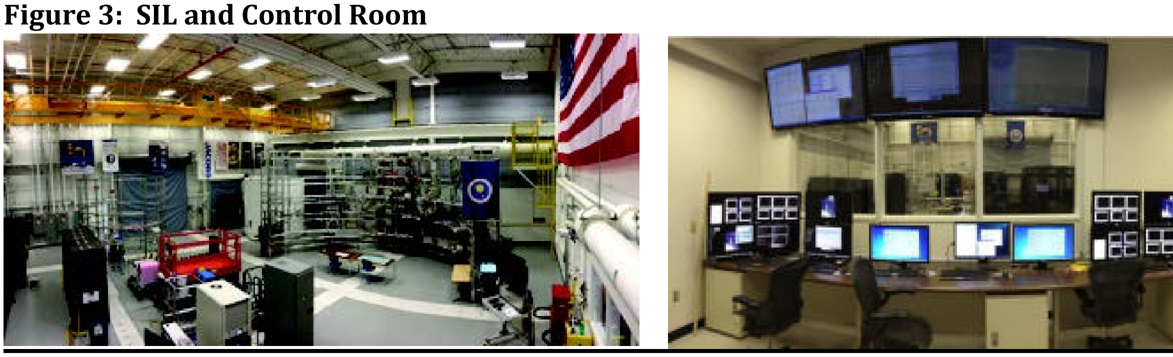
Figure 2: ITL Mock-up and Control Room



Source: NASA/Lockheed Martin

First used during the Space Shuttle Program, the SIL now supports development of the SLS by providing an integrated testing environment for the rocket's flight software and avionics hardware and accommodating a variety of avionics configurations and integrated simulations for demonstrating real-time SLS flight control during ascent (see Figure 3). In addition to on-site software testing capabilities, the SIL provides remote access to an EGS-provided emulator.[15]

Figure 3: SIL and Control Room



Source: NASA

[15] The EGS-provided emulator is used to develop and test the vehicle-to-ground interfaces of Orion, SLS, and EGS Ground Systems. The emulator runs EGS ground support equipment simulations and interfaces with flight vehicle simulations.

NASA Has Taken Appropriate Steps to Manage GFAS Development, but Actions are Needed to Minimize Risks to Future Software Development Efforts

We found that the EGS Program has taken appropriate steps to manage GFAS development efforts, implementing a flexible software development effort, appropriate oversight, and risk management processes. However, we found that challenges from a parallel hardware and software development environment resulted in needed revisions to GFAS and contributed to increased development costs. In addition, it took NASA and Lockheed Martin 2 years to resolve information technology security issues and delayed the GFAS team from obtaining remote access to the emulator at ITL. Collectively, as of October 2019, GFAS development had cost $51 million, about $14 million more than originally planned. Although EGS managers expect GFAS to be ready in time to launch Artemis I, it is essential that the Agency incorporate lessons learned from cross-program development, integration, and testing challenges to minimize risks to future software development.

Management Implemented a Flexible Software Development Approach with Appropriate Oversight and Risk Mitigation

In our judgement, the GFAS team has implemented an appropriate software development methodology given that Orion and SLS are still in development. The software development life cycle is the methodology that gives structure to the process of writing application software, ensures the development team does not skip a step in any phase of the project, and helps the project meet deadlines. For GFAS, EGS selected a hybrid software development life-cycle approach—a blend of the Waterfall and Scrum software development processes—to create the application code used for Artemis I.

Generally, a Waterfall approach allows the development team to produce software as one large project, where the product "owner" only sees the finished software at the end of the project. Pros and cons of this approach are described in Table 1.

Table 1: Waterfall Software Development Pros and Cons

Waterfall	
Pros	**Cons**
Design requirements agreed to at project start	Limited stakeholder involvement
Production documentation written in tandem with code development	Unsuitable for complex projects
Highly structured process with concrete milestones	Unsuitable for projects with changing requirements

Source: NASA OIG analysis of software developers' information.

In contrast, the Scrum methodology approaches a software development effort as a series of small projects called sprints—producing working software in iterations. This type of agile software development is often used when project requirements are likely to change or are not completely known at the start of the project. For each software iteration, the teams identify requirements and then design, develop, and test the software to determine if it meets those requirements. For example, after the GFAS team develops a software iteration, it is tested at Kennedy with emulators to simulate the applicable hardware and software ground processing and launch configurations. Pros and cons of the Scrum software development approach are described in Table 2.

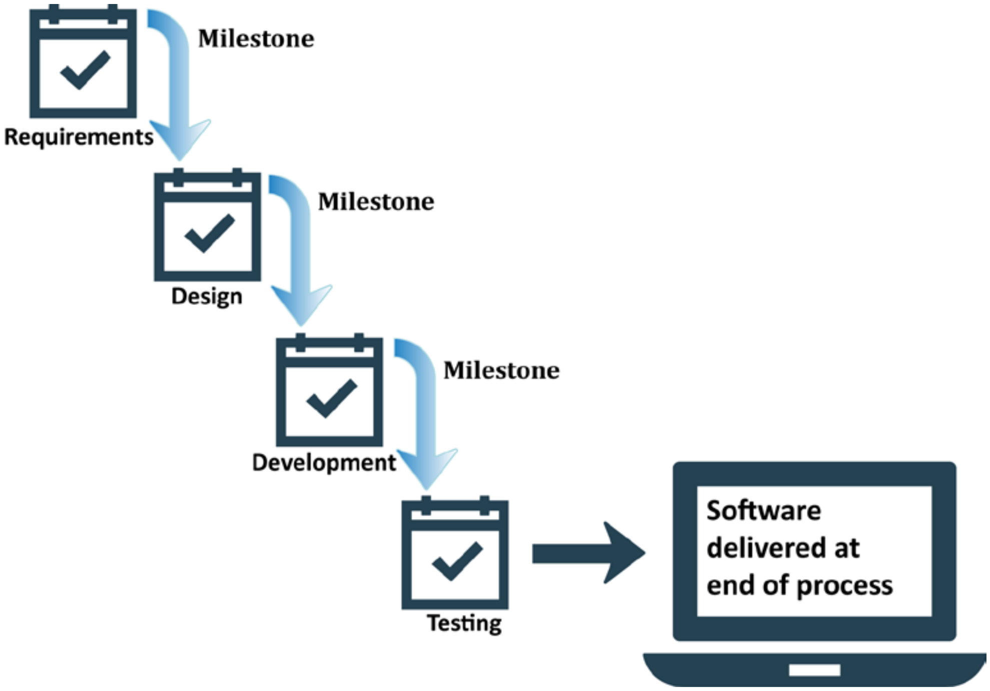
Table 2: Scrum Software Development Pros and Cons

Scrum	
Pros	**Cons**
Continuous stakeholder involvement	Deliverable delays
Best for large, complex projects	Requires highly skilled, experienced team
Flexible, ability to adjust to changing requirements	Daily sprint meetings are time consuming

Source: NASA OIG analysis of software developers' information.

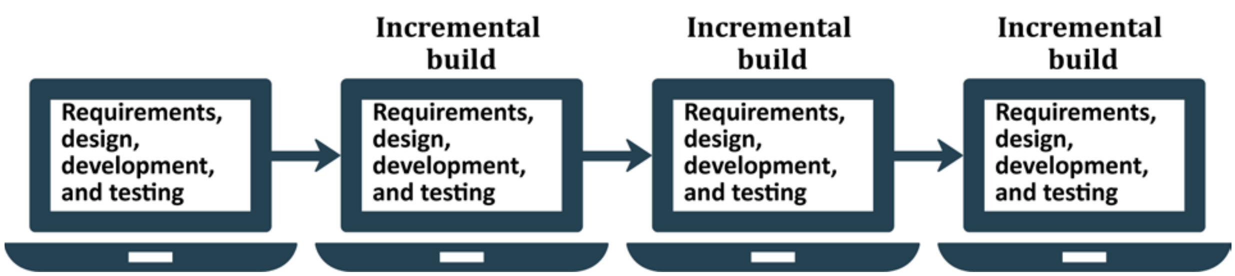
As shown in Figures 4 and 5 below, both methodologies use requirements identification, design, development, and testing. The key difference between Waterfall and Scrum software development is how those steps are implemented in the software development process.

Figure 4: Phases of the Waterfall Software Development Method



Source: NASA OIG.

Figure 5: Iterations of Working Software in the Scrum (Agile) Software Development Method



Source: NASA OIG.

The GFAS team developed a hybrid approach that combines Waterfall's sequential processes—requirements, design, development, and testing—with Scrum's incremental software builds. This hybrid approach enabled simultaneous development and testing of subsystems including avionics, electrical, and mechanical. According to EGS officials, the hybrid approach helps the GFAS team to manage the ever-changing Orion and SLS requirements through continuous feedback and delivery. Moreover, GFAS managers established a methodology that allows development teams to work on their subsystems in parallel to mitigate impacts from changing requirements and flight software data products.

GFAS Oversight Follows Best Practices

We found that the software development team is following NASA and Institute of Electrical and Electronics Engineers best practices by having GFAS tested and approved by independent organizations outside of the development team.[16] NASA provides oversight of Jacobs' development of GFAS and together the NASA and the GFAS team approve the requirements, design, development, and testing of the software. During periodic reviews, technical oversight is further provided by NASA officials from the Technical Review Panel and Integrated Engineering Review Board.[17] Lastly, teams from NASA's Office of Safety and Mission Assurance and the Independent Verification and Validation Program independently evaluated the software to identify and help resolve mission and safety critical defects during the GFAS development.[18] Oversight and testing by these independent organizations validate that time-critical software commands as defined by the OMRS, such as opening a liquid oxygen purge valve for gas flow, have been satisfied. NASA officials told us this multi-pronged oversight provides an additional layer of software functionality validation.

GFAS Risk Management Process Complies with NASA Policy

We found the GFAS team was complying with NASA policy and following the risk management processes established by the EGS Program.[19] The GFAS team identified and reported risks to responsible officials and assessed and scored each risk based on likelihood and consequence. As of October 2019, the GFAS team was managing two top risks related to Orion/SLS interdependencies and the development schedule, as we describe in the following sections. Subsequently, these risks were elevated to the program level within EGS and ESD for tracking and management.

Risk management is a proactive decision process that continuously assesses what could go wrong (risks), analyzes and prioritizes the risks, implements strategies to deal with those risks, and assures effectiveness of the implemented strategies. From an Orion, SLS, and EGS integration perspective, a risk framework is used to inform decision-making by identifying risk drivers (e.g., safety, technical, cost, and schedule requirements) and continuously monitoring those risks across all three programs. For example, the GFAS team has identified the SLS Green Run test results—a test of SLS avionics, navigation, propellant systems, and flight software controlling the first 8 minutes of flight—as a risk to GFAS software development. Specifically, in February 2018, NASA stated that the Green Run test was scheduled for spring 2019; however, SLS development challenges delayed testing until January 2020. Until the SLS Program completes this test, analyzes the results, and provides the data to GFAS, its potential impacts to the GFAS software development program are unknown.

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16 NASA Procedural Requirements (NPR) 7150.2C, *NASA Software Engineering Requirements* (November 19, 2014) and Institute of Electrical and Electronics Engineers Standard 1012, *Standard for System, Software, and Hardware Verification and Validation* (August 2, 2019).

17 The Technical Review Panel is a forum for discussing the scope and rationale for all requirements. Membership for the Technical Review Panel includes the Jacobs GFAS Technical Integrator, NASA GFAS Technical Lead, Systems Engineering Integration and Operations, and the Chief Engineer. The Integrated Engineering Review Board reviews and endorses GFAS work.

18 The Goddard Space Flight Center manages the Independent Verification and Validation Program, which operates under the Office of Safety and Mission Assurance, and resides at the Katherine Johnson Independent Verification and Validation Facility in Fairmont, West Virginia. The Program was established in 1993 as a result of recommendations made by the National Research Council and the Report of the Presidential Commission on the Space Shuttle Challenger Accident.

19 NPR 8000.4B, *Agency Risk Management Procedural Requirements* (December 6, 2017).

Although the GFAS team has established an appropriate risk management strategy, it is too early to determine how well NASA officials will identify and analyze the integrated risks across Orion, SLS, and EGS programs to mitigate potential issues. In January 2019, the Aerospace Safety Advisory Panel issued a similar finding and found that although each of the space flight programs identifies, tracks, and communicates risks using similar approaches, it did not know enough about how risks are integrated across all three programs to analyze their interdependencies.[20]

Cross-Program Development, Integration, and Testing Challenges

Although NASA followed appropriate processes for the GFAS development efforts, the Agency encountered many challenges from a parallel development environment where software was being developed at the same time as hardware, emulators, and OMRS. Challenges contributing to GFAS revisions and increased costs include:

- OMRS Changes. ESD officials explained that the initial philosophy was to integrate Orion, SLS, and EGS software products early and often; however, implementing this philosophy proved difficult in a parallel development environment. Because each individual program is responsible for developing its respective OMRS, a fundamental understanding of the others' OMRS, their genesis, and the consequences of nonperformance is mandatory for successful integration. Nevertheless, changes in each program's OMRS continue to occur, and the process to certify that GFAS meets these requirements is constantly changing, limiting the GFAS team's ability to effectively plan resource requirements. For instance, in August 2019, the GFAS team needed an additional 190 hours of work to reconcile modified OMRS resulting from changes associated with Orion flight software updates. Although changes to OMRS were expected as the designs matured and were tested, the volume of GFAS rework due to parallel development was unanticipated.

- Interface Maturation. The readiness of detailed interfaces between the Orion flight software and GFAS was more complex than anticipated. Specifically, trying to synchronize 148,000 Orion Compact Unique Identifiers (CUI) that directly link to the completion of software content has been difficult.[21] The Orion CUIs are used extensively within the OMRS, which drive GFAS requirements and content. Due to the immaturity of the spacecraft software, there was considerable "churn" in the Orion CUIs, resulting in rework in GFAS code and displays. Early previews and product deliveries along with regular interactions at the technical and management levels were established to help manage the extent of Orion CUIs.

- Concurrent Emulator Development. Prior to buildup of the ITL and SIL, Kennedy's Customer Avionics Interface Development and Analysis laboratory was the prime location for integrating and operating the simulations and emulations delivered from Orion and SLS. For example, SLS developed and delivered eight emulators to the Kennedy laboratory in April 2015, and two additional emulators in July 2018. Concurrently, EGS developed emulators that run EGS ground support equipment and interface with flight vehicle simulations provided by the other

[20] Aerospace Safety Advisory Panel Annual Report for 2018 (January 2019).

[21] A Compact Unique Identifier (CUI) represents specific hardware end items within a software application. Generally, CUIs are used for data display or logging purposes within GFAS.

programs. EGS delivered its emulators to the SIL in January 2017, and ITL in June 2017. With the high demands for testing at the ITL, the Orion Program set up an alternate location for some GFAS testing at the Houston Orion Test Hardware facility and EGS developed and delivered its emulator to the facility in March 2018.

Taken together, the integration of the multiple, parallel development efforts and continued delays in Orion and SLS hardware required inordinate flexibility on the part of ESD managers, who stated that a proactive and integrated cross-program team is in place to ensure completion of the remaining GFAS development testing.

Lack of Remote Access to the EGS Emulator at the Integrated Test Laboratory

The two laboratories needed for integrated testing of Artemis flight systems with the EGS ground systems—the Lockheed Martin ITL in Colorado and NASA's SIL in Alabama at Marshall Space Flight Center—are in high demand, and the GFAS team said scheduling time at either is a challenge. To help with the offline updates and troubleshooting of the EGS emulator at Marshall Space Flight Center, the SIL offers remote access—meaning that the GFAS team can perform some configuration updates, software patching, and commanding of SLS avionics and flight control hardware without having to be on-site at the laboratory. Conversely, this type of remote access was not available to the EGS emulator at the ITL, which would have allowed the GFAS team to "buy down" schedule risks by providing software testing and resolution of programming errors while avoiding delays associated with travel and mitigating scheduling difficulties for on-site laboratory access.

Because of Lockheed Martin's information security concerns, NASA information security requirements, challenges in determining an appropriate network architecture, and the need to invest in additional firewalls, it took the past 2 years for the EGS and Orion programs to implement appropriate solutions.[22] EGS officials explained that they worked with Orion and Lockheed Martin officials to resolve the access issue by splitting testing functionality into two parts, with the team able to first establish telemetry remote access to the EGS emulator at the ITL in September 2019. The second phase—the ability to command the EGS emulator at the ITL from Kennedy—was completed in November 2019.

Although remote access to the EGS emulator does not eliminate the need for travel to the ITL, GFAS officials said that it will reduce GFAS development risks and increase flexibility for software testing. Looking forward, remote access will be important for increasing testing efficiency in future hardware and software updates, such as when NASA transitions SLS from using the Interim Cryogenic Propulsion Stage to the Exploration Upper Stage for Artemis IV.[23]

Cost and Schedule Impacts

As of October 2019, GFAS had cost about $14 million more than initially planned due in part to integration challenges associated with the parallel development efforts. Moreover, EGS managers will be challenged to ensure that the additional GFAS development work and integrated testing is complete

[22] Firewalls block unauthorized computer network access. A firewall may be implemented using hardware, software, or a combination of both.

[23] In October 2019, NASA announced that it had taken steps to ensure production of up to 10 SLS core stages to support Artemis missions through the next decade.

in time for the Artemis I launch. NASA made initial cost estimates based on the anticipated size and complexity of the GFAS software and consulted with Shuttle subject matter experts in an attempt to mitigate some of the unknown variables. However, late delivery of Orion and SLS hardware and continuously changing requirements from both programs resulted in NASA underestimating the level of effort needed to develop GFAS, resulting in cost increases. As shown in Table 3, GFAS spent $51 million on software development and testing through September 2019.

Table 3: GFAS Funding

Fiscal Year (dollars in millions)							
Budget Authority	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**Total**
2016 Funding Plan	--	$8.5	$10.2	$10.2	$4.2	$3.5	$36.6
Actual Cost	$2.2	$6.1	$8.6	$9.4	$12.3	$12.4	$51.0

Source: NASA Budget Data.

Until Orion and SLS OMRS are finalized, the GFAS team lacks crucial information needed to complete and test their software. For example, in November 2019, the Orion capsule moved to Plum Brook Station in Sandusky, Ohio, where it will undergo environmental testing in conditions simulating the vacuum and temperature of space.[24] Meanwhile, the SLS Core Stage did not ship to Stennis Space Center for its 6 months of SLS Green Run testing until January 2020. Unforeseen setbacks delayed Orion’s testing at Plum Brook and the SLS Green Run test at Stennis multiple times.

Nevertheless, EGS officials said they expect to have GFAS ready for the Artemis I launch, even though, as of January 2020, the Human Exploration and Operations Mission Directorate was still in the process of determining a new launch date. ESD officials said cross-program processes and working groups were in place and have evolved over time to provide a robust capability to resolve integration and parallel development challenges in a timely manner. These processes and working groups use a standard software tool that is reviewed by ESD, Orion, SLS, and EGS to identify issues that must be resolved prior to integrated GFAS testing. Cross-program issues are assigned a criticality, a due date, and a Problem Resolution Team owner responsible for resolving these issues. The Problem Resolution Team reports progress every other week to senior management and issues are elevated to the Joint Integrated Control Board for resolution and disposition when required.

[24] Plum Brook Station is a component facility of Glenn Research Center. The Space Environments Complex at Plum Brook houses the world's largest Space Simulation Vacuum Chamber as well as powerful reverberant acoustic chambers and a high capacity mechanical vibration test facility.

CONCLUSION

Nearly every piece of hardware in use on a NASA launch vehicle, spacecraft, ground system, or network requires software to monitor or control its operation. Importantly, EGS software—providing computer console applications and displays for pre- and post-launch activities for Orion and SLS—was the third-most critical task in terms of scheduling to meet the planned November 2020 Artemis I launch date. As hardware and software capabilities are developed on the Orion and SLS flight systems, GFAS is vital to the overall development and implementation of ground applications to launch Artemis I.

Overall, we found the NASA EGS Program has taken appropriate steps to manage the GFAS development efforts. That said, the Agency needs to continue to improve cross-program integration and testing to ensure GFAS readiness for the Artemis I launch. Specifically, we found that changes in OMRS continue to occur due to parallel development challenges among the Orion, SLS, and EGS programs, contributing to increased GFAS costs and schedule delays. In addition, it took 2 years for NASA and Lockheed Martin to resolve information security issues and provide EGS with remote access to its emulator at the ITL in Colorado.

As NASA continues its progress toward the Artemis I launch, and in order to ensure GFAS is functional and ready, it is essential that the Agency implement cross-program development, integration, and testing lessons learned as early as possible to avoid unnecessary delays and cost increases.

Recommendations, Management's Response, and Our Evaluation

As the Agency prepares for the Artemis I launch and matures techniques and testing across the Orion, SLS, and EGS programs, we recommended the Associate Administrator for Human Exploration and Operations:

1. Establish procedures for continually revising documentation and processes for efficient integration of flight software development and testing requirements to minimize the risks associated with parallel program development.

2. Document and implement lessons learned regarding the process of identifying, negotiating, and implementing information technology security mitigation steps to obtain remote access and functionality with contractor laboratories.

We provided a draft of this report to NASA management who concurred with the recommendations and described planned actions to address them. We consider the proposed actions responsive to our recommendations and will close the recommendations upon completion and verification of the proposed actions.

Management's comments are reproduced in Appendix B. Technical comments provided by management have also been incorporated, as appropriate.

Major contributors to this report include Raymond Tolomeo, Science and Aeronautics Research Director; Mindy Vuong, Project Manager; Mike Beims; Wayne Emberton; Linda Hargrove; and Matt Ward.

If you have questions or wish to comment on the quality or usefulness of this report, contact Laurence Hawkins, Audit Operations and Quality Assurance Director, at 202-358-1543 or laurence.b.hawkins@nasa.gov.

Paul K. Martin
Inspector General

Appendix A: Scope and Methodology

We performed this audit from March 2019 through February 2020 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.

Our overall objective was to evaluate NASA's management of GFAS development relative to achieving technical objectives, meeting milestones, and controlling costs. To conduct our audit, we assessed whether NASA has taken appropriate steps in its software development and adequately managed the risks given the complexities of a parallel hardware and software Artemis development environment. We identified key technical risks, reviewed project schedule status, and analyzed current and past financial data. We also reviewed relevant documentation used in GFAS development decision making and status reports. Lastly, we discussed the technical risks, cost to schedule impacts, and the cross-program dependencies with responsible officials, engineering staff, and contractors to gain their perspective on progress and challenges as the GFAS team works towards the current schedule milestones. The scope of this audit was GFAS' readiness to support Artemis I launch.

Use of Computer-Processed Data

We used limited computer-processed data to perform this audit. Specifically, we obtained access to NASA financial systems and reviewed various budget reports for fiscal years 2014 through 2020. We verified the accuracy of select data by reviewing related documentation, interviewing agency officials, and analyzing actual cost data. From these efforts, we determined the information obtained was sufficiently reliable for this audit.

Review of Internal Controls

We reviewed and evaluated the internal controls associated with NASA's management of GFAS. We concluded that the internal controls, except for those practices discussed in the report, complied with Agency requirements and best practices. The recommendations presented in the report, if implemented, should correct the identified weaknesses affecting GFAS development.

Prior Coverage

Although the NASA Office of Inspector General (OIG) has not issued any reports in the last 5 years directly related to GFAS, it has issued reports on other aspects of Artemis I development. Unrestricted reports can be accessed at https://oig.nasa.gov/audits/auditReports.html and http://www.gao.gov, respectively.

NASA Office of Inspector General

2018 Report on NASA's Top Management and Performance Challenges (November 15, 2018)

NASA's Management of the Space Launch System Stages Contract (IG-19-001, October 10, 2018)

NASA's Plans for Human Exploration Beyond Low Earth Orbit (IG-17-017, April 13, 2017)

NASA's Management of the Orion Multi-Purpose Crew Vehicle Program (IG-16-029, September 6, 2016)

Audit of the Spaceport Command and Control System (IG-16-015, March 28, 2016)

Launch Support and Infrastructure Modernization Efforts: Assessment of the Ground Systems Needed to Launch SLS and Orion (IG-15-012, March 17, 2015)

Government Accountability Office

NASA Human Space Exploration: Persistent Delays and Cost Growth Reinforce Concerns over Management of Programs (GAO-19-377, June 19, 2019)

NASA: Assessments of Major Projects (GAO-19-262SP, May 30, 2019)

NASA Major Projects: Portfolio Is at Risk for Continued Cost Growth and Schedule Delays (GAO-18-576T, June 14, 2018)

NASA: Assessments of Major Projects (GAO-18-280SP, May 1, 2018)

NASA Human Space Exploration: Integration Approach Presents Challenges to Oversight and Independence (GAO-18-28, October 19, 2017)

NASA Human Space Exploration: Delay Likely for First Exploration Mission, (GAO-17-414, April 27, 2017)

NASA Human Space Exploration: Opportunity Nears to Reassess Launch Vehicle and Ground Systems Cost and Schedule (GAO-16-612, July 27, 2016)

APPENDIX B: MANAGEMENT'S COMMENTS

National Aeronautics and Space Administration
Headquarters
Washington, DC 20546-0001

MAR 1 3 2020

Reply to Attn of: Human Exploration and Operations Mission Directorate

TO: Assistant Inspector General for Audits

FROM: Associate Administrator for Human Exploration and Operations Mission Directorate

SUBJECT: Agency Response to OIG Draft Report, "NASA's Management of Ground and Flight Application Software (GFAS) Development" (A-19-008-00)

The National Aeronautics and Space Administration (NASA) appreciates the opportunity to review and comment on the Office of Inspector General (OIG) draft report entitled, "NASA's Management of Ground and Flight Application Software (GFAS) Development" (A-19-008-00), dated February 13, 2020.

NASA appreciates the OIG's review and believes that implementing the associated recommendations will strengthen NASA's ability to successfully manage ground and flight application software development for the complex integrated missions the Agency is undertaking.

In the draft report, the OIG makes two recommendations addressed to the Associate Administrator for Human Exploration and Operations Mission Directorate relating to the maturity of techniques and testing across the Orion, Space Launch System (SLS), and Exploration Ground Systems (EGS) programs.

Specifically, the OIG recommends the following:

As the Agency prepares for the Artemis I launch and matures techniques and testing across the Orion, SLS, and EGS programs, the Associate Administrator for Human Exploration and Operations Mission Directorate (HEOMD) should:

Recommendation 1: Establish procedures for continually revising documentation and processes for efficient integration of flight software development and testing requirements to minimize the risks associated with parallel program development.

Management's Response: NASA concurs. The Exploration Systems Development (ESD) Cross-Program Systems Integration (CSI) organization is responsible and accountable for technical integration across the ESD Enterprise (Orion, SLS, and EGS). The OIG fairly noted the challenges that are faced in parallel development programs, and NASA has taken steps to address these challenges as they occur. NASA will brief the OIG on these steps and will continue to monitor this area to ensure efficient integration of flight software development and testing requirements to minimize the risks associated with parallel program development.

Estimated Completion Date: April 30, 2020.

Recommendation 2: Document and implement lessons learned regarding the process of identifying, negotiating, and implementing information technology security mitigation steps to obtain remote access and functionality with contractor laboratories.

Management's Response: NASA concurs. The EGS Program will fully document the lessons learned resulting from the impacts of parallel program development of GFAS identified in this report. HEOMD will continue to utilize the expertise of ESD CSI organization to assure current and future programs take appropriate action to obtain remote-access and functionality with contractor laboratories, as well as, recommending any necessary adjustments to resultant NASA policy documentation.

Estimated Completion Date: September 30, 2020.

We have reviewed the draft report for information that should not be publicly released. As a result of this review, we have not identified any information that should not be publicly released.

Once again, thank you for the opportunity to review and comment on the subject draft report. If you have any questions or require additional information regarding this response, please contact Lynne Loewy on (202) 358-0549.

Douglas Loverro

APPENDIX C: REPORT DISTRIBUTION

National Aeronautics and Space Administration

Administrator
Deputy Administrator
Associate Administrator
Chief of Staff
Associate Administrator for Human Exploration and Operations Mission Directorate

Non-NASA Organizations and Individuals

Office of Management and Budget
    Deputy Associate Director, Energy and Space Programs Division

Government Accountability Office
    Director, Contracting and National Security Acquisitions

Congressional Committees and Subcommittees, Chairman and Ranking Member

Senate Committee on Appropriations
    Subcommittee on Commerce, Justice, Science, and Related Agencies

Senate Committee on Commerce, Science, and Transportation
    Subcommittee on Aviation and Space

Senate Committee on Homeland Security and Governmental Affairs

House Committee on Appropriations
    Subcommittee on Commerce, Justice, Science, and Related Agencies

House Committee on Oversight and Reform
    Subcommittee on Government Operations

House Committee on Science, Space, and Technology
    Subcommittee on Investigations and Oversight
    Subcommittee on Space and Aeronautics

(Assignment No. A-19-008-00)