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LEVERAGING DIGITAL ENGINEERING FOR SPACE GUARDIANS AND SPACE EXPLORERS

ANGELIA P. BUKLEY AND RONALD J. BIRK
THE AEROSPACE CORPORATION

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DR. ANGELIA P. BUKLEY

Dr. Angelia P. Bukley is an assistant principal director in the Human Exploration and Space Flight Division, Civil Systems Group, at The Aerospace Corporation. She has over 35 years of experience working in the space enterprise supporting both military and civil space programs. She has over 100 technical publications to her credit and nearly 30 awards for technical merit and service. She holds a Ph.D. in electrical engineering with a specialty in control theory from the University of Alabama in Huntsville.

RONALD J. BIRK

Ronald Birk is associate principal director in the Development Directorate, Civil Systems Group, at The Aerospace Corporation. He has over 38 years of experience working in the space enterprise supporting civil and military space programs. He has more than 20 publications associated with space and related complex systems. Birk serves as executive vice president on the Board of the American Astronautical Society and co-chair of the CONFERS Technical Working Group. He holds a bachelor's degree in physics from the University of Notre Dame.

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Summary

This paper analyzes the National Aeronautics and Space Administration and the United States Space Force approaches to digital engineering implementation along with an investigation of the possibilities for a more coordinated approach between the two. The potential advantages of a coordinated approach are discussed. Five inquiry-based evaluation criteria have been developed for application to four different approaches that might be embraced by the two organizations. A qualitative comparison of the four approaches is presented in the form of an analysis matrix and description. While the assessment does not reveal a clearly optimal path, the process informs the value of a coordinated approach over independent approaches.

Introduction

This paper asserts that a common, or at least coordinated, approach to digital engineering can contribute to efficiencies across U.S. space agencies, organizations, and the commercial sector to accelerate development and deployment. The incorporation of the digital engineering process could significantly improve the pace of evolution of space systems in the national interest.[1] Space-faring government organization missions revolve around space systems. The National Aeronautics and Space Administration (NASA) mission includes advancing space systems for explorers, science, and applications. The U.S. Space Force (USSF) mission is to protect national interests in space systems. The primary NASA mission is human exploration in and beyond low Earth orbit. The development plans of both organizations include increasingly integrated space systems to provide essential, sustained operations.

These organizations and our nation benefit from reliable and interoperable launch, communications, navigation, and related systems operating as a sustained ecosystem in space. Coupling national interests in space systems with national "commercial first" policies drive the needs for evolved engineering approaches. There is just too much data from too many organizations for engineers and operators to develop, deploy, and evolve these systems using legacy engineering methods. Said another way, it is not feasible to engineer and operate these systems using 8.5" x 11" sheets of paper. One of the *Space Force Vision for a Digital Service*[2] tenets focuses on digital engineering to rapidly mature solutions to deliver capabilities faster. Likewise, NASA recognizes the importance of a "Digital Transformation."[3]

Through organization-specific and enterprise-wide efforts, including commercial space, both NASA and the Space Force conceive, design, develop, and implement complex space systems of systems to support their architectures needed for mission success. Vast amounts of engineering data and information are required to orchestrate these designs and ensure viable solutions. To enable superior national ecosystems in space, especially as activity expands to cislunar space, space explorers and space guardians, as USSF servicemembers are now called, and can benefit from synergies of common engineering functions and processes. It is for this reason that this paper focuses on NASA and the USSF.

Digital engineering can enable cooperation and process commonality. This paper discusses attributes and challenges of digital engineering and enterprise integration to benefit agency, organization, and national interests. Commonalities and differences of Space Force and NASA approaches to digital engineering are discussed, along with potential policy options.

Throughout this paper, several terms associated with digital engineering are used. Below are definitions of the terms with which the reader should become acquainted.[4]

- Digital Engineering (DE) is defined as an integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines to support lifecycle activities from concept through disposal.
- Authoritative Source of Truth (ASOT) is defined as a recognized repository for current and accurate data-driven models containing elements of the system technical baseline traced from current state to other points along the lifecycle available to connected systems and stakeholders to affect and track key decisions.
- Enterprise Integration (EI) is defined as a structured process of coordinating across stakeholders to inform decisions to sustain systems of systems operations across the enterprise to deliver critical national benefits in the face of evolving threats and changing operating environments.
- A space ecosystem is defined as a collection of integrated systems and stakeholders managed and balanced to ensure sustainability.

Digital Engineering Enables Cooperation and Process Commonality

The United States relies on space systems for exploration and defense along with many other applications in everyday life. Space activities are expanding beyond the geosynchronous belt to encompass the whole of cislunar space (Figure 1).[5] This paper uses cislunar to refer to objects under the combined gravitational influence of the Earth and moon, comprising current high traffic orbits such as low Earth orbit (LEO) and geostationary orbit (GEO) as well as five equilibrium points in the gravitational field known as Lagrange points, which could be hot spots of activity in the future.

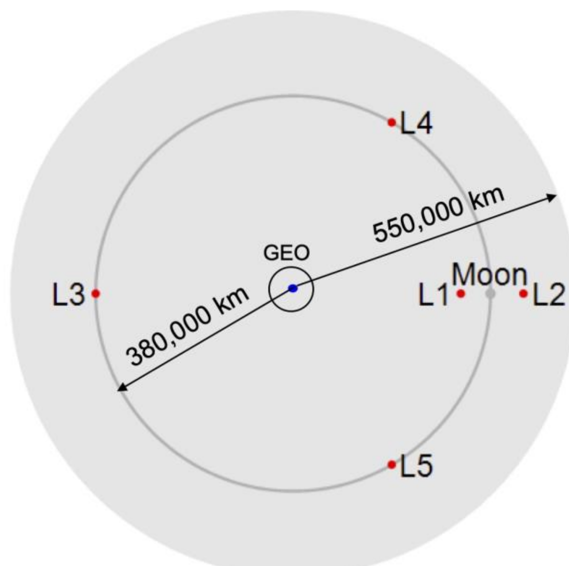

Figure 1: Map of cislunar space from LEO to Lagrange points.

Exploration and operations in cislunar space spans the purview of multiple organizations, agencies, and the private sector. Cooperation among these stakeholders contributes to furthering U.S.

exploration goals while ensuring the protection, safety, and security of our satellites and spacecraft. Both crewed and non-crewed space systems operating throughout cislunar space benefit from government organizations leveraging common functions, processes, and technologies to operate and evolve sustainable space ecosystems. Synergy of government and private sector investments can further advance the development, deployment, and evolution of transportation, communication, navigation, surveillance, power, and other essential functional infrastructure operating together as ecosystems in space.

Successful expansion of cislunar operations will also depend upon a transition from legacy architectures of stove-piped space systems to integrated space ecosystems. The systems, interconnections, and operations across these ecosystems are intended to be rapidly developed, deployed, and evolved to stay ahead of global competition and emerging threats to national interests. Enterprise integration and DE processes can be used to more efficiently and dependably deliver interoperable, evolvable ecosystems to meet national goals and objectives.

Digital Engineering can be applied to address a significant challenge for space activities: the need to process *more information* at *faster speeds* among a *more diverse group of stakeholders*. Evolving space systems require a continuous flow of large volumes of dynamically changing data and information for sustained and reliable operations. These systems are distributed in space and owned and operated by different organizations. Moreover, because the information moving through these systems requires near-zero latency tolerance, it is not feasible for humans to process the information, make decisions, and control operations at the speed of need. Legacy engineering tools and processes used for space systems launched over the past several decades are losing the capability to keep up. Innovative engineering tools are required to design, acquire, develop, test, integrate, evolve, and operate these interoperable, interconnected, interrelated space systems.

Digital Engineering facilitates implementation of systems in architectures, connecting sources seamlessly and continuously over the lifecycle of systems development, deployment, and evolution in a digital environment.[6] The transformative nature of DE takes full advantage of integrating all engineering and related programmatic work, data, knowledge, and wisdom across the enterprise. This integration is key for producing and exploiting authoritative sources of truth (ASOTs). Defined concisely, an ASOT is an entity such as a person, governing body, or system that applies expert judgement and rules to proclaim a digital artifact is valid and originates from a legitimate source.[7] In other words, it is a concept that is used to ensure that every person or entity working on a common activity bases their decisions on the same data. For engineering, space traffic management, and other data essential to safety and security, nationally recognized ASOTs are foundational to operations of evolving ecosystems in space. The goal of an ASOT is to enable delivery of the right data to the right person or system at the right time. An Authoritative Source of Truth must be governed to be effective and to protect integrity. ASOTs must be established using clear standards, procedures, and guidelines to promote inherent value.

DE is an improvement over legacy engineering approaches where static and isolated data sources are used independently to affect the design of complicated systems after which all system elements must be integrated to meet mission requirements. Individual engineering disciplines have developed and used models and simulations for a long time, albeit typically stove-piped by discipline. Information exchanges between analyses and analysts have traditionally relied upon manual interpretation, translation, conversion, and data entry. The use of concurrent design tools has improved the communications among the various discipline teams designing space systems. DE brings everything together, including design, schedule, cost, risk, and test.

An exemplar national mission for applying digital engineering is Space-based Environmental Monitoring (SBEM). National benefits of current and accurate global weather measurements drive collaboration across the Space Force and NASA, along with other organizations, such as commercial and international SBEM providers. To design a resilient architecture, multiple tools, processes, and analyses are integrated into a digital engineering ecosystem (DEE). Multiple ASOTs inform the digital engineering ecosystem to integrate an enterprise view to assess threats and identify vulnerabilities. DE is used to optimize architectures to increase probability of mission success. Model-based systems analyses inform cross-organization mission needs in the national interest. Requirements, systems (e.g., spacecraft, payloads), and capabilities (e.g., communications, navigation) can be optimized based on enterprise needs analysis in the face of evolving threats. The government reference design, captured in a digital twin*, is matured over the lifecycle of the mission to maintain a technical baseline. The digital environment informs design, budget, and performance reviews providing decision support for multiple stakeholder agencies, organizations, owners, operators, and developers of each of the systems as shown in Figure 2. USSF, NASA, and NOAA are stakeholder

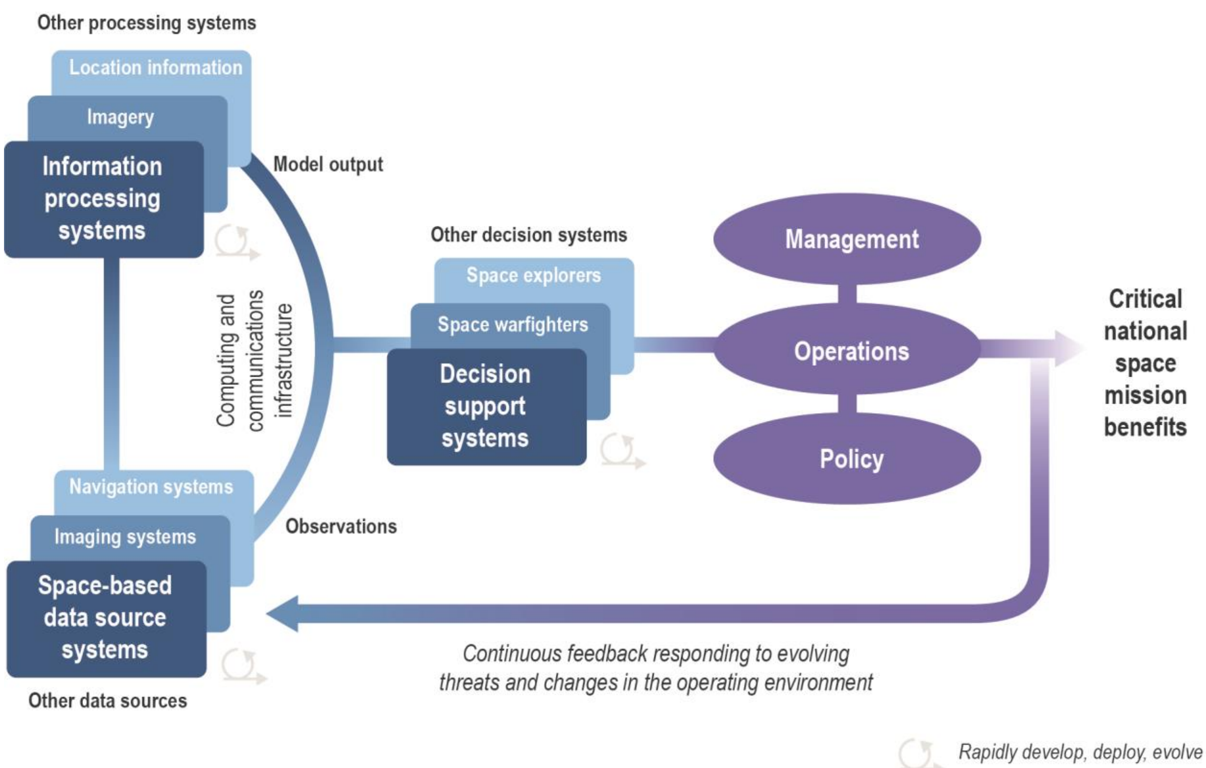

Figure 2: Enterprise integration decision value chain for organizations, owners, operators, developers for Space-based Environmental Modeling.

*Defined in Appendix A.

organizations for SBEM. Each organization has multiple roles in one enterprise architecture, each providing satellite observing systems, each contributing to environmental modeling, and each applying data and forecasts to a range of nationally critical applications. Private sector organizations also provide observations, modeling, and decision support functions in concert with U.S. government organizations to deliver critical national benefits. Achieving and sustaining national mission success requires enterprise integration across all organizations, owners, operators, and developers of SBEM systems and data flows.

Enterprise Integration and the Legacy of NASA-DOD Cooperation

Full benefits of DE data and system integration will not reach their full potential without *enterprise integration* across multiple relevant agencies and organizations. Enterprise integration for space systems is needed to maintain up-to-date information for real time operations and decision making. As shown in Figure 2, this process involves horizontal and vertical integration of systems and their interconnections as well as data interchange and distributed computing. Continuous integration must be conducted to stay current in a constantly changing operating environment with dynamically evolving threats and opportunities.[8] The intensive flow of data through an enterprise integration framework is enabled by digital engineering, digital system models, and digital engineering ecosystems.

> Enterprise Integration is a structured process of coordinating across stakeholders to inform decisions to sustain systems of systems operations across the enterprise to deliver critical national benefits in the face of evolving threats and changing operating environments.

The concept of combining and integrating efforts across the U.S. space enterprise is not new, especially when focusing on the case of NASA cooperation with DOD entities. Cooperation between NASA and DOD traces back to the Air Force and its predecessor organizations with the predecessor of NASA, the National Advisory Committee on Aeronautics (NACA) in the 1940s and 50s.[9] Excellent examples of collaboration include Kennedy Space Center and Cape Canaveral Air Force Station (now Space Force Station) on development of early launch systems, like the Agena, and use of NASA’s shuttle to launch Air Force satellites in the 1980s.[10] While collaborative projects have numerous challenges and obstacles, both technical and bureaucratic, recognition of common interests and needs between the two organizations has persisted to the present.[11]

NASA and the Space Force signed a memorandum of understanding (MOU) on 21 September 2020 placing increased emphasis on collaboration in cislunar space.[12] Later, in response to the MOU, NASA and the Space Force established six Technical Collaboration and Coordination Groups addressing:[13]

- On-orbit Servicing and Manufacturing (OSAM)
- Space Based Optical Communication
- Positioning, Navigation, and Timing
- Electric Propulsion
- Space Nuclear Power and Propulsion (including Nuclear Thermal and Nuclear Electric Propulsion)
- Trusted Autonomy

The Space Force has expressed an interest in coordinating with NASA on DE to advance capabilities in these areas. And while interagency and commercial cooperation on space activities can be beneficial for national competitiveness, collaboration raises challenges related to authoritative sources of truth and risks to cybersecurity that must be addressed. Despite these challenges, a common, or at least coordinated, approach to DE can contribute to efficiencies across U.S. space agencies and the commercial sector to accelerate development, deployment, and evolution of space systems.

U.S. Space Force and NASA Approaches to Digital Engineering

National missions for space guardians and explorers share common needs to bring multiple systems from different providers together in space to provide a range of functions. Both NASA and the Space Force recognize benefits of applying DE across the full lifecycle for systems, systems of systems, and ecosystems through coordination among system owners, developers, and operators. This paradigm shift creates an information technology network challenge to ensure appropriate, current, trusted, and secure data from all systems are available to all other systems and users authorized for access at different classification levels. A benefit of this process is providing current and consistent information for management and policy decisions and support for operations.

NASA and the Space Force share common objectives for DE implementation as shown in the Venn diagram in Figure 3. These objectives are:

- Modernize how the organization designs, develops, operates, and sustains space systems
- Establish and provision Authoritative Sources of Truth for their enterprise
- Ensure cyber secure and safe connection of people, processes, data, and capabilities across an end-to-end digital enterprise
- Apply across system lifecycle activities from concept through disposal
- Develop a digitally fluent workforce
- Engage with the Space Industrial Base
- Engage across the supply chain

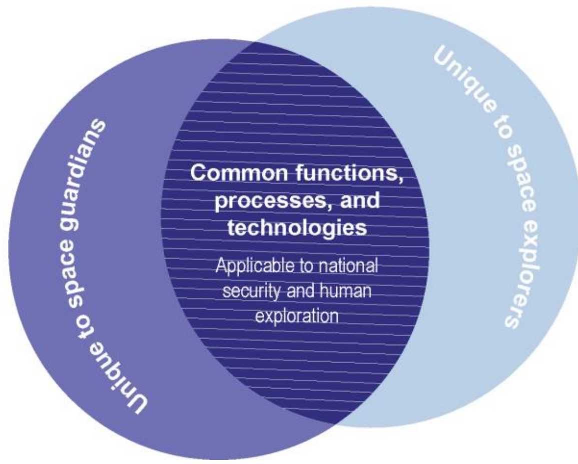

Figure 3: USSF and NASA common functions, processes, and technologies overlap.

The U.S. Space Force Vision for a Digital Service, released in May 2021, describes *"an interconnected, innovative, digitally dominant force."* The Space Force aims to exploit digital solutions leveraging information and data to accelerate the ability to develop, field, and operate joint space capabilities with unparalleled speed and proficiency. NASA is taking a more incremental approach to Digital Transformation (DT).[14] NASA leaders express a vision of DT fully leveraging evolving digital technologies to advance agency missions with enhanced efficiency. While Space Force and NASA share a common rationale as well as common elements, differences between their DE implementation plans have implications for the space enterprise.

NASA and USSF Digital Engineering Implementation Overview

The Space Force digital strategy includes digital engineering, digital workforce, digital operations, and digital headquarters. The Space Force plans to apply DE to manage the complexity of space systems across the development lifecycle. DOD plans to "manage requirements and testing from the warfighter to the developer and back again as a continuous digital thread." The approach includes enterprise-level architectures capturing optimized system designs linked to threat models and desired warfighter outcomes.

The Space Force plan includes establishing resilient digital infrastructure with an interoperable, low-latency network. A federated Digital Engineering Ecosystem (DEE) with requisite expertise, in concert with digital tools and processes allows users to produce and manipulate the data and models to support their analysis. A DEE enables timely, reliable, and secure access from virtually anywhere. The DEE facilitates agile collaboration across the Space Force for all mission-related activities across every focus area. The plan includes applying continuous, agile development to maintain DEE performance and security over time to keep pace with evolving capabilities and threats, ensuring guardians always have modern and reliable technology at their fingertips.

NASA released their Digital Engineering Acquisition Framework Handbook in April 2020.[15] While this document provides detailed acquisition guidance to be applied to individual projects and programs, NASA has not published top-down guidance for the enterprise at the same level as the Space Force vision for moving to a digital service.

The NASA Handbook provides acquisition guidance for Data Requirements Descriptions (DRDs) and contractual Statements of Work (SOW) to support a digital engineering ecosystem. For NASA, like the Space Force, a digital engineering ecosystem enables collaborative digital engineering across the full system lifecycle. The ecosystem provides a common platform for stakeholders with authoritative sources of data and models to integrate across organizations and disciplines supporting lifecycle activities from concept through disposal.

Both USSF and NASA recognize the importance of Authoritative Sources of Truth for digital engineering applications. From DOD Digital Engineering Strategy, the authoritative source of truth must contain key elements of the system

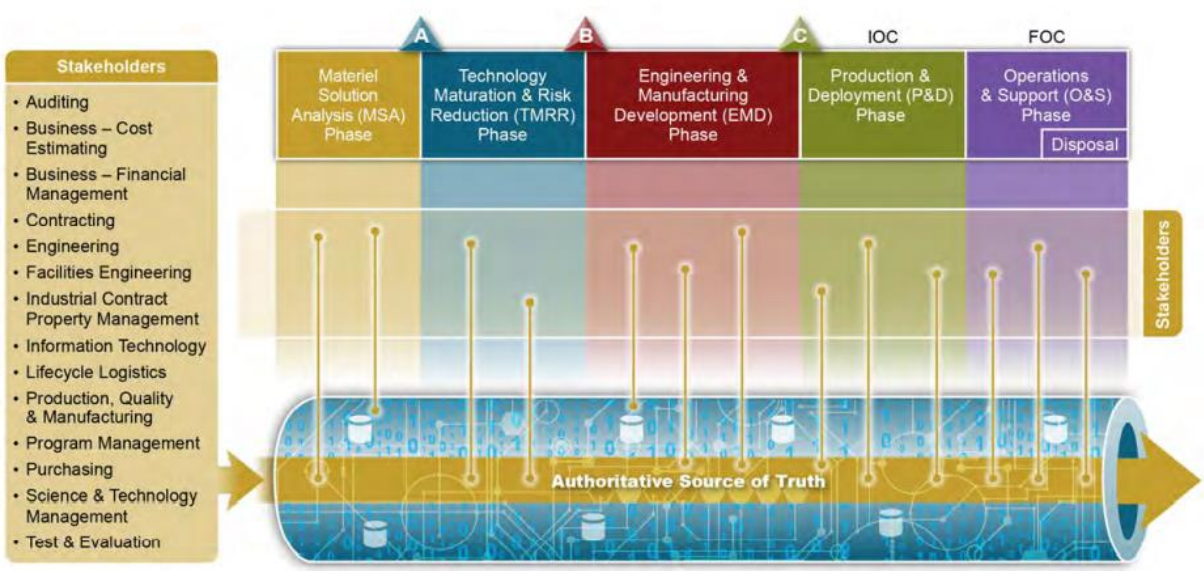

Figure 4: Illustration of the ASOT used throughout the system lifecycle. (Source: DOD Digital Engineering Strategy)

technical baseline traced from a current state to other points spanning the lifecycle as shown in Figure 4. Also shown on the left side of the figure, ASOT is a common baseline of essential information across multiple stakeholders. This connectedness and traceability (referred to as a "digital thread") ensures constituent models are kept up-to-date and relevant, and their data-driven effects are communicated and propagated to other systems/stakeholders in a timely manner to optimally affect and track key decisions.

NASA also describes ASOT in terms of spanning the lifecycle. "The owners of digital ecosystems or the community for digital engineering ecosystems provides stakeholders with an authoritative source of truth that assures confidence in the quality of the digital artifact across disciplines, domains, and life-cycle phases."

In terms of cybersecurity, all contractor information systems and networks are subject to the security requirements in NIST SP 800-171. DOD security and cybersecurity for data and information, including handling classified information, associated with each of these elements are subject to the myriad of established policies captured in the DOD Cybersecurity Policy Chart.[16] As these practices and policies apply to all data information systems on internal and external government and contractor systems, including clouds and with cloud service providers, they cover ASOT for digital engineering.

Implementation of agile practices allow both organizations to quickly create and field incremental solutions using Development, Security, and Operations (DevSecOps) factors to advance software development and incorporate security protection. Digital Twins assimilate the incremental changes and tie elements together across the lifecycle, enabling collaboration with mission partners as part of agile development and testing of capabilities as well as seamless transition to operations and ongoing sustainment.

Differences Between the Two Approaches

Differences between approaches to DE for NASA and the Space Force are primarily in the "how," "who," and "when," along with considerations for classified access, as outlined in Table 1.

The USSF approach to Digital Transformation is much broader than the NASA approach. The Space Force approach includes personnel, culture, training, security, processes, decision making, empowerment, and operations across the organization and across the lifecycle. The Space Force vision for digital engineering is organization-wide with policy that all USSF projects going forward will be "born digital." On the other hand, NASA is taking an incremental transformational approach to DE starting with acquisition as described in their *Digital Engineering Acquisition Framework Handbook*.

NASA applies DE to specific programs and projects. The NASA Digital Transformation Office reports plans to assess approaches to expand to an enterprise-level strategy. NASA embraces digital transformation in terms of digitizing and streamlining paper processes, integrating previously siloed data to improve mission outcomes, and enhancing partnerships using new, cyber secure collaboration tools. Nearly 200 digital transformation success stories have been collected from across NASA.

Agency-wide coordination has been missing in the NASA digital transformation effort. NASA leadership wants to share best practices in digital solutions, avoid duplication and gaps, ensure interoperability, and encourage cooperation among all stakeholders. In the spring of 2019, NASA leadership approved an agency digital

Table 1: Comparison of Approaches Between NASA and the USSF			
Description	**NASA**	**Space Force**	**Observations**
Top Level Docs	NASA Digital Transformation	DOD Digital Engineering Strategy	Differing levels of applicability, ConOps, and applications
Governance Model	Project/Acquisition Level	Organization-wide	Differing level and type of governance
Working Level Docs	NASA DE Acquisition Handbook	USSF Vision for Digital Service	Differing approaches to inform enterprise implementation
Common Area 1: ASOT	Value of Authoritative Source of Truth		Space-based systems operating in an ecosystem need common, trusted authoritative sources of truth
Common Area 2: Lifecycle	Recognition that DE Spans Lifecycle		From CONOPS to architecture to acquisition through to disposal
Common Area 3: Standards	Benefits of Organization and Voluntary Consensus Standards		Systems interoperability benefits from common standards
Difference Area 1: Culture	Limited top-down governance; 7120.5 engineering direction	Top-Down Command and Control	NASA science, collegial culture Space Force command and control culture
Difference Area 2: Commercial	Acquisition Guidelines	Owns Development Platform and Technical Baseline	NASA directs DE deliverables per acquisition Space Force provides DE baseline for all providers
Difference Area 3: Classification	Majority Unclassified	Majority Classified	Impacts complexity of common databases and models

transformation strategy, with the Office of Chief Technologist leading coordination in partnership with the Office of Chief Information Officer.

The NASA Digital Transformation Office focus is on where the enterprise needs to go and architecting digital solutions to accelerate mission outcomes. Six thrusts include (1) data, (2) modeling, (3) process transformation, (4) collaboration, (5) artificial intelligence/machine learning, and (6) culture and workforce changes. It is stated in the NASA *DE Acquisition Handbook* that "A NASA-wide policy or standardized approach for ensuring data integrity, access, and successful transfer does not currently exist..." The handbook emphasizes evolving from paper to digital processes.

The Space Force Vision embraces a holistic "Digital HQ" approach that:

- Calls for urgent, imminent digital instantiation for the organization
- Forms a shared DE ecosystem
- Builds common infrastructure within DEE

According to Kristen Baldwin, Deputy Assistant Secretary of the Air Force for Science, Technology and Engineering, and USAF Maj Gen Kimberly Crider (ret), digital engineering is changing Air Force and Space Force space systems lifecycles. Digital engineering using computer-generated integration for design, build, and test is the path forward for the military becoming more agile in fielding and maintaining new space systems. The USSF policy is that all projects going forward will be "born digital," and the USSF will own the development platform and technical baseline for their national defense space architecture.[17]

Policy Options for Digital Engineering Collaboration

Accounting for similarities and differences, there are several national and organization-level options to compare and analyze in an enterprise-level consideration of digital engineering policy going forward:

- Both organizations move forward independently
- Both organizations adopt one or the other approach
- Both converge to a combinational approach

Pros and cons for each of these options are addressed in the section below based on applying criteria associated with elements affected by DE collaboration.

We propose five key elements and associated criteria to compare these approaches: authoritative sources of truth, enterprise integration, space industrial base, supply chain, and organizational continuity. Differing approaches to DE collaboration between USSF and NASA may optimize some of these elements more than others. This analysis could provide insight for establishing agency priorities for collaboration on DE going forward.

Elements Affected by Digital Engineering Collaboration

The following five elements in the space enterprise are affected by NASA and USSF policies and implementation of DE in the context of advancing U.S. space capabilities in the national interest.

1. **Authoritative Sources of Truth.** Clear demarcation and governance of ASOTs through U.S. government organization collaboration with focus on visibility, accessibility, interoperability of the engineering data and information associated with space systems development contributes to efficiencies across the space enterprise.

   Associated inquiry-based criteria include:

   a. Are the same authoritative sources of truth for data and models used by multiple U.S. agencies, organizations, and companies across the development lifecycle?

   b. Are the ASOT repositories used to inform systems that interface, interact, or are interoperable with other systems in national mission architectures?

   c. Is there an impact to safe and secure operations and mission success if data and models are not consistent, trusted, and secure?

2. **Enterprise Integration.** U.S. government organization collaboration on systematic, sustainable processes of integrating disparate systems of systems owned and operated by different entities enables synergies needed for the rapidly evolving space ecosystems. Collaboration can foster enterprise integration through policies, security postures, and adherence to data and other systems standards to enable interoperability.

Associated inquiry-based criteria include:

a. Do national security and exploration missions depend on integration of space systems, ground support systems, decision support systems, in the face of evolving operating environments and threats?

b. Are there plans for agile DevSecOps to evolve the systems over time with rapid software updates, hardware refreshes, and evolving artificial intelligence/machine learning (AI/ML) algorithms?

c. Are developers, owners, and operators of any given system dependent on information and interoperability from and with counterparts for other systems across the enterprise?

3. **Space Industrial Base (SIB).** U.S. commercial companies are developers, suppliers, owners, and operators of U.S. space systems.

   Associated inquiry-based criteria include:

   a. Are SIB organizations building multiple systems for multiple organizations where they can benefit from common ASOT, DT, DEE?

   b. Does the workforce of the SIB require common expertise, competency models, tools, and processes to design, develop, deploy, and operate multiple systems across the enterprise?

   c. Is there a need for efficiency and effectiveness through common, secure modules, subsystems, and systems across the enterprise?

4. **Supply Chain.** U.S. space systems require trust and confidence in all components, including assured microelectronics. This assurance requires assured availability, protection, and security of all systems, subsystems, and component level elements.

   Associated inquiry-based criteria include:

   a. Are common components, from Application Specific Integrated Circuits (ASICS) to capacitors, being used in multiple space systems?

   b. Is there a common, searchable source of information to know which system designs include specific components that are available from U.S. sources?

   c. Is there a common alert system across the enterprise to notify of anomalies or issues with components?

5. **Organizational Continuity and Cost.** NASA has well-established ways of executing systems engineering with substantial heritage (i.e., NPR7120.5D). NASA is incrementally moving towards DE, but there is yet no coordinated overall agency mandate to do so. On the other hand, the *Vision for a Digital Service* document declares the USSF will become the world's first fully digital service.

   The culture of both organizations needs to be considered however things move forward. NASA has over 60 years of established cultural norms, design methodologies, and program execution methods. NASA Centers each operate with their own local culture. While USSF is a nascent organization, there are legacy U.S. Air Force cultures, processes, and procedures.

   Associated inquiry-based criteria include:

   a. To what degree must the established organizational cultures adapt to change to implement DE?

b. Is management and organizational leadership likely to implement the approach?

c. Are there resource impacts to both time and funding to implement DE?

d. Who bears the cost of DE implementation? How is the cost burden shared?

Assessing Inquiry-based Criteria Across Elements for Four Options

There are pros and cons for each of these options. Noting that digital engineering approaches are relatively nascent and still need to be proven, all paths require changes in culture, practices, and processes. Options for a way forward are summarized in Table 2 and described below.

Option 1: The USSF and NASA move forward independently – Pros include neither organization is required to change cultures; neither must coordinate common DE processes, standards, and structures for ASOT and DEE. Cons include gaps in consistency and completeness of ASOT databases; risk of incompatible system interfaces and operational functionality; and lost efficiencies because of duplicative approaches. Moving forward independently leads to limited opportunities for enterprise integration, coordination, and continuity across the SIB. It also limits full insight into supply chain issues. Finally, an assessment of the costs of moving forward independently must be executed.

Options 2 and 3: One organization adopts the other's approach – Pros include efficiencies of shared knowledge and scale. Cons include one of the organizations needing to change workforce culture to align with the other, which could be a monumental task. For NASA, each center has established cultures and processes. This effects efficiency of adoption of any new enterprise level approaches. The Space Force is currently challenged to establish "born digital" operating processes in short order and there would be challenges to coordinate with another organization. As in the first option, the costs associated with either organization adopting the other's approach must be assessed.

Table 2: Policy Options for DE Collaboration

Option	Change from NASA Current Policy	Change from USSF Current Policy
Option 1: Status Quo	None	None
Option 2: Adopt Space Force Approach	NASA adopts agency-wide strategy and governance, directs enterprise-wide governance to centers	None
Option 3: Adopt NASA Approach	None	USSF drops top-down vision and governance and focuses on select projects, increases level of detailed acquisition guidance
Option 4: Combinational Approach	NASA evolves agency-wide strategy and governance with focus on full lifecycle of projects starting with architectures and acquisitions leveraging lesson learned from USSF	USSF evolves organization-wide approaches with increased guidance for acquisitions and experience from NASA projects

Table 3: Options and Elements Matrix for Analysis					
Elements / Options	ASOT Collaboration	Enterprise Integration	Space Industrial Base	Supply Chain	Organizational Continuity and Cost†
1. Maintain Current Approaches	Moderate Value	Low Value	Low Value	Moderate Value	None – status quo
2. Adopt Space Force Approach	High Value	Moderate Value	High Value	Moderate Value	Extremely Challenging for NASA
3. Adopt NASA Approach	Moderate Value	Moderate Value	Moderate Value	Moderate Value	Moderately Challenging for USSF‡
4. Combinational Approach	High Value	Moderate Value	High Value	High Value	Moderately Challenging for both

Option 4: A combinational approach may serve both organizations and the U.S. well. This effort could begin by initially collaborating on common approaches to maintaining authoritative source of truth repositories. Perhaps a benchmarking exercise would be useful in assessing the best features of each approach. Enterprise integration drives collaboration that can benefit from common approaches to a national digital engineering ecosystem. Efficiencies derived from reducing or eliminating duplicative activities might be an advantage. Coordination across the SIB would evolve, while continuing collaboration on supply chain monitoring to benefit both NASA and the USSF. Lessons learned from the USSF establishment of a digital force along with best practices developed by NASA for digital acquisition can be tailored and applied across organizations to accelerate development, deployment, and evolution of capabilities. Pros include benefits of diversity of culture and thought for both agencies. Cons include changes to culture and lack of time for negotiating agreements on common understanding and support for mutually agreeable approaches to DE, ASOT, and DEE affecting SIB and supply chain.

Conclusion

Evolving time-honored and proven engineering practices on an enterprise scale is inherently difficult. This is also true at an organization level. However, there are foundational drivers for evolving approaches for engineering and operating space systems of systems. The reality is that there is too much engineering data, which is changing

† Costs must be assessed and included in the decision process. Status quo would mean no change in planned funding profiles, which is easy for each to manage. However, cost of duplicative activity and redundancy must be assessed.

‡ While cultural change would be a challenge for the USSF given its USAF heritage, the organization is new and still malleable. Changing the culture at NASA would be a monumental undertaking.

quickly and distributed across many organizations, for individuals (engineers and operators) to sustainably manage the space systems using legacy engineering approaches. Recognizing these challenges and drivers informs the thesis for this paper. An intent here is to review current and evolving engineering approaches for key U.S. spacefaring organizations to inform policies in the national interest.

Criteria associated with five discrete elements affected by NASA and Space Force policies and implementation of digital engineering are applied to inform an assessment of the merits of the thesis of this paper that "coordinated approaches to digital engineering can result in efficiencies across U.S. agencies, organizations, and the commercial sector to accelerate development, deployment, and evolution of space systems." Criteria associated with the elements of Authoritative Sources of Truth, Enterprise Integration, Space Industrial Base, Supply Chain, and Organizational Continuity are applied in the context of three options. Option 1 to Maintain Current Approaches, Options 2 and 3 to Adopt the Approach of one organization or the other, and Option 4 to establish a Combinational Approach.

Results reveal pros and cons for each. While the assessment provided in this paper does not reveal a clearly optimal path, the process informs the value of a coordinated approach over independent approaches. Further review and coordination can inform policy decisions to optimize benefits of leveraging digital engineering for space guardians and space explorers. Finally, best practices and lessons learned derived from this USSF and NASA effort, whichever option is pursued, could be shared with other agencies and organizations that leverage space to support their key functions and operations.

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Appendix A.
Digital Engineering Overview

The Digital Engineering Ecosystem (DEE), illustrated in Figure A1, comprises four interacting layers to enable model-driven, risk-informed decision analytics at every phase of a program. The *Know-See-Think-Do* approach is critical to making timely and effective decisions.[18]

- The **Know** layer is knowledge management, serving as a repository of all relevant knowledge, data, reports, and authoritative sources of truth.
- The **See** layer is where engineers and analysts can readily find relevant geometries, data, reports, authoritative truth sources, etc. required to translate data into an assessment of performance of materials, components, subsystems, and systems.
- The **Think** layer includes risk analysis of cost, schedule, expected performance, and affordability.
- The **Do** layer is the decisionmaking step that includes weighing all variables analyzed flowing up layer-to-layer through the DE ecosystem.

Digital system models (DSMs) are used to integrate authoritative technical data and associated artifacts defining all aspects of the system for specific activities throughout the lifecycle. DSM-interconnected processes, methods, and tools are used to store, access, analyze, and visualize data and to model evolving systems to address stakeholder needs and improve safety.

The method by which the data synchronization and knowledge transfer is accomplished is through the implementation of digital threads and digital twins, which are key elements in the DE ecosystem. The digital thread is a critical capability in model-based systems engineering (MBSE) and the foundation for a digital twin. The term "digital thread" is also used to describe the traceability of the digital twin back to the requirements, parts, and control systems that make up the physical asset. Digital Twins are used to assess performance of as-built systems in their operational environment.[19] The DE knowledge base is used for operator training and assessing potential operational scenarios for guardians and explorers.

> A Digital Twin is an integrated digital representation of an entity of interest that uses increasingly refined models, simulations, and data over time to inform decisions about that entity of interest.

Digital Engineering facilitates implementation of systems for architectures comprising the space enterprise.[20] The transformative nature of DE takes full advantage of integrating all engineering and related programmatic work, data, knowledge, and wisdom across the enterprise. Digital threads are a representation of the data flows associated with space enterprise integration.[21] The digital thread is the lowest level design and specification for a digital representation of a physical item or system.

> A Digital Thread is a communication framework that allows a connected data flow and integrated view of the asset's data throughout its lifecycle across traditionally siloed functional perspectives.

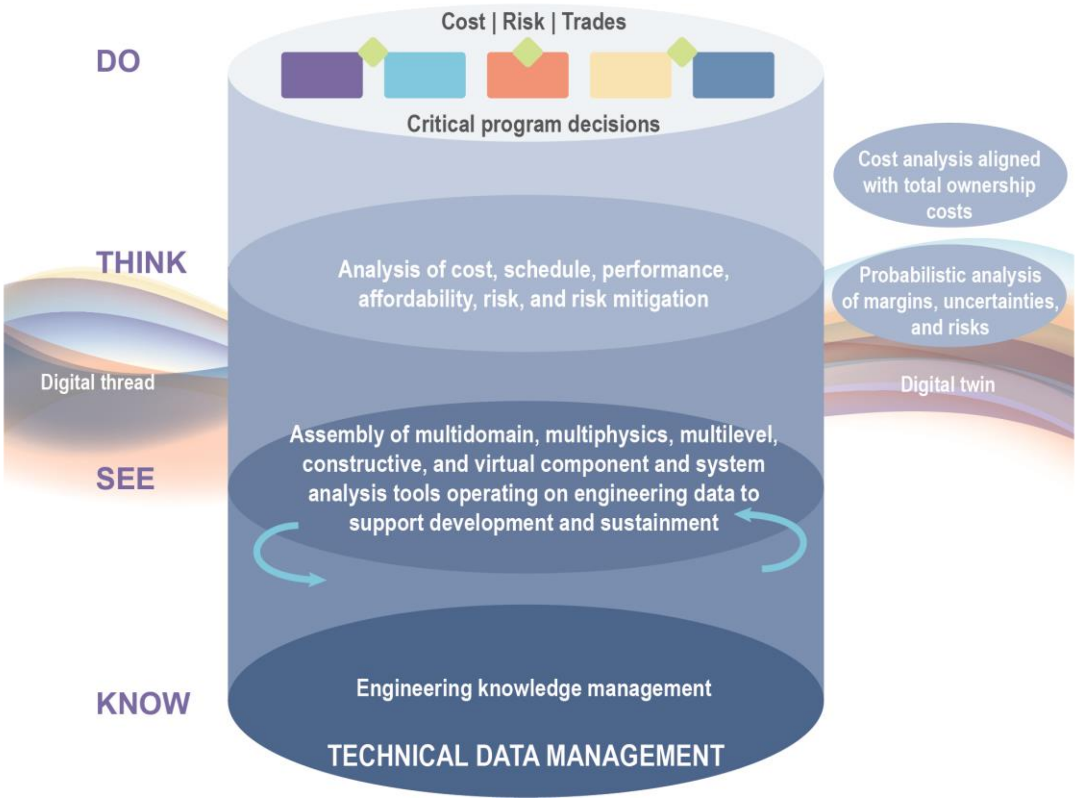

Figure A1: The "Know, See, Think, Do" Digital Engineering Ecosystem. *Derived from Kraft (2020)*

References

[1] Office of Space Commerce, “National Space Policy,” December 2020 (https://www.space.commerce.gov/policy/national-space-policy/).

[2] USSF, “U.S. Space Force Vision for a Digital Service,” May 2021 (https://media.defense.gov/2021/May/06/2002635623/-1/-1/1/USSF%20VISION%20FOR%20A%20DIGITAL%20SERVICE%202021%20(2).PDF).

[3] NASA IT Talk, “Digital Transformation at NASA”, June 2019, Volume 9, Issues 1-2 (https://www.nasa.gov/sites/default/files/atoms/files/396062_jan-jun_2019_it_talk_design_final_003.pdf)n

[4] Office of the Deputy Assistant Secretary of Defense for Systems Engineering, *Department of Defense Digital Engineering Strategy*, June 2018 (https://ac.cto.mil/wp-content/uploads/2019/06/2018-Digital-Engineering-Strategy_Approved_PrintVersion.pdf).

[5] Space, “Space Force and NASA focused on cislunar space in new agreement,” September 2020 (https://www.nasa.gov/sites/default/files/atoms/files/nasa_ussf_mou_21_sep_20.pdf).

[6] Office of the Deputy Assistant Secretary of Defense for Systems Engineering, *Department of Defense Digital* Engineering *Strategy*, June 2018 (https://ac.cto.mil/wp-content/uploads/2019/06/2018-Digital-Engineering-Strategy_Approved_PrintVersion.pdf).

[7] Object Management Group Standards Development Organization, “Authoritative Source of Truth,” Model Based Systems Engineering Wiki (https://www.omgwiki.org/MBSE/doku.php?id=mbse:authoritative_source_of_truth).

[8] U.S Interagency Working Group on Earth Observations, “USGEO Strategic Plan for U.S. Integrated Earth Observation Systems,” April 6, 2005 (https://webarchive.library.unt.edu/eot2008/20080921235808/http://usgeo.gov/docs/EOCStrategic_Plan.pdf).

[9] Aldridge, Edward C. “Pete,” “The Air Force Civil-Industrial Partnership,” in *The U.S. Air Force in Space: 1945 to the 21st Century*, Edited by R. Cargill Hall and Jacob Neufeld, 1995 (https://media.defense.gov/2010/Oct/01/2001329745/-1/-1/0/AFD-101001-060.pdf).

[10] Day, Dwayne A, “Invitation to Struggle: The History of Civilian-Military Relations in Space,” Chapter 2 in Exploring the Unknown: Selected Documents in the History of the US. Civilian Space Program, Volume II: External Relationships, The NASA History Series, John M. Logsdon, editor, NASA 1996 (https://history.nasa.gov/SP-4407/ETUv2.pdf).

[11] Eleazer, Wayne, “Space Myths: DoD and NASA cooperation,” The Space Review, October 16, 2016 (https://www.thespacereview.com/article/3074/1).

[12] National Aeronautics and Space Administration, “Memorandum of Understanding Between the National Aeronautics and Space Administration and the United States Space Force,” September 21, 2020 (https://www.nasa.gov/sites/default/files/atoms/files/nasa_ussf_mou_21_sep_20.pdf).

[13] Engelund, W, “NASA Space Technology Collaboration and Coordination Priority Opportunities with the U.S. Space Force,” presented at Explore Space Tech, May 4, 2021.

[14] NASA IT Tech Talk, Volume 9, Issues 1-2, January-June 2019 (https://www.nasa.gov/sites/default/files/atoms/files/396062_jan-jun_2019_it_talk_design_final_003.pdf).

[15] NASA, Digital Engineering Acquisition Framework, April 2020 (https://standards.nasa.gov/file/38386/download?token=LdmxVVcB).

[16] DoD Cybersecurity Policy Chart (https://dodiac.dtic.mil/dod-cybersecurity-policy-chart/).

[17] The Space Policy Show: Inside Digital Engineering and the US Air Force, The Aerospace Corporation Center for Space Policy and Strategy, May 13, 2021 (https://aerospace.org/events/space-policy-show-inside-digital-engineering-and-us-air-force).

[18] Kraft, E.M., “Digital Engineering Enabled Systems Engineering Performance Measures,” AIAA 2020-0552, AIAA SciTech Forum, Orlando, FL, January 6 - 10 2020 (https://doi.org/10.2514/6.2020-0552).

[19] AIAA Digital Twin: Definition and Value December 2020 (https://www.aiaa.org/docs/default-source/uploadedfiles/issues-and-advocacy/policy-papers/digital-twin-institute-position-paper-(december-2020).pdf).

[20] Office of the Deputy Assistant Secretary of Defense for Systems Engineering, *Department of Defense Digital Engineering Strategy*, June 2018 (https://sercuarc.org/wp-content/uploads/2018/06/Digital-Engineering-Strategy_Approved.pdf).

[21] What is the Digital Thread? | Digital Thread Definition, NxREV, May 7, 2018 (https://nxrev.com/2018/05/digital-thread/#:~:text=Digital%20Thread%20Definition%20According%20to%20Tech%20Target%2C%20the,view%20of%20an%20asset%20throughout%20the%20manufacturing%20lifecycle.%E2%80%9D).