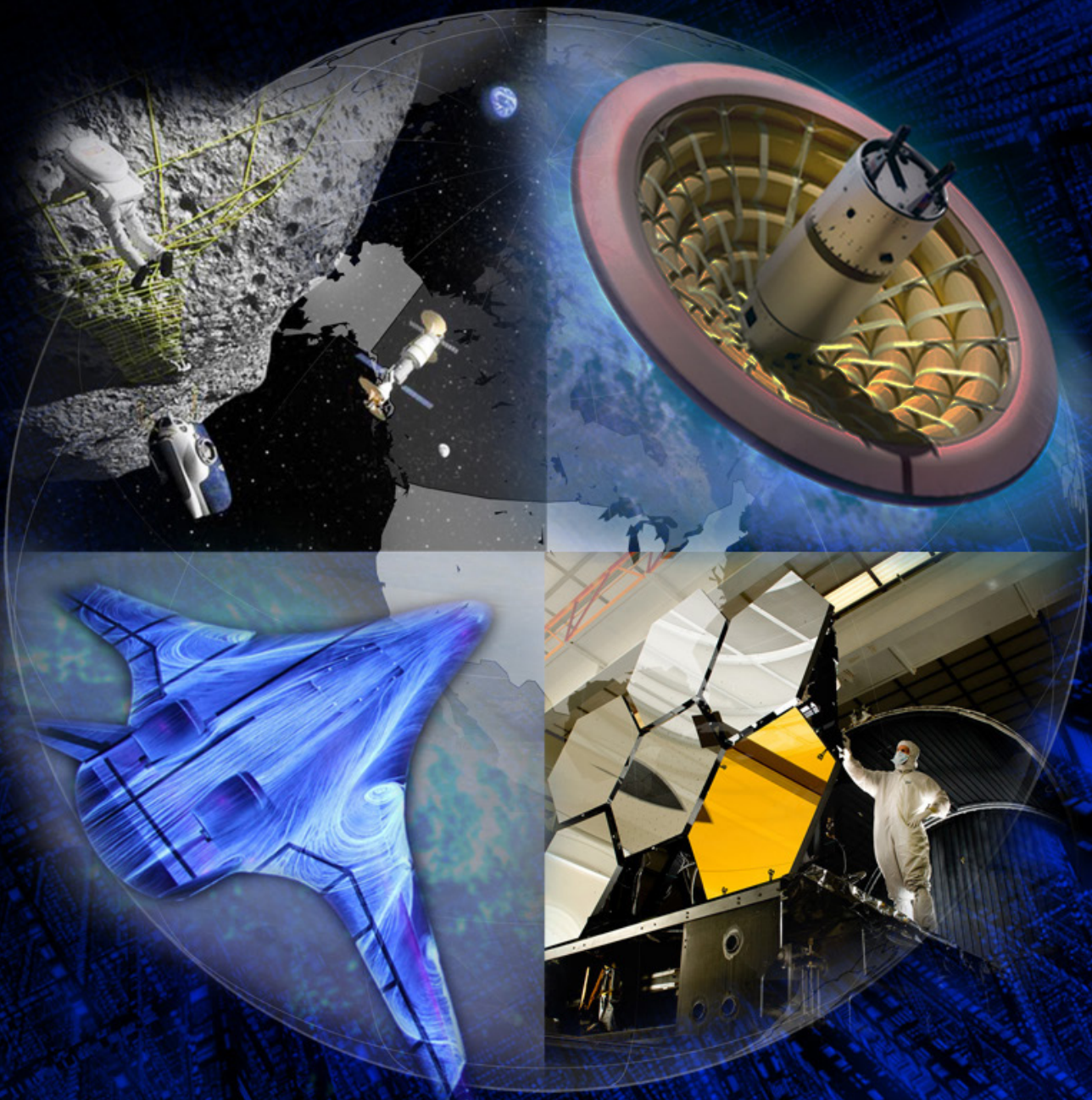




# NASA Technology Roadmaps

## TA 11: Modeling, Simulation, Information Technology, and Processing



July 2015



## *Foreword*

NASA is leading the way with a balanced program of space exploration, aeronautics, and science research. Success in executing NASA's ambitious aeronautics activities and space missions requires solutions to difficult technical challenges that build on proven capabilities and require the development of new capabilities. These new capabilities arise from the development of novel cutting-edge technologies.

The promising new technology candidates that will help NASA achieve our extraordinary missions are identified in our Technology Roadmaps. The roadmaps are a set of documents that consider a wide range of needed technology candidates and development pathways for the next 20 years. The roadmaps are a foundational element of the Strategic Technology Investment Plan (STIP), an actionable plan that lays out the strategy for developing those technologies essential to the pursuit of NASA's mission and achievement of National goals. The STIP provides prioritization of the technology candidates within the roadmaps and guiding principles for technology investment. The recommendations provided by the National Research Council heavily influence NASA's technology prioritization.

NASA's technology investments are tracked and analyzed in TechPort, a web-based software system that serves as NASA's integrated technology data source and decision support tool. Together, the roadmaps, the STIP, and TechPort provide NASA the ability to manage the technology portfolio in a new way, aligning mission directorate technology investments to minimize duplication, and lower cost while providing critical capabilities that support missions, commercial industry, and longer-term National needs.

The 2015 NASA Technology Roadmaps are comprised of 16 sections: The Introduction, Crosscutting Technologies, and Index; and 15 distinct Technology Area (TA) roadmaps. Crosscutting technology areas, such as, but not limited to, avionics, autonomy, information technology, radiation, and space weather span across multiple sections. The introduction provides a description of the crosscutting technologies, and a list of the technology candidates in each section.

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# Executive Summary

This is Technology Area (TA) 11: Modeling, Simulation, Information Technology, and Processing, one of the 16 sections of the 2015 NASA Technology Roadmaps. The Roadmaps are a set of documents that consider a wide range of needed technologies and development pathways for the next 20 years (2015-2035). The roadmaps focus on “applied research” and “development” activities.

The Modeling, Simulation, Information Technology, and Processing TA focuses on advances in foundational capabilities for flight computing and ground computing; physics-based and data-driven modeling, simulation, and software development; and information and data processing frameworks, systems, and standards. Taken as a whole, TA 11 has impact on most of the NASA technology portfolio. The foundational modeling, simulation, information technology, and processing technologies in this area enable the development of application-specific modeling, simulation, and information technologies as found throughout the other technology roadmaps. TA 11 technologies also form the base of Agency-wide capabilities needed to meet the ever-increasing modeling, simulation, information technology, and processing demands of NASA’s missions in exploration, science, and aeronautics. Hence, these technologies are an important component of solutions to NASA’s greatest challenges.

## Goals

The overarching goal of TA 11 is to develop computing, modeling and simulation, and information technologies that are the basis of new solution paradigms across the breadth of NASA’s missions. TA 11 focuses on enabling the NASA mission by developing modeling, simulation, information technology, and processing technologies that ultimately increase NASA’s understanding and mastery of the physical world.

High-level goals for each of the major themes of the roadmap are shown in Table 1. These goals include development of technologies needed for transformational flight and ground computing; increased modeling productivity and fidelity throughout NASA’s broad mission portfolio; simulations that enable management of uncertainty and risk across the entire system life cycle; and unprecedented increases in NASA’s ability to effectively utilize its wealth of data, including observational, sensor, simulation, and test data.

**Table 1. Summary of Level 2 TAs**

11.0 Modeling, Simulation, Information Technology, and Processing	Goals: Develop computing, modeling and simulation, and information technologies that are the basis of new solution paradigms across the breadth of NASA’s missions. Enable the NASA mission through development of virtual technologies that increase NASA’s understanding and mastery of the physical world.
11.1 Computing	Sub-Goals: Develop scalable, radiation-hardened flight processors, memory management and flight software to support more autonomous operations and data triage at the point of data collection. Exploit exascale supercomputing, data storage, and software development capabilities to enable 1,000 times larger mission-driven computations.
11.2 Modeling	Sub-Goals: Develop autonomous, integrated, and interoperable approaches for models and model development. Increase productivity, improve performance, and manage risk through improvements in autonomy and integration in modeling for NASA’s future missions.
11.3 Simulation	Sub-Goals: Develop best-physics simulations of operative mechanisms that enable increases in system performance and management of uncertainty and risk across the entire lifecycle of NASA’s distributed, heterogeneous, and long-lived mission systems.
11.4 Information Processing	Sub-Goals: Develop software frameworks and toolsets that efficiently and reliably manage greatly increased volume, variety, and velocity of data across the science, engineering, and mission data lifecycle while maintaining security of data. Enable advanced missions, effective remote and human-system collaboration, and greater system and crew autonomy through advanced software.



## ***Benefits***

Some of the major benefits of high-fidelity modeling and simulation, supported by high-performance computing and information processing, include expansion of the possible solution space enabling new design concepts; insight into the relationships between flight environments and system response; large-scale data analysis and integration that enables new scientific discoveries; training and decision-support systems that increase performance and safety while decreasing cost by using modeling and simulation directly in mission systems; near real-time numerical experimentation to explore mission trade space; and evaluation of complex systems throughout their lifecycle.

TA 11 technologies are broadly applicable to NASA's missions in exploration, science, and aeronautics. They impact not only the initial stages of mission planning but also the design, development, and certification process, and the long-term sustainment of vehicles and analysis of mission data. Ultimately, they will help to give decision makers the capabilities needed to manage risk, cost, and schedule for NASA's most demanding missions.

Technology Area 11  
Modeling, Simulation, Information  
Technology, and Processing Roadmap 1 of 2

Enabling Technology Candidates  
Mapped to the Technology Need Date

National Aeronautics and  
Space Administration

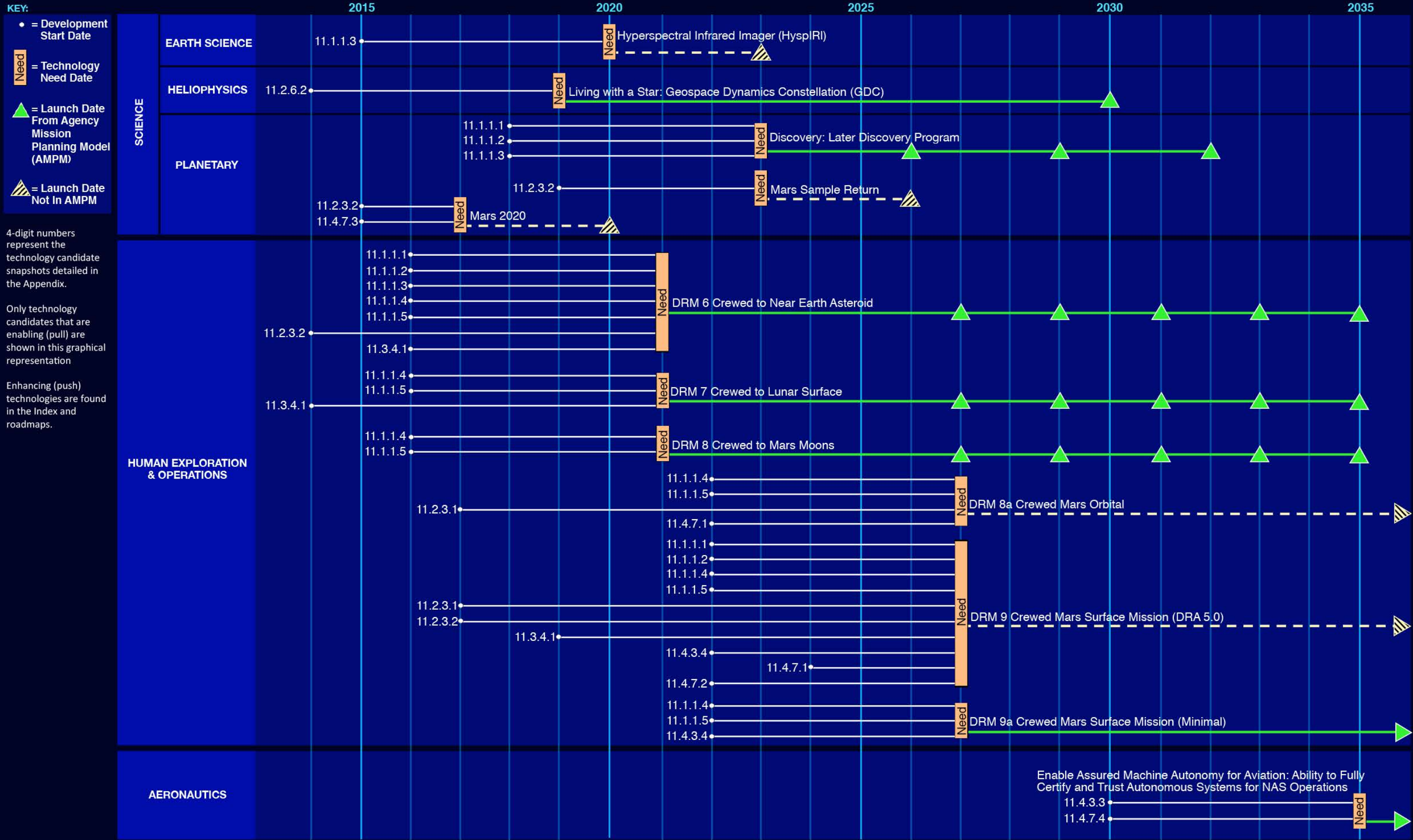


Figure 1. Technology Area Strategic Roadmap



Technology Area 11  
Modeling, Simulation, Information  
Technology, and Processing Roadmap 2 of 2

Enabling Technology Candidates  
Mapped to the Technology Need Date

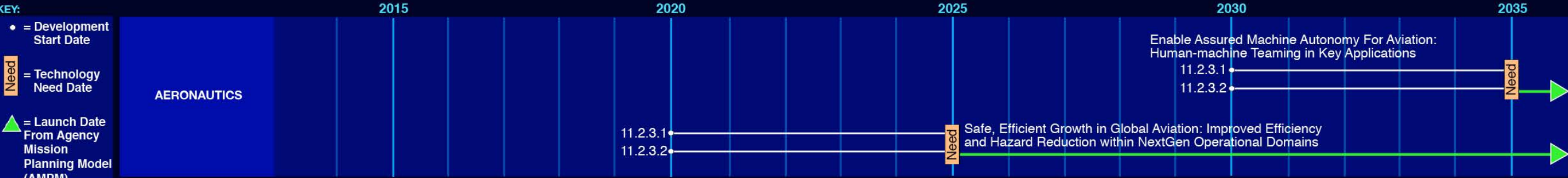


Figure 1. Technology Area Strategic Roadmap (Continued)

# Introduction

The topic area of Modeling, Simulation, Information Technology, and Processing spans nearly the entire NASA mission portfolio (see Figure 1). Although parts of TA 11 are discipline-specific, most of this technology area (TA) enables future disciplinary modeling and simulation technologies as found throughout the other technology roadmaps. While the other roadmap efforts address needs from specific domain perspectives, TA 11 focuses on needed advances in flight and ground computing, foundational and crosscutting elements of modeling and simulation, and science and engineering information processing. In the present roadmap, Modeling and Simulation are listed separately as a result of the legacy of the previous version. However, they are highly interrelated, as seen in the roadmap contents, and are often referred to collectively.

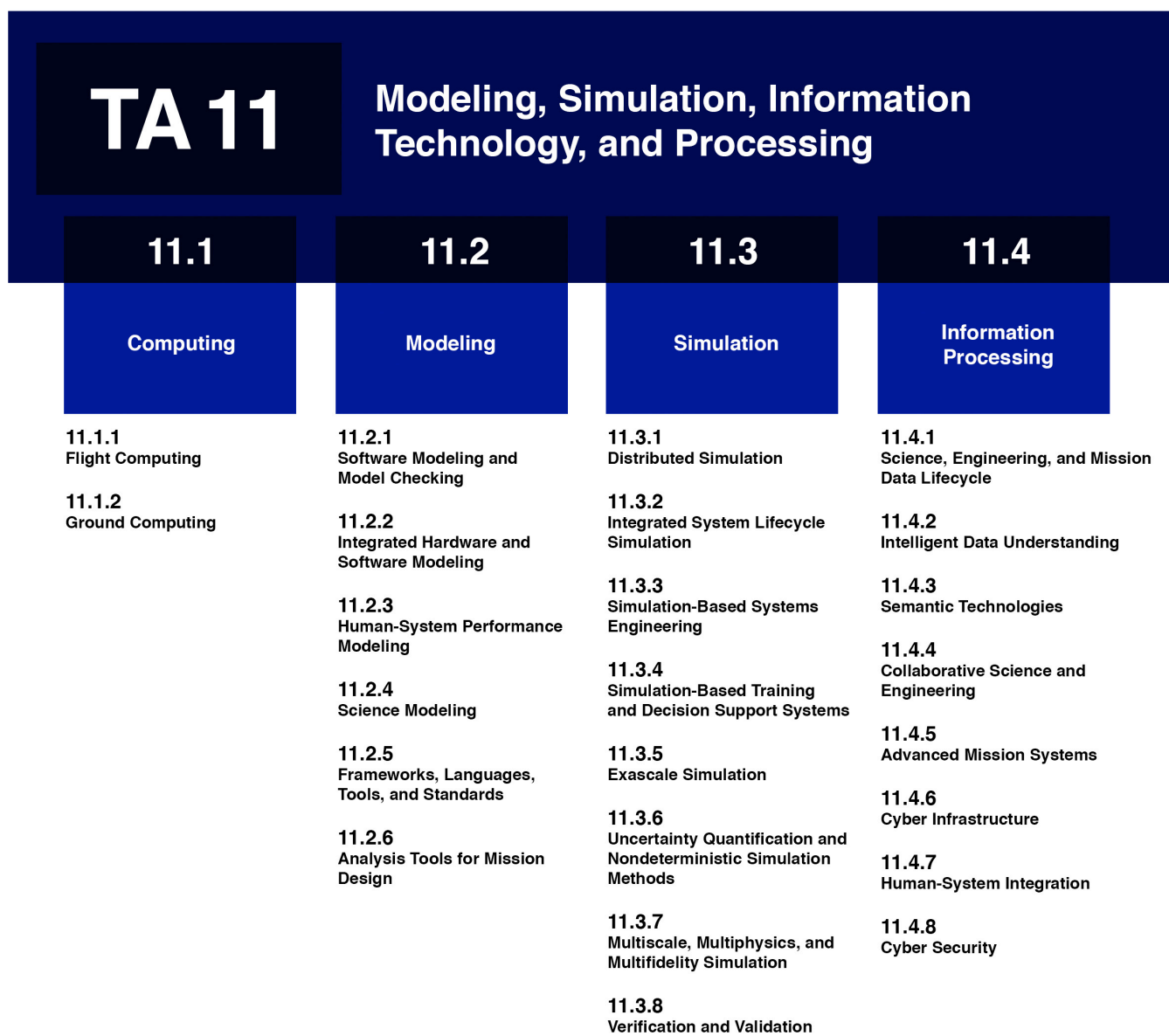


Figure 2. Technology Area Breakdown Structure (TABS) Technology Areas for Modeling, Simulation, Information Technology, and Processing



## 11.1 Computing

Computing encompasses innovative approaches to flight and ground computing that have the potential to increase the robustness of future aerospace systems and science return on long-duration exploration missions. Innovative computing architectures are required for integrated, multi-scale data-analysis and modeling in support of both science and engineering. Computing technologies can be grouped into the following general categories:

- **11.1.1 Flight Computing:** Includes technologies to support greater computation and data management at the point of collection onboard. In some cases, data reduction at the point of collection through intelligent triage methods may be required. Flight computing technologies include ultra-reliable, radiation-hardened platforms, which, until recently, have been extremely costly and limited in performance. Future radiation hardening will be achieved by a combination of traditional parts-level hardening, rad-hard-by-design (RHBD) techniques, and architectural support for software-based fault tolerance techniques.
- **11.1.2 Ground Computing:** Includes exascale supercomputing and data storage, as well as quantum, cognitive, and other types of advanced computing for Big Data analysis and high-fidelity physics-based simulations for Earth and space science, as well as aerospace research and engineering.

## 11.2 Modeling

Modeling encompasses technologies needed to support autonomous, integrated, and interoperable modeling capabilities throughout NASA's broad mission portfolio. The main topics in this section span software and hardware modeling, human-system modeling, large-scale data processing, and mission modeling. Modeling technologies have been grouped into the following general categories:

- **11.2.1 Software Modeling and Model Checking:** Includes technologies for dramatically more efficient software defect prevention, detection, and removal through a combination of methods applied at each phase of software development, including requirements, design, coding, and testing.
- **11.2.2 Integrated Hardware and Software Modeling:** Provides the ability to evaluate hardware and software systems and expose the complex and unintended interactions between the hardware and software components early in the design process; transform designs into models that can be assessed and analyzed for integrated system performance; ensure verification of interface requirements; and identify possible failure modes early in the design process and continuously use the model throughout the development, testing, and operation of the system.
- **11.2.3 Human-System Performance Modeling:** Ensures that new and relevant human-related technologies are infused into all vehicle and habitat designs and associated operational concepts. Digital human models will have their greatest impact on mission design if the validated models can be seamlessly integrated within mission models.
- **11.2.4 Science Modeling:** Uses mathematical models to quantify the interactions between the various quantities describing physical processes as a function of underlying variables, such as space and time. Inputs to science models include a large array of information from many current and future scientific instruments.
- **11.2.5 Frameworks, Languages, Tools, and Standards:** Provides a common set of frameworks, languages, tools, and standards that will enable the management of both short- and long-term complexity in sharing, exchanging, and integrating numerous models from diverse sources. These technologies will reduce the costs associated with modeling and simulation development.

- **11.2.6 Analysis Tools for Mission Design:** Maximizes return on investment and flexibility of future missions while minimizing the costs and risks associated with their launch and operations. These technologies mitigate issues related to large numbers of variables in mission architectures that contain monolithic, distributed, or disaggregated assets.

## 11.3 Simulation

Simulation encompasses technologies that enable management of uncertainty and risk across the entire lifecycle of NASA's distributed, heterogeneous, and long-lived mission systems. Improvements in simulation are resulting in increased predictive accuracy and decreased experimentation and expense. Simulation technologies can be grouped into the following general categories:

- **11.3.1 Distributed Simulation:** Provides the ability to model the sequential (time- and state-based) behavior of a defined system across a geographically-distributed and network-connected collection of inhomogeneous computer systems.
- **11.3.2 Integrated System Lifecycle Simulation:** Enables the interfaces, algorithms, and collaborative, networked platforms necessary for development of large, complex, multi-decadal, systems of systems.
- **11.3.3 Simulation-Based Systems Engineering:** Integrates ultra-high fidelity simulation with a vehicle's onboard integrated vehicle health management system, maintenance history, and all available historical and fleet data to develop a "digital twin" that mirrors the life of its flying twin and continuously forecasts its health, remaining useful life, and probability of mission success.
- **11.3.4 Simulation-Based Training and Decision Support Systems:** Provides new approaches for the development of human-in-the-loop full mission testing and training simulations that are needed to reduce time and costs and ensure mission success and safety.
- **11.3.5 Exascale Simulation:** Develops physics-based exascale environments that are needed to support the emerging requirements of multifaceted mathematics in complex systems, such as algorithms and analysis of methodologies for multi-scale and multi-physics simulation. These environments extend simulation performance and capability, the ability to seamlessly generate representative meshes, and the ability to numerically validate exascale data from various sources in near-real time.
- **11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods:** Identifies, classifies, models, and propagates all forms of uncertainty present in a system to enable understanding and management of their impact on system performance, robustness, reliability, and safety.
- **11.3.7 Multiscale, Multiphysics, and Multifidelity Simulation:** Develops methods needed to represent physical processes at operative length and time scales and unify best-physics representations across multiple disciplines.
- **11.3.8 Verification and Validation:** Provides technologies needed to ensure that numerical solutions are correct and properly represent governing physical processes. Validation is heavily dependent on technologies for experimentation and measurement found throughout the other roadmaps.

## 11.4 Information Processing

Information Processing encompasses numerous increasingly important capabilities across the entire mission and science data lifecycle that require new approaches for addressing NASA's numerous Big Data challenges. New approaches are required for triaging data with intelligent onboard algorithms and thoroughly analyzing the data using ground-based systems. Information processing technologies can be grouped into the following general categories:



- **11.4.1 Science, Engineering, and Mission Data Lifecycle:** Supports the increasingly data-intensive nature of NASA science and exploration missions including the need to consider the data lifecycle from the point of collection to the application and use of the data.
- **11.4.2 Intelligent Data Understanding:** Provides the ability to automatically mine and analyze datasets that are large, noisy, and of varying modalities, including discrete, continuous, text, and graphics, and extract or discover information that can be used for further analysis or decision making.
- **11.4.3 Semantic Technologies:** Technologies that enable data understanding, analysis, and automated consulting and operations.
- **11.4.4 Collaborative Science and Engineering:** Allow distributed teams with disparate expertise and resources, including those of partner agencies and contractors, to work in a unified manner.
- **11.4.5 Advanced Mission Systems:** Include technologies assisting in mission planning, execution and monitoring, and supporting autonomous and automated systems in Earth-side and remote flight missions.
- **11.4.6 Cyber Infrastructure:** Includes storage and computation, data management services, distributed deployments, crosscutting application to engineering, science and mission needs, cyber security and assurance, and the lifecycle of data archiving and preservation.
- **11.4.7 Human-System Interaction:** Provides advances in information systems and interface design that are needed to streamline access to mission systems and information to enhance mission capabilities and enable increased onboard autonomy.
- **11.4.8 Cyber Security:** Involves protecting information systems and data from attack, damage, or unauthorized access, and requires technologies for assurance of full-lifecycle information integrity and cyber security situational awareness and analysis.

# TA 11.1: Computing

Current flight computing systems provide limited support for real-time data analysis and decision making. Primary technical challenges for moving to higher speeds, greater capacity, and real-time analytics include radiation hardening of components and reducing power needs and leakages. The state of the art (SOA) for flight computing falls one or two orders of magnitude short of the processing needs of future NASA flight applications, with technical challenges like reliability and power efficiency. Top goals for this type of computing include providing radiation-hardened processing and memory management capabilities that can support increasing computational demands from flight software that processes ever-increasing amounts of data.

NASA operates some of the largest supercomputers in the world; they are needed to support high-fidelity modeling and simulation and large-scale data analysis across all mission areas. However, future demands for ground computing will be increasingly difficult to meet because of pervasive issues like large system reliability, high power usage, and low sustained performance, 10% or less of peak, on real NASA computations. Currently, quantum and cognitive computing are still unproven technologies, though progress has been made in both algorithms and hardware.

## Sub-Goals

In the area of flight computing, the increase in data generated from instruments will require more onboard computing capabilities, including scalable, radiation-hardened processors, memory management, flight software to support more autonomous operations, and flight software to provide data triage directly at the point of data collection. This will particularly help NASA's exploration missions, where data and communication constrain operational capabilities.

The most pressing goal for ground computing is to achieve and exploit exascale supercomputing, data storage, and software development capabilities, which will enable 1,000 times larger mission-driven computations for Earth and space science, aerospace research and engineering, and space exploration. With quantum and cognitive computing, the goal is to solve problems that an exascale supercomputer cannot, such as optimizing a rover's complex schedule or finding "interesting" correlations across multiple Earth science observational data.

**Table 2. Summary of Level 11.1 Sub-Goals, Objectives, Challenges, and Benefits**

Level 1		
11.0 Modeling, Simulation, Information Technology, and Processing	Goals:	Develop computing, modeling and simulation, and information technologies that are the basis of new solution paradigms across the breadth of NASA's missions. Enable the NASA mission through development of virtual technologies that increase our understanding and mastery of the physical world.
Level 2		
11.1 Computing	Sub-Goals:	Develop scalable, radiation-hardened flight processors, memory management and flight software to support more autonomous operations and data triage at the point of data collection. Exploit exascale supercomputing, data storage, and software development capabilities to enable 1,000 times larger mission-driven computations.



Table 2. Summary of Level 11.1 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3	
11.1.1 Flight Computing	<b>Objectives:</b> Increase onboard autonomy and enable large-scale data triage to support more capable instruments. Support reliable onboard processing in extreme environments to enable new exploration missions.
	<b>Challenges:</b> Effective radiation hardening technologies and processing approaches for extreme environments using multiple techniques including parts-level hardening, rad-hard-by-design (RHBD) techniques, and architectural support for software-based fault tolerance. Meeting processing needs, energy constraints, and reliability requirements for missions.
	<b>Benefits:</b> Provides pinpoint landing, hazard avoidance, rendezvous-and-capture, and surface mobility directly tied to the availability of high-performance space-based computing. Lowers spacecraft vehicle mass and power by reducing the number of dedicated systems needed to implement onboard functions. Provides power-efficient high-performance radiation-tolerant processors and the peripheral electronics required to implement functional systems. Could also benefit commercial aerospace entities and other governmental agencies that require high-capability spaceflight systems.
11.1.2 Ground Computing	<b>Objectives:</b> Support 1,000X larger mission computations to enable high-fidelity simulation and large-scale data analysis. Enable efficient, secure surge computing into the cloud, to meet peak supercomputing demands. Demonstrate efficient solution of complex NASA problems through quantum and cognitive computing.
	<b>Challenges:</b> Increasing the computing capacity, energy efficiency, communication bandwidth, programmability, and reliability of supercomputers and data systems. Increasing the scale, efficiency, and robustness of supercomputer software. Efficient and reliable methods for packaging supercomputing tasks for the cloud, and cloud-based data security models. Scaling quantum computers to the size needed to solve real NASA problems. Training cognitive systems for use on NASA missions.
	<b>Benefits:</b> Enables high-fidelity modeling and simulation and large-scale data analysis for advancing all areas of Earth science, space science, and aeronautics research, as well as many activities in space exploration. Provides flexibility for NASA's supercomputing capability to utilize surge computing in the cloud. Provides more efficient solutions for specific complex problems through quantum and cognitive computing.

### TA 11.1.1 Flight Computing

Current NASA missions use single radiation-hardened computers providing a few tens to a few hundred million operations per second (MOPS) with power consumption of 20 Watts (W) to 30W. NASA's current workhorse radiation-hardened flight computer is rated at 200 MOPS with a power consumption of 5W at the chip level and 20W at the board level.

The current trend in commercial computing systems is toward increasing the number of cores per chip while decreasing power utilization. One example of this type of processing being developed by another government agency and commercial industry provides up to 44 billion operations per second (GOPS) of throughput at approximately 20 W. While this processor does not meet many of NASA's objectives for power management and fault tolerance, it serves as a proof of principle that such a machine can be developed for reasonable cost and schedule from currently-available technologies. This supports a general technology theme of developing general-purpose processors over specialized processors (e.g., field-programmable gate arrays and graphical

processing units) with bundled operating systems and flight software development environment support.

A directly relevant current development by NASA and another government agency is a next-generation spaceflight computer with at least 24 cores on a chip and architectural support for very-low-power operation and a range of fault tolerance methods.

### ***Technical Capability Objectives and Challenges***

Three areas of flight computing that are critical to next-generation needs for science and exploration include processors, memory, and high-performance flight software. Scalable, multi-core processors and memory that have a range of capabilities for fault tolerance and recovery are needed for use in radiation fields to support an increasingly software-intensive onboard environment. High-density onboard memory technologies are also needed to operate in radiation environments with minimal power requirements, supporting both volatile and non-volatile storage. Flight software, called on to perform a range of functions, including increasing autonomy, will require techniques for state-based design and verification techniques to manage complexity at design time and ensure reliability and safety in operations.

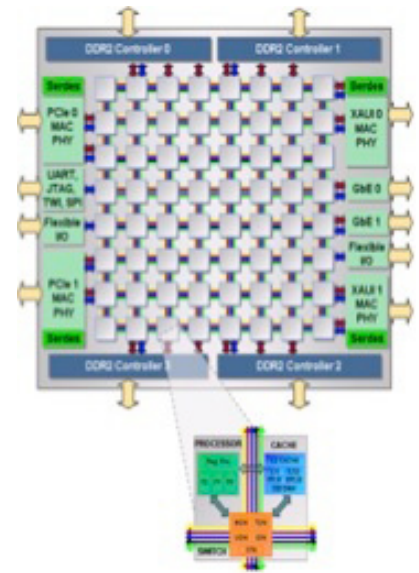
Historically, flight computing has focused on fairly tight-loop operations. Future trends show generalization toward varied requirements for flight computing, including hard real-time, mission-critical calculations that often involve vision-based algorithms such as those for entry, descent, and landing (EDL); high-data-rate instrument throughput imperatives, such as those for hyper-spectral and synthetic aperture radar; and the increasing use of model-based reasoning techniques like those for mission planning and fault management. Future NASA flight computing systems must provide architectural support across this spectrum of computational drivers, including uncertainty, distribution, concurrency, and operations.

As more capable science instruments observe and capture larger volumes of data, there is a need to develop methods for data reduction and triage at the point of collection. The introduction of intelligent machine-learning algorithms onboard is a critical technology area that is important for helping to address the entire end-to-end observing path in data-driven environments. Furthermore, the need to respond to and update observation plans is a critical part of moving towards more autonomous operations. This paradigm shift will require new onboard capabilities as demands for computation, storage, and software continue to grow to enable more autonomous operations coupled with onboard data services.

Additionally, new paradigms for fleet management and sustainment, such as the Digital Twin, which are enabling to extended autonomous operations, amplify the need for robust onboard computing. At the opposite end of the flight-computing spectrum, there is a need for low-power embedded computers with increased performance and power efficiency. These computers can enable miniaturization for future instruments and subsystems in small mission classes and distributed avionics architectures for larger mission classes.

### ***Benefits of Technology***

Pinpoint landing, hazard avoidance, rendezvous-and-capture, and surface mobility are directly tied to the availability of high-performance space-based computing. In addition, multi-core architectures have significant potential to implement scalable computing, thereby lowering spacecraft vehicle mass and power by reducing the number of dedicated systems needed to implement onboard functions. These requirements are equally important to space science and human exploration missions. In addition, power-efficient, high-performance, radiation-tolerant processors and the peripheral electronics required to implement functional systems could also benefit commercial aerospace entities and other governmental agencies that require high-capability spaceflight systems.



**Flight Computing**



Table 3. TA 11.1.1 Technology Candidates – not in priority order

TA	Technology Name	Description
11.1.1.1	Radiation-hardened General Purpose Flight Processor	Enables general-purpose onboard processing in the space radiation environment using a combination of traditional parts-level hardening, rad-hard-by-design (RHBD) techniques, and architectural support for software-based fault tolerance techniques.
11.1.1.2	Radiation-hardened High-Capacity Memory	Enables volatile and non-volatile, radiation-hardened memory management for flight computing using a combination of traditional parts-level hardening, rad-hard-by-design (RHBD) techniques, and architectural support for software-based fault tolerance techniques.
11.1.1.3	High Performance Flight Software	Enables onboard, high performance autonomy and data processing processing taking advantage of flight processor and memory management advances in flight computing.
11.1.1.4	Low Power Embedded Computer	Enables low-power processor for embedded processing within small systems incorporating low-power processor designs and provide architectural support for power scalability.
11.1.1.5	High Speed Onboard Networks	Enables onboard, high-speed networks for sensor data.

## TA 11.1.2 Ground Computing

This technology area is composed of four classes of ground computing technologies, including exascale supercomputing, quantum computing, cloud supercomputing, and cognitive computing.

*Supercomputing:* NASA operates some of the world's largest supercomputers in support of its mission. Despite the current power of NASA supercomputers, the largest single computations performed thus far are able to use only 70,000 processors and achieve only about 10% of the peak computing of those processors, and must be restarted periodically due to challenges of limited system communication performance, programmability, reliability, and power efficiency.

*Quantum Computing:* Quantum algorithms may solve certain challenging computational problems, such as optimization or pattern recognition, exponentially faster than is possible using current computing paradigms. As a result, universities, government laboratories, and major corporations are developing both quantum computing algorithms and hardware. Approximately one dozen alternative approaches for implementing quantum computers and algorithms have been developed and used to solve simple problems. Most importantly, quantum error correction is possible so it is not necessary to achieve perfection in quantum hardware.

Advances have also been made on specialized quantum computing devices, such as the quantum-annealing machine developed, in part, by NASA. A 512-qubit quantum annealing system called D-Wave Two is currently operational.

*Cloud Supercomputing:* Cloud systems virtualize computing servers, meaning that the user's software stack runs in a server simulation environment that can expand and contract among, and be moved between, physical servers. Currently, huge public clouds provide computing on demand.

*Cognitive Computing:* Synaptic brain-like processors are being funded by other government agencies and commercial industry. One such processor is a novel brain-inspired chip architecture based on a scalable, interconnected, configurable network of "neurosynaptic cores" that brings memory, processors, and communication into close proximity to emulate the brain's computing efficiency, size, and power usage, and our ability to make good decisions with imprecise and incomplete data. A cognitive computing programming paradigm has been developed for programming these systems.



Ground Computing

### ***Technical Capability Objectives and Challenges***

Supercomputing, enabled by exascale computing, data storage, and programming technologies, must overcome challenges in maximum application scale, reliability, and energy efficiency. Specifically, within 10 years, NASA supercomputing must achieve at least 1,000 times greater application performance, 50 petaflops sustained; 10 times greater mean time between application failure, mean time between failure (MTBF) of 100 hours; and 500 times better energy efficiency, 400 gigaflops per Watt. The combination will enable supercomputing technology to meet NASA's exponentially growing demands for large-scale computation in support of mission goals, within available supercomputing facility power.

NASA scientists are currently exploring quantum computing to solve combinatorial optimization problems, such as mission planning and scheduling, anomaly detection, and decision making in complex system operation, and optimizing air traffic. In mission planning, the number of possible plans can be astronomical, so classical computers can only find approximate solutions. A sufficiently large quantum computer might be able to find the optimal solution to mission planning and scheduling, resulting in greater mission productivity and lower risk. The challenge is to produce a quantum computer that can maintain coherence of a sufficiently large number of entangled qubits, such as 1,024.

While some NASA applications have been hosted in the cloud, broader NASA use of the cloud requires the technology to achieve transparency of use and information technology (IT) security equivalent to that of moderate-impact NASA systems. Achieving these technology objectives will enable NASA to use the cloud for surge supercomputing when needed to meet mission-critical time constraints by transparently sending computations to public clouds. Experiments in surge supercomputing show that it is currently too labor intensive and expensive to move supercomputer computations to the cloud and that the maximum surge capacity is too small to make a meaningful difference. With technology to automatically package computations for the cloud, many of these challenges can be overcome within five years, enabling NASA computing to surge at least 50% above NASA's supercomputing capacity, with a time penalty of only 10% for those jobs sent to the cloud. If these goals can be met, cloud supercomputing may impact near-term space exploration missions. However, the usefulness of these technologies requires cloud usage to become cost competitive with internal NASA supercomputing.

Cognitive computing based on artificial neurons and synapses could be an efficient means of demonstrating the human ability to learn from examples and observation, interact verbally, find complex relationships in data, and adapt to circumstances without reprogramming. This will enable a dramatic acceleration in the advancement of NASA science missions through Big Data analysis and will enable more adaptable deep-space robotic probe missions. Cognitive computers must have up to 40 million times more neurons and synapses than current models and use far less power.

### ***Benefits of Technology***

The dramatic advancements in Ground Computing are enabling to many of the other technologies in TA 11 and throughout the other 14 technology roadmap sections. Future paradigms for modeling and simulation, Big Data, and machine intelligence, among others, are enabled by supercomputing and support advancements in every science domain, throughout all facets of aeronautics research and in many aspects of space exploration. Similarly, efficient surge computing into the cloud will provide additional flexibility to NASA's supercomputing capability. Quantum and cognitive computing will provide more efficient solutions for specific complex problems.



Table 4. TA 11.1.2 Technology Candidates – not in priority order

TA	Technology Name	Description
11.1.2.1	Exascale Supercomputer	Provides peak computational capability of $\geq 1$ exaflops, $10^{18}$ floating point operations per second, for exascale performance of NASA computations, with excellent energy efficiency and reliability, to support NASA's exponentially growing high-end computational needs.
11.1.2.2	Automated Exascale Software Development Toolset	Provides automated, exascale application performance monitoring, analysis, tuning, and scaling.
11.1.2.3	Exascale Supercomputer File System	Provides online data storage capacity of $\geq 1$ exabyte, enabling data storage for exascale modeling and simulation (M&S) and data analysis, with sufficient performance and reliability to maintain productivity for a broad array of NASA applications.
11.1.2.4	Quantum Computer	Utilizes quantum effects such as superposition and entanglement to enable solution of certain computational problems, like optimization or pattern recognition, where an exhaustive search of all possibilities or computations by a conventional computer would be infeasible.
11.1.2.5	Public Cloud Supercomputer	Provides additional resources for NASA supercomputer users, such as for mission-critical computing in an emergency.
11.1.2.6	Cognitive Computer	Provides efficient, adaptable brain-like computing, using synthetic neurons and synapses, programmed by learning from instances to sense, predict, and reason.
11.1.2.7	High Performance Data Analytics Platform	Provides a computer storage environment optimized for high-performance data analytics, supporting interactive exploration and analysis with petabyte-scale observational and computed data sets.

## TA 11.2: Modeling

Many current modeling capabilities are insufficient to meet NASA's increasingly aggressive mission demands. Often, these existing modeling approaches are not sufficiently robust, comprehensive, or efficient and result in decreased productivity and performance, increased risk, and lack of system integration. TA 11.2 includes new technologies that are needed to mitigate these shortcomings and enable NASA's future missions. Technologies include those related to Software Modeling and Model Checking; Integrated Hardware and Software Modeling; Human-System Performance Modeling; Science Modeling; Frameworks, Languages, Tools, and Standards; and Analysis Tools for Mission Design.

### *Sub-Goals*

Overall goals in modeling for NASA's future missions are aimed at increasing productivity, improving performance, and managing risk through improvements in autonomy and integration. Various aspects of this technology area are aimed at supporting mission planning and execution, vehicle development and performance, and determination of risk throughout the mission life cycle.

**Table 5. Summary of Level 11.2 Sub-Goals, Objectives, Challenges, and Benefits**

Level 1		
11.0 Modeling, Simulation, Information Technology, and Processing	Goals:	Develop computing, modeling and simulation, and information technologies that are the basis of new solution paradigms across the breadth of NASA's missions. Enable the NASA mission through development of virtual technologies that increase our understanding and mastery of the physical world.
Level 2		
11.2 Modeling	Sub-Goals:	Develop autonomous, integrated, and interoperable approaches for models and model development. Increase productivity, improve performance, and manage risk through improvements in autonomy and integration in modeling for NASA's future missions.
Level 3		
11.2.1 Software Modeling and Model Checking	Objectives:	Decrease time required to detect and identify software defects and the time required to determine and implement the correct mitigation strategy.
	Challenges:	Increased automation, particularly in symbolic analysis, model checking, software testing, and knowledge representation.
	Benefits:	Matures software modeling and assurance techniques to keep pace with increasing software requirements. Provides assurance of novel software development techniques as they are introduced into practice.
11.2.2 Integrated Hardware and Software Modeling	Objectives:	Supports the design of integrated hardware and software for aerospace systems by capturing design information from domain experts, representing that information so that computers can process it, and creating tools to facilitate the analysis of the information.
	Challenges:	Managing the interactions between hardware/ software and system-level design decisions for components that are becoming more interdependent.
	Benefits:	Revolutionizes space system development and integration through integrated hardware-software modeling. Reduces cost while improving accuracy by identifying interface mismatch and correcting the problems early in the design process can significantly reduce costs. Captures and incorporates lessons learned that provides valuable insights to engineers and developers.



Table 5. Summary of Level 11.2 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3	
11.2.3 Human-System Performance Modeling	Objectives: Develop and integrate high-fidelity models of vehicle/habitat systems and crew-vehicle interfaces into a virtual real-time mission operations simulation environment, complete with instrumentation to measure crew-system interactions and crew performance.
	Challenges: Seamless integration of digital human models within mission-specific models. Iterative model development to guide model capability enhancements.
	Benefits: Provides cost-effective analyses of a wide range of both nominal and off-nominal operations scenarios needed to develop an understanding of both human decision processes and the enhancement to decision making provided by advanced decision support tools from both crew and mission-control perspectives. Ensures that new and relevant capabilities are infused into all vehicle and habitat designs and associated operations concepts.
11.2.4 Science Modeling	Objectives: Synthesis of vast quantities of information from many current and future scientific measurements, relating the information to physical processes and planning for future missions.
	Challenges: Improvements in storage, processing, assimilation, and visualization technologies are required, including data mining, automated metadata acquisition and reasoning, and high-end computing.
	Benefits: Sustains, improves, and creates the next-generation of science models that will facilitate the path toward new scientific discovery in Earth Science, Heliophysics, Astrophysics and Planetary Science. Develops modeling capabilities that take advantage of state of the art hardware and software technologies to maximize the science return of future missions. Makes future missions more cost-effective since these capabilities can maximize the return on investment of next-generation observing systems.
11.2.5 Frameworks, Languages, Tools, and Standards	Objectives: Dramatically increase in number of design cycles per system development phase.
	Challenges: Development of libraries of re-useable, tailored and executable systems models and corresponding mission requirements models.
	Benefits: Provides guidance for establishing the robust baseline architecture thus facilitating tradeoffs analysis, enabling large-scale reuse, supporting architectural decisions, and tailoring evaluations for project development milestones. Provides flexibility and expressiveness required to define complex systems quickly and effectively through the reuse of common entities across multiple spacecraft projects.
11.2.6 Analysis Tools for Mission Design	Objectives: Develop general and sustainable risk models for trade space analysis.
	Challenges: Difficult to integrate complex and distributed mission aspects, projects, systems, lifecycles, and science and engineering domains and to tie the mission design to cost and risk factors. Fidelity of the models utilized within these tools. Development of the common framework and component library needed to address portability for generalized use.
	Benefits: Increases the accuracy of science modeling and enables design of future observing systems by predicting and optimizing their impacts on the science models.

## TA 11.2.1 Software Modeling and Model Checking

Flight software defect prevention, detection, and removal are currently accomplished by a combination of methods applied at each phase of software development: requirements, design, coding, and testing. Although most test methods focus on the coding and testing phases, the most serious defects are inserted in the requirements and design phases. The issue with using multiple methods applied at different phases is the excessive time required to detect and identify a defect and the additional time required to determine and implement the correct mitigation strategy.

### **Technical Capability Objectives and Challenges**

Although current methods have demonstrated substantial and quantifiable benefits on real flight software, there is widespread agreement among experts that many serious challenges remain. Many of these challenges are related to the need for increased automation, particularly in the areas of symbolic analysis, model checking, software testing, and knowledge representation.

### **Benefits of Technology**

Future missions will continue to rely on software-intensive systems to meet their objectives. Continued research is required to further mature software modeling and assurance techniques to keep pace with the ever-increasing software requirements anticipated for these missions. Additional research is expected to be required for assurance of novel software development techniques as they are introduced into practice.

**Table 6. TA 11.2.1 Technology Candidates – not in priority order**

TA	Technology Name	Description
11.2.1.1	Hybrid Model Checking	Automates symbolic analysis of discrete and continuous variables governing a system, along all the paths linking different states of a system.
11.2.1.2	Automated Software Testing Environment	Provides automated generation of tests and corresponding coverage analysis for specified coverage criteria.
11.2.1.3	Software Development Environment with Program Synthesis	Provides automated reasoning and knowledge representation for software generation in space applications.

## **TA 11.2.2 Integrated Hardware and Software Modeling**

Recent experiences with deep-space systems have highlighted cost growth issues during integration, testing, and operations. These include changes to the design late in the life cycle, often resulting in a ripple effect of additional changes in other areas, unexpected results during testing due to unplanned interaction of fault responses, and operational limitations placed on the spacecraft based on how the system was tested, in order to “fly-as-you-test”. These issues cause cost and schedule growth during system development.

As part of one of NASA’s software test verification processes, the verification team is providing the integration capabilities that allow flight software to be executed on actual flight processors while being integrated with a full-featured simulation. This allows scenario-based testing to be performed where the flight software is executed in a “test-like-you-fly” approach. Here, the vehicle avionics components are integrated with complex high-fidelity simulation models combined with a flight data bus-capable input/output (I/O) pump that makes this type of test configuration possible. The simulation feeds the I/O pump with all of the inputs necessary to fully populate the flight data bus, allowing a flight computer to interact with the same interfaces as it would in actual flight.

One international research project is developing system software using a co-engineering approach and focusing on evaluation of system-level correctness, safety, dependability, and system performance of onboard computer-based aerospace systems. This project includes development of a system-level integrated modeling (SLIM) language for modeling and specifying hardware or software systems, covering hardware, software operations, and time-dependent dynamics. It is used to model the interaction between the physical world and the hardware or software system, including fault modeling. These techniques will significantly improve the reliability of modern and future space missions.



### **Technical Capability Objectives and Challenges**

There are three important technical capabilities that are essential to modern approaches to performing integrated hardware and software engineering in today's computation-intensive engineering environment. These capabilities include capturing the design information from domain experts, representing that information so that computers can process it, and creating tools to facilitate the analysis of the information to support the design of integrated hardware and software for space systems. In particular, technologies from elsewhere in this roadmap, like TA 11.3.2 Modeling and Simulation Lifecycle Simulation and TA 11.4.3 Information Processing Semantic Technologies, are especially important to facilitate capturing design knowledge to support the integrated hardware or software design process.

Unfortunately, traditional documentation and engineering design tools do not allow an efficient use of modern computer resources during the design process. The reasons for this include, but are not limited to:

- Voluminous design documentation and unstructured data are not easily represented for automated computer processing,
- Incompatible terminology use by diverse stakeholders,
- Manual interpretation of the system models, especially when design changes must be propagated,
- Re-modeling of the system in order to perform individual analysis.

### **Benefits of Technology**

Integrated hardware-software modeling technology has the potential to revolutionize space system development and integration, which is one of the most challenging tasks, especially for designing large numbers of complex spacecraft systems with complex intersystem dependency. Reducing cost while improving accuracy is another benefit of this technology, since identifying interface mismatch and correcting problems early in the design process can significantly reduce costs. Furthermore, these technologies can provide game-changing capabilities for the capture, can incorporate lessons learned, and can help ensure that valuable insights are available to future engineers and developers.

**Table 7. TA 11.2.2 Technology Candidates – not in priority order**

TA	Technology Name	Description
11.2.2.1	Hardware/Software (HW/SW) Interface Modeling Specification Language	Provides a formal specification language to enable automatic generation of integrated hardware and software artifacts.
11.2.2.2	Intelligent Hardware and Software Interface Reasoning Framework	Provides automated tools to intelligently support human designers in producing integrated HW/SW interface design models such as those for interface requirements, implementations; includes constraint checking, test plan generation, support of automated test execution, and reuse of standard library models of HW & SW interfaces.
11.2.2.3	Automated Design Specification Knowledge Capture Systems	Provides an automated design specification knowledge capture system to combine design knowledge from a multitude of space hardware and software systems into an integrated system representation.

### **TA 11.2.3 Human-System Performance Modeling**

Historically, NASA has developed mission operations concepts, including the specification of function and task allocations, operator interface designs, and procedure development, primarily based on input from experts in systems engineering design and development, paired with limited human-in-the-loop testing. The process has produced several examples of operational design concepts that were a poor match to human capabilities and limitations, both for in-flight operations and ground-based operations and support. The mission and operational risks posed by these sub-optimal designs have been addressed through extensive training and heavy reliance on ground-based expertise to assist crews with safety-critical operations and activities in real time.

On next-generation missions to destinations beyond the Earth-Moon system, the ability to address human performance-based operational risk via training and expertise from the ground will be greatly limited. For example, real-time ground assistance for the most time-critical operations will not be available to crews for such missions due to communication interruptions and delays. Additionally, budget limitations are greatly restricting plans for human-in-the-loop operational testing and validation in ground-based operational simulators.

Experience with the benefits of ground-based testing for operating flight-critical elements of Apollo missions, most notably the lunar module, shows that some testing of next-generation operational concepts in ground-based simulation facilities will be absolutely essential to ensure mission success and crew safety. The scope, turnaround time, and cost of such testing can be reduced greatly if human performance can be predicted with a high degree of accuracy by human performance models during iterative development. Similarly, designs for ground support and processing will greatly benefit from model-based evaluation.

### ***Technical Capability Objectives and Challenges***

It is necessary to develop and integrate high-fidelity models of candidate vehicle and habitat systems and crew-vehicle interfaces into a virtual real-time mission operations simulation environment, complete with instrumentation to measure crew-system interactions and crew performance. The human-systems modeling approach—that is, integrating systems engineering models and human performance models into processes and tool development—will ensure that new and relevant capabilities are infused into all vehicle and habitat designs and associated operations concepts.

Digital human models will have their greatest impact on mission design if the validated models can be seamlessly integrated in mission models. Preliminary analyses of human performance in recent simulations of spacecraft mission operations reveal that human multitasking performance exhibits patterns that are predictable and repeatable, rendering such performance amenable to computational modeling. However, to close the gap between the predictive capabilities of current models and the capabilities required to support future missions, an iterative model development approach is required in which data from human-in-the-loop simulations of mission operations inform and guide model capability enhancements. In this approach, a SOA model makes detailed predictions for operator performance in the context of a candidate operations concept. Operator performance from a human-in-the-loop simulation of the concept is then captured and analyzed. Performance data are compared to model predictions to identify differences between actual and predicted performance. These differences inform and guide enhancements of the models. Models are validated on tasks representative of the mission operations environments.

Human Factors evaluates human-system performance at multiple levels of complexity. In general, the adequacy of computational models is inversely correlated with the level of task complexity. Models for prediction of simple performance parameters, such as reaction time, provide excellent estimates across a range of task types, such as simple reaction time versus choice reaction time, populations like young versus old, male versus female, and operational factors like fatigue, stress, and noise. However, even SOA models of human performance in a multitasking operational environment, such as a spacecraft crew responding to an off-nominal situation, can be confounded by the myriad of factors impacting the multiple agents involved. Other government agencies and other interested parties have developed extensive anthropometric models; however, all these models assume operations in a 1-G environment. While they provide a useful foundation, they are not directly extensible to hyper- and micro-G operations and will need to be extended to NASA's mission environments.

### ***Benefits of Technology***

These technologies will enable cost-effective analyses of a wide range of nominal and off-nominal operations scenarios needed to develop an understanding of both human decision processes and the enhancement to decision making provided by advanced decision support tools from both crew and mission-control



perspectives. The cost of developing this type of model-based technology is amortized by a number of additional uses of the results:

- a platform for industry and academic partners to incorporate and test decision-support technologies and conduct additional performance studies;
- an incubator for human-systems technology spinoffs, such as natural language command and control interfaces with smart device and smart home applications;
- a medium for hands-on involvement with deep-space mission operations concepts by the public through web-based operational simulations and associated gaming capabilities;
- a means to engage and involve the next generation of scientists and engineers in deep-space mission development activities and science, technology, engineering, and math (STEM) education;
- an integration laboratory to develop advanced solutions to off-nominal situation management in related operational domains such as robotic missions, distributed military operations, and next-generation airspace operations; and
- in-situ distributed training systems for just-in-time training for crew and mission support personnel.

**Table 8. TA 11.2.3 Technology Candidates – not in priority order**

TA	Technology Name	Description
11.2.3.1	Integrated Human-Systems Models	Estimate human-system performance for concept, design, and operational validation and verification.
11.2.3.2	Human Digital Twin	Provides predictive models of human performance at multiple levels of complexity for individuals as well as groups, for a wide range of tasks, under a wide variety of mission-relevant shaping factors.
11.2.3.3	Toolset for Automated Task Generation for Human-System Modeling	Provides ability to unobtrusively capture, measure, and analyze task performance to feed into human and human-system modeling technologies.

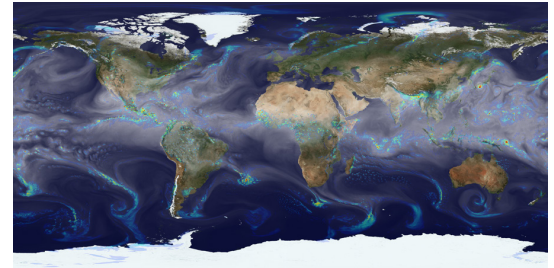
## TA 11.2.4 Science Modeling

Earth science modeling and assimilation are core elements of the science program needed to improve the prediction of weather and extreme weather events and to model global land cover change, global water cycles, and the climate system. Data assimilation uses available observations together with a model forecast to provide the best estimate of the state of a physical system. Similarly, in Heliophysics, modeling, and numerical simulations have recently become very important for understanding the overall dynamics of the Sun-to-Earth or Sun-to-planet chain and forecasting and describing space weather.

Currently, only about half of science models run on SOA high-performance computing (HPC) systems. Due to the large proportion of legacy code, many of these models do not take full advantage of newly available data or new models. Sustaining and extending the use of these models requires scientists to utilize SOA HPC capabilities for scalability and to provide full interoperability with multiple programming languages, newly-available data, standards, and other models. In addition, being able to reproduce and compare results over long timeframes requires carefully-defined quality metrics and common descriptive “dictionaries” or “ontologies” that will ensure accurate and reliable scientific results. The HPC systems themselves need to be made more resilient to execution anomalies so that hardware and software failures do not require the complete restart of simulations that execute for multiple days.

### ***Technical Capability Objectives and Challenges***

Models and assimilation systems, as well as numerical simulations, are the main tools for synthesizing the large array of information from many current and future scientific measurements to relate them to physical processes and plan for future missions. Two specific examples of such modeling are Earth system modeling and assimilation and heliophysics modeling. Earth science models “help to quantify the interactions and balances between the various components acting on a wide variety of scales in both space and time” [2008 Earth Science Modeling and Assimilation (ESMA)].



**Science Modeling**

Significant improvements in storage, processing, assimilation, and visualization technologies are required, including data mining, automated metadata acquisition and reasoning, and high-end computing. These technologies are related to those described in TA 11.4, but are unique since they are designed to satisfy very specific science modeling challenges and requirements. Some specific heliophysics modeling challenges include multi-scale problems for processes on scales of  $\sim 1$  kilometer (km) that determine evolution of system of  $> 10^7$  km; time scales with the solar cycle of about 11 years, and the proton cyclotron time of about 1 second (s); systems of about  $10^6$  km that generate km-scale features, such as auroral arcs; coupling to lower atmosphere and other planetary environments; particle models coupling to fluid models; and analysis of complex data sets.

One possible crosscutting revolutionary technological concept for all science and exploration systems is the “sensor web,” which represents a new paradigm for data assimilation that may result in significant improvements in science modeling. Sensor webs are intelligent data collection systems comprised of widely-deployed, heterogeneous sensors using a common backend ontology and an application programming interface (API). A sophisticated communications fabric will enable rapid, seamless interaction between instruments and science numerical models, enabling the data assimilation system to identify an “optimal” sequence of targeted observations and autonomously collect data at specific locations in space and time based on the system’s understanding of the process being measured, as well as the capabilities, like mobility and sensitivity, and needs, like power and uptime limits of the sensors.

Capabilities required in this area over the next decades include:

- Near-term capabilities that deal with sustaining and improving legacy science models by developing interoperable parallel libraries and standards that will increase the use of high-performance computing for science modeling.
- Mid-term capabilities that include the development of Big Data analytics methodologies; advanced forms of discovery and reasoning that are specifically geared towards science modeling to enable models to integrate terabytes of diverse datasets; as well as distributed and remote data, in a seamless, fast, secure, and automated fashion.
- Long-term capabilities that include data provenance and data quality metrics to ensure long-term validation and continuity of scientific results over long periods of times, across multiple programs and instruments. Other long-term capabilities will build interactive models through real-time optimization.

### ***Benefits of Technology***

The capabilities described herein are essential to sustain, improve, and create the next generation of NASA science models that will facilitate the path toward new scientific discovery in Earth Science, Heliophysics, Astrophysics, and Planetary Science. Modeling capabilities that take advantage of SOA hardware and software technologies maximize the science return of all future missions. Additionally, developing a sensor web infrastructure would make future missions more cost-effective, as these capabilities can maximize the return on investment of next-generation observing systems.



The technologies described in this section of the roadmap will enable sustaining and improving of legacy science models and building the framework for future interactive models. In particular, these technologies will take full advantage of SOA HPC systems and of all data and models available in a transparent and seamless fashion.

**Table 9. TA 11.2.4 Technology Candidates – not in priority order**

TA	Technology Name	Description
11.2.4.1	Fortran Compatible and Interoperable Parallel Libraries	Enable the many legacy models to take advantage of newly available data and other models, and to improve their capabilities.
11.2.4.2	High Performance Processor Toolset for Science Modeling	Facilitates retrospective analyses, or reanalyses, that integrate a variety of observing systems with numerical models that run on HPC systems.
11.2.4.3	Quality Metrics for Science Data	Encode dataset variable characteristics and related quality to derive inter-comparison rules between datasets and ensure accurate and reliable scientific results.
11.2.4.4	Toolset for Concurrent Data Diagnostics and Acquisition for Science Modeling	Optimizes the application of the models by identifying model uncertainties, relating them to data gaps, and visualizing intermediate results.
11.2.4.5	Software Infrastructure for Sensor Webs	Enables data and information acquisition, fusion, and integration in an interoperable fashion.

## TA 11.2.5 Frameworks, Languages, Tools, and Standards

The SOA in component frameworks targeting development of real-time applications is represented by three commercial industry projects. The first is a project that aims to provide theory and tools needed for cost-efficient engineering and re-engineering of distributed component-based software and is focused on embedded systems in the automotive, telecommunication, and automation industries. The second is an open and standardized automotive software architecture, jointly developed by automobile manufacturers, suppliers, and tool developers to establish open standards for automotive electrical/electronic architectures that will provide a basic infrastructure to assist with developing vehicular software, user interfaces, and management for all application domains. The third project is an initiative for providing freely-distributable technology for the design and implementation of predictable real-time software for embedded devices with support for the unified modeling language (UML) state-charts semantic. All of these technologies support an overall model-based systems engineering (MBSE) capability.

### *Technical Capability Objectives and Challenges*

Modeling and simulation frameworks are needed to support the increasing complexity of NASA missions. Using these frameworks, technologies and alternatives can be evaluated in a repeatable manner and mission system changes can be more effectively planned and monitored. Recently, architecture frameworks have been established that define a common approach for architecture description, presentation, and integration. The frameworks are intended to ensure that architecture descriptions can be compared and related across boundaries.

The benefits of using uniform architecture frameworks across the Agency cannot be realized without a set of case studies available for system engineers to review. There is a need to develop some key exemplars of architectural views for specific organizations and projects in order to help clarify the use of this technology. By modeling a full project, such as ground system architecture, within an architecture framework, the method and models can serve as templates for future projects.

There are four different technologies discussed herein to support the development of advanced MBSE frameworks, languages and tools, and standards. These capabilities include creating a library of reusable systems modeling language (SysML) models of NASA-related systems; developing different space systems

profiles to support all exploration and science programs; developing automated tools to link requirements models, system design, implementation artifacts, data pedigree, and software codes; and developing executable codes that include design model artifacts.

### ***Benefits of Technology***

Using an aerospace-specific system-modeling framework provides guidance for establishing the robust baseline architecture, facilitating tradeoffs analysis, enabling large-scale reuse, supporting architectural decisions, and tailoring evaluations for project development milestones.

Developing a library of NASA-specific SysML models that are common across multiple projects will facilitate the adoption of MBSE, a critical technology for NASA systems engineering. Such an asset library can provide the flexibility and expressiveness required to define complex systems quickly and effectively through the reuse of common entities across multiple spacecraft projects. A modeling framework populated with a set of reusable NASA models and profiles that support all missions will have tremendous impacts on lifecycle costs of NASA missions.

**Table 10. TA 11.2.5 Technology Candidates – not in priority order**

TA	Technology Name	Description
11.2.5.1	Library of Reusable NASA Related System Models	Enables sharing across NASA centers and supports all NASA exploration mission products and process production.
11.2.5.2	Profiles for Spacecraft, Space Robotics, and Space Habitats	Creates NASA system profiles to support system engineers and can support auto generation of design artifacts and guide downstream engineering work.
11.2.5.3	Robust Mission Requirements Modeling	Provides a comprehensive set of aerospace/NASA specific requirement and process models that can be shared with all NASA mission programs and projects. These models are linked and traced to all development artifacts. Also, these requirement models can be tailored to fit the needs for specific missions context.
11.2.5.4	Executable Models	Define the execution semantics and a complete library of executable models that have precise and unambiguous semantics, shared across NASA centers, and support all NASA exploration mission products and process production.

## **TA 11.2.6 Analysis Tools for Mission Design**

The complexity of missions and resulting requirements for mission design are significantly increasing because of the numerous ongoing developments in spacecraft, instrumentation, autonomy, and intelligent software, coupled with ever-increasing cost and risk constraints. Analysis tools need to be developed for designing complex missions while taking advantage of the latest technology developments and to trade mission designs based on multiple variables while minimizing cost and risk.

Currently, most available tools represent ad-hoc and/or individual mission design components, often based on commercial-off-the-shelf (COTS) systems, and do not take advantage of integrated, MBSE approaches. Additionally, cost and risk models are often based on larger and monolithic missions, with a limited amount of autonomy, and need to be adapted to more complex missions, such as distributed, fractionated, or heterogeneous missions.

### ***Technical Capability Objectives and Challenges***

Some of the technology challenges associated with the development of analysis tools include the difficulty to integrate multiple missions aspects, projects, systems, lifecycles, and science and engineering domains, and to tie the mission design to cost and risk factors. Other challenges deal with the fidelity of the models utilized within these tools. For example, there is very little data available to develop models needed for risk reduction.



Another component of designing missions—specifically, science missions—is based on the use of observing system simulation experiments (OSSEs) to quantify the impact of observations from future space systems by mimicking the process of data assimilation. OSSEs are currently used increasingly in earth science; however, because the application is on a case-by-case basis, the general framework and components are re-designed for each new application. Hence, the main challenge is development of the common framework and component library needed to address their portability for generalized use. A straightforward metric for the systematic and more generalized use of OSSEs is the decrease in model uncertainty.

### ***Benefits of Technology***

The benefits of this technology are to generalize the use of OSSEs, not only in earth science, but also heliophysics and, potentially, planetary science. This technology will be used to increase the accuracy of science modeling, as well as to design future observing systems by predicting and optimizing their impacts on the science models.

**Table 11. TA 11.2.6 Technology Candidates – not in priority order**

TA	Technology Name	Description
11.2.6.1	Science Performance Evaluation Toolset for Distributed Missions	Performs trade space analysis as a function of the multiple variables that define distributed missions. A Distributed Spacecraft Mission (DSM) is defined here as a mission that involves multiple spacecraft to achieve one or more common goals.
11.2.6.2	Toolset for Cost Analysis of Complex Missions	Generalizes and extends current models; develops new models to accurately estimate the cost of complex missions, including but not limited to constellations of nanosats, CubeSats and minisats, taking into account learning curve parameters.
11.2.6.3	Toolset for Cost Risk Analysis of Complex Missions	Develops new analysis models to accurately estimate the risk of complex missions.
11.2.6.4	Observing System Simulation Experiments (OSSE) Framework and Component Library	Develops the OSSE workflow environment and capabilities by integrating OSSEs with the middleware and software libraries, and multi-disciplinary model integration.

## TA 11.3: Simulation

Most current simulation capabilities are based on heuristics and similitude and are often insufficient to meet NASA's increasingly aggressive mission demands. Because these existing simulations are not grounded in an understanding of the underlying physical processes, they often do not have applicability beyond the test conditions for which their various coefficients and parameters were tuned. Application of most of these simulations results in large but undetermined uncertainties, sub-optimal performance, and increased cost and risk.

TA 11.3 includes new technologies that are needed to mitigate these shortcomings and enable NASA's future missions. Technologies include those related to Distributed Simulation; Integrated System Lifecycle Simulation; Simulation-Based Systems Engineering; Simulation-Based Training and Decision Support Systems; Exascale Simulation; Uncertainty Quantification and Nondeterministic Simulation Methods; Multiscale, Multiphysics, and Multifidelity Simulation; and Verification and Validation.

### *Sub-Goals*

Overall goals in simulation for NASA's future missions are aimed at integrating disciplinary technologies at various levels, increasing vehicle and mission performance, fully exploiting exascale computing, developing foundational physics-based simulation capabilities, and managing uncertainty and risk.

**Table 12. Summary of Level 11.3 Sub-Goals, Objectives, Challenges, and Benefits**

Level 1		
11.0 Modeling, Simulation, Information Technology, and Processing	Goals:	Develop computing, modeling and simulation, and information technologies that are the basis of new solution paradigms across the breadth of NASA's missions. Enable the NASA mission through development of virtual technologies that increase our understanding and mastery of the physical world.
Level 2		
11.3 Simulation	Sub-Goals:	Develop best-physics simulations of operative mechanisms that enable both increases in system performance and management of uncertainty and risk across the entire lifecycle of NASA's distributed, heterogeneous, and long-lived mission systems.
Level 3		
11.3.1 Distributed Simulation	Objectives:	Provide large scale, shared, and secure immersive environments to support distributed team-based development and analysis of information. These environments must allow for rapid development and inclusion of new information and knowledge, provide an interface where intelligent agents can work alongside humans, and manage the authority elements necessary to meet national and international intellectual property and national security requirements.
	Challenges:	Increase bandwidth, develop an intelligent data exchange standard to maximize overall distributed system performance, and implement intelligent verification tools to ensure compliance with the standards.
	Benefits:	Enables different NASA centers, as well as commercial and international partners, to better cooperate and coordinate their models and simulations, and data related to them thus eliminating inefficiencies from duplicate efforts, and enable truly large-scale simulations. Evaluates and improves the quality and reliability of the models, simulations, and analysis, as described in the Columbia Accident Investigation Board (CAIB) Report.



Table 12. Summary of Level 11.3 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3	
11.3.2 Integrated System Lifecycle Simulation	Objectives: Develop interfaces, algorithms, and collaborative, networked platforms necessary to integrate individual technologies into large, complex, multi-decadal, systems of systems.
	Challenges: Information sharing across simulation capabilities, programs and projects including storage and management of huge multi-decadal data and development of federated modeling approaches.
	Benefits: Provides greater insight throughout the product development lifecycle through simulated understanding of system performance figures of merit thus reducing cost and improving reliability.
11.3.3 Simulation-Based Systems Engineering	Objectives: Develop technologies that support critical decision-making by mitigating the effects of variability and uncertainty for missions and mission environments where testing and measurement systems alone are insufficient or cost-prohibitive.
	Challenges: Accurately representing the physical behavior of the system throughout its lifecycle, thus assuring the model becomes the basis of a "Digital Twin" of the physical system.
	Benefits: Decreases lifecycle cost, reduces risk, and increases the probability of mission success. Provides both a ultra-high fidelity simulation that is continuously updated using sensor data and a rapid assessment capability to inform crew of emerging concerns.
11.3.4 Simulation-Based Training and Decision Support Systems	Objectives: Develop a software environment that enables astronauts to remain proficient in their training for long-duration exploration missions especially in the robotics and EVA domains.
	Challenges: Development of scalable software systems for onboard simulation-based trainers, including those that execute on laptop computers.
	Benefits: Increases the fidelity of design verification, reduces mission cost, and enhances mission success.
11.3.5 Exascale Simulation	Objectives: Develop new approaches for simulation software that fully exploit the high performance computing environment, tools for grid generation and adaptive mesh refinement, and methods to combine various sources of data for validation.
	Challenges: Lack of interfaces with appropriate level of refinement, the lack of a common infrastructure among different physics operators, the lack of multi-language support and assurance of future support, and the lack of extensibility for larger or future problems.
	Benefits: Provides a multi-resolution programming model that minimizes concerns of the underlying hardware and separates them from the development of algorithms supporting research. Facilitates the development of innovative numerical methods through improved error estimation techniques, comprehensive uncertainty propagation techniques, more sophisticated stochastic and Bayesian approaches, and overall risk reduction. Leverages extreme-scale development environments including computational frameworks and toolkits, thereby enabling simulation of increasingly complex problems at reduced execution times. Provides sharing of a common infrastructure and software design process supporting computationally intensive simulation.
11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods	Objectives: Identify, classify and model all forms of uncertainty present in a system, with the objective of understanding their impact on system performance, robustness, reliability and safety.
	Challenges: Computationally efficient approaches that are suitable for very low probability events, including accommodation of epistemic uncertainty (uncertainty due to a lack of knowledge).
	Benefits: Implements new efficient algorithms and software tools to facilitate deployment of near-term and future missions to both reduce costs and improve reliability and robustness. Provides accurate and efficient assessments of the true state of uncertainty thus enabling design policies that can overcome uncertainty while meeting mission performance and reliability goals without imposing undue conservatism.

Table 12. Summary of Level 11.3 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3	
11.3.7 Multiscale, Multiphysics, and Multifidelity Simulation	Objectives: Representation of the physics of fundamental processes that operate over different length and time scales and between disparate physical processes.
	Challenges: Development of concise mathematical bases for determining well-posed problems Determination of error propagation across length and time scales. Quantify the effect of uncertainty at all length and time scales.
	Benefits: Improves the understanding, design, and optimization of physical systems having a hierarchical interdependence of physical processes.
11.3.8 Verification and Validation	Objectives: Enable automation of verification and validation procedures.
	Challenges: Uneven use across all disciplines, leading to deficiencies in disciplinary and multidisciplinary modeling and simulation efforts.
	Benefits: Reduces the risks associated with unverified and unvalidated software to include project risk thus enabling quantification of confidence in the simulations and decrease time required to make critical decisions while reducing overall project costs.

### TA 11.3.1 Distributed Simulation

NASA has three types of distributed simulation. For one type, systems and applications run at a single location and the larger team views the simulation from distributed immersive clients. Provisions are made to allow the team members to view the simulations live or, in many cases, after the fact from stored and shared information. The second type of simulation uses locally-distributed processes with tightly coupled synchronous communication. The third type of distributed simulation type uses widely-distributed processes with loosely-coupled, asynchronous communications. NASA's work with this type of simulation has borrowed heavily from the distributed simulation community started by another government agency for tools and standards.

NASA has used all three types of distributed simulations for training and analysis. The first two types have been used for years for training simulations and engineering analysis. Examples include full task trainers, path analysis simulations for robotic operations involving multiple operators, and complex engineering analysis simulations that are distributed to utilize greater computing power.

NASA first used a loosely-coupled simulation to develop the distributed interactive simulation (DIS) for training of rendezvous and capture scenarios between the International Space Station (ISS) and a transfer vehicle from an international space agency. This training simulation has been highly successful and has led to development of other applications that enable real-time collaborative interaction between space system simulations located at different centers or even agencies to analyze mission architectures.

#### **Technical Capability Objectives and Challenges**

There is a need for large-scale, shared, and secure immersive environments to support distributed team-based development and analysis of information. These environments must allow for rapid development and inclusion of new information and knowledge, provide an interface where intelligent agents can work alongside humans, and manage the authority elements necessary to meet national and international intellectual property and national security requirements. In addition, these environments must allow for significantly varied communications capabilities, including those associated with teams comprised of members located on Earth and in space.

There is also an increasing need to include live aircraft into distributed National Airspace System (NAS) simulations to support air traffic management research and enable integration of unmanned aircraft systems (UAS) into the NAS. In one scenario, one or more live aircraft may fly uncertified experimental systems in a test range while participating in a distributed NAS simulation; the simulated information is sent to the live aircraft to

deceive its systems and/or crew into reacting as if they were flying in the NAS, rather than over the test range. In another scenario, a distributed simulation may assess new technologies using live traffic information rather than canned or simulated traffic. This shadow capability may also involve one or more cooperating live assets in the NAS.

### ***Benefits of Technology***

Having NASA-wide standards for distributed simulations and technologies that support those standards will provide a number of benefits; however, two benefits stand out. One benefit is that it will enable different centers, as well as commercial and international partners, to better cooperate and coordinate their models and simulations and related data. This will help eliminate inefficiencies from duplicate efforts and enable truly large-scale simulations. The second benefit is that it will help to evaluate and improve the quality and reliability of the models, simulations, and analysis, as described in the Columbia Accident Investigation Board (CAIB) Report.

**Table 13. TA 11.3.1 Technology Candidates – not in priority order**

TA	Technology Name	Description
11.3.1.1	Immersive Environments for Distributed Simulation of NASA Systems	Enables real-time collaborative interaction between space system simulations located at different centers or even agencies to analyze mission architectures.
11.3.1.2	High-Speed Computer Networks	Enable advances in network technology to support distributed simulation for moving, sharing, and allowing secure interaction with large data sets.
11.3.1.3	Standardized NASA Simulation Interoperability Infrastructure	Facilitates the development of large-scale distributed simulations and supports the large-scale integration of multi-disciplinary simulation elements for integrated systems analysis and design.
11.3.1.4	Standardized Space Simulation Data Exchange Standard	Provides a data exchange standard that supports air- and space-based simulation and defines the principal state representations, reference frames, units, etc. required for meaningful interoperability between distributed simulation elements.
11.3.1.5	Cross-Domain Simulation Toolset and Integration Framework	Creates a coordinated and managed collection of models, simulations, and applications for aircraft and spacecraft modeling. This will include models of the principal domain-specific elements that compose a complex aircraft or spacecraft system.

## **TA 11.3.2 Integrated System Lifecycle Simulation**

NASA tools and analysis capabilities address all phases of a system's lifecycle, including concept development that often combines heuristic information with more generic physics-based approaches, preliminary and detail design that relies heavily on computer-aided design/computer-aided engineering (CAD/CAE), fabrication that is instantiated by basing manufacturing requirements on details provided by drawing and model-based designs, and operations and multiple logistic activities that are planned using event-based simulation assessments. Tools also exist to support supply chain management, industrial base management, simulation-based test, operational support, and capability re-utilization.

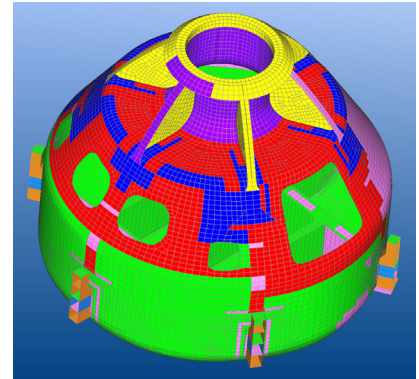
Increased formalization is needed to nurture emerging simulation and analysis capabilities and enable information sharing across simulation capabilities, programs, and projects. A federated model approach is needed to enable NASA simulations to be utilized efficiently by multiple parties, including contracted suppliers and international partners. Similarly, enterprise-based applications of product and lifecycle management systems are needed to organize and distribute system simulation; and model repositories are needed to allow exploitation of previously-developed models to aid in rapid development of future systems.



### Technical Capability Objectives and Challenges

The primary focus here is not for single technology simulation improvement, but for development of the interfaces, algorithms, and collaborative, networked platforms necessary to apply individual technologies to large, complex, multi-decadal, systems of systems. Implementation of MBSE, and model-based collaborative efforts in general, will enable more efficient and flexible system lifecycle simulations. Although progress is being made, analysis object formats and integration still require considerable development.

Provisions to allow for storage and management of huge multi-decadal data are nascent. A merging of Big Data capabilities with product data management systems and knowledge management will assist active product development and the intelligent planning of future projects. Distributed simulation technologies will enable team members to provide the data and functionality needed without exposing proprietary information to users outside of the developer's organization. Multi-fidelity models and the ability to share verified functional behaviors, both open and proprietary, will enable detailed systems integration activities to be performed early enough in the lifecycle to make a significant positive impact on system lifecycle cost.



**Simulation Based Systems Engineering**

### Benefits of Technology

A primary benefit to having a broad-based integrated system lifecycle simulation capability is greater insight throughout the product development lifecycle through simulated understanding of system performance figures of merit. Additionally, development of the next product with similar features can be accomplished in a much shorter development cycle by extension and reconfiguration of already-proven simulation components.

**Table 14. TA 11.3.2 Technology Candidates – not in priority order**

TA	Technology Name	Description
11.3.2.1	Model and Simulation Interface Specifications	Provide capability to stakeholders in lifecycle simulation to ensure accurate and efficient collaboration of analysis objects across a distributed simulation. SysML descriptors of federate behavior and implementing high-level architecture code will be created.
11.3.2.2	Federated Simulations	Quantify product behavior throughout the system lifecycle and to predict operational behavior. Federated simulations enable an enterprise to allow all geographically diverse and computationally non-heterogeneous participants to supply federate models to an enterprise simulation execution.
11.3.2.3	Enterprise-Level Modeling and Simulation Repositories	Develop enterprise-level technologies for the sharing of model federates and simulation federations across all NASA interested parties.

### TA 11.3.3 Simulation-Based Systems Engineering

Future generations of aerospace vehicles will require lighter mass while being subjected to higher loads and more extreme service conditions over longer time periods than the present generation of vehicles. The requirements placed on systems and subsystems ranging from propulsion and energy storage to structures and thermal protection will be greater than previously experienced, while demands on long-term reliability will increase. Thus, the extensive legacy of historical flight information that has been relied upon since the Apollo era will likely be insufficient to certify these new vehicles or to guarantee mission success. Additionally, the extensive physical testing that provided the confidence needed to fly previous missions has become increasingly expensive to perform.

Future simulation-based system engineering capabilities require both the development of new enabling technologies and the integration of these technologies. Simulation-based systems engineering employs computational modeling and simulation methods to aid in design, development, certification, and sustainment of complex aerospace vehicles and systems throughout their lifecycles. As systems become more complex and as total lifecycle costs increase, greater reliance on simulation-based systems engineering will be required to reduce costs and meet challenging performance and schedule requirements.

### ***Technical Capability Objectives and Challenges***

Simulation-based systems engineering technologies support critical decision-making where testing and measurement systems alone are insufficient or cost prohibitive; they are becoming increasingly important as budgetary constraints and performance requirements increase. They mitigate the effects of variability and uncertainty and are enabling the development of long-duration autonomous vehicles. Most importantly, they will enable design, development, certification, and sustainment for missions and mission environments where testing is impossible.

Achieving these objectives requires that the simulation accurately represent the physical behavior of the system throughout its lifecycle, thus assuring the model becomes the basis of a “Digital Twin” of the physical system. Among the technologies included herein are multi-domain modeling (MDM) that describes the behavior of the system, including mechanical, thermal, electrical, and chemical behavior; high-performance simulation (HPS) technologies that optimize and solve the large system of mathematical equations; a comprehensive and highly-integrated adaptive model updating (ADU) system to ensure that the simulation continues to accurately represent the flying vehicle or system throughout the mission; advanced diagnostics and prognostics (ADP) that are used to predict reliability, system performance, and probability of mission success or failure; and robust decision-making (RDM) that implements an outcome-based decision-making approach that integrates TA 11.3.3 to simulate the behavior of the system under a wide array of environmental and loading conditions. Finally, onboard predictive physics-based vehicle simulation is a simplified simulation that is suitable for real-time assessment.

### ***Benefits of Technology***

Traditional modeling and simulation approaches that are used to predict the behavior of a system based on current system state and inputs to that system, become increasingly inaccurate and unrepresentative as system complexity increases, environments and loadings become more extreme, and the system ages. Furthermore, risk increases when decisions are made under highly uncertain conditions often related to spaceflight. In contrast, the integrated approach discussed herein will enable management of the system throughout the mission life cycle. These technologies decrease overall lifecycle cost, reduce risk, and increase the probability of mission success.

**Table 15. TA 11.3.3 Technology Candidates – not in priority order**

TA	Technology Name	Description
11.3.3.1	Multi-Domain Modeling (MDM) Frameworks	Enables modeling of physical systems, including sensors and measurement points, across multiple domains for modeling of system behavior under nominal and off-nominal conditions.
11.3.3.2	High-Performance Simulations (HPS)	Provide highly efficient numerical methods and algorithms for efficient solutions to large systems of equations for simulation models.
11.3.3.3	Adaptive Model Updating (ADU) Toolset	Provides highly integrated vehicle state monitoring and predictive capabilities that accurately monitor the physical behavior of a vehicle or vehicle component, update the multi-domain physics-based model for correlation of the model with the behavior of the physical system, estimate service life, and determine inspection intervals.
11.3.3.4	Advanced Diagnostics and Prognostics (ADP) Toolset	Provides capability to accurately assess the probability that a fault or failure will impact mission success.



Table 15. TA 11.3.3 Technology Candidates – not in priority order - Continued

TA	Technology Name	Description
11.3.3.5	Robust Decision-Making (RDM) Framework	Provides the ability to evaluate the mission trade space and to make decisions that ensure the maximum probability of mission success using the models of uncertainties identified in Section 11.3.6.
11.3.3.6	Onboard Predictive Physics-Based Vehicle Simulation	Provides a reduced-order vehicle simulation capability for space exploration crews using response surface method or other computationally efficient methods for rapid assessment on low-power onboard computer systems.

## TA 11.3.4 Simulation-Based Training and Decision Support Systems

Human-in-the-loop testing and training facilities are used throughout the lifecycle of all NASA missions for validating mission concepts, performing trade studies, verifying design implementations, supporting the development of procedures and methods for off-nominal event problem solving, and training operators, ground crew, and flight crew. The fidelity of such simulations is driven by either the specific questions being asked or the training requirements.

### *Technical Capability Objectives and Challenges*

New approaches for the development of human-in-the-loop full mission testing and training simulations are needed to provide onboard simulation-based training, reduce time and costs, and ensure mission success and safety. Given the expected length of future missions, effective and efficient onboard training will be critical for maintaining and retraining task proficiency and learning new and unforeseen tasks during the mission. Such a capability must also provide accurate feedback to the crew. This onboard training objective requires that software systems are scalable with respect to supported platforms, which usually means that the trainers execute on laptop computers.

Maintainable software architectures and simulation frameworks are necessary to sustain long-duration exploration missions. Crew will need onboard just-in-time training systems that are low mass, low volume, low power, exhibit high-task fidelity, and have the ability to measure relevant performance parameters to adapt the training and inform the crew of their mission readiness. In the near future, immersive virtual reality, such as sight, sound, and touch, will likely be commonly available to enable refresher training or just-in-time training for long-duration missions.

### *Benefits of Technology*

Human-in-the-loop testing and training facilities are used across all NASA missions throughout the lifecycle for validating mission concepts, performing trade studies, verifying design implementations, supporting the development of procedures and off-nominal event problem solving, and training operators, ground, and flight crew. Improvements in simulation technology will increase the fidelity of design verification, reduce mission cost, and enhance mission success.

Table 16. TA 11.3.4 Technology Candidates – not in priority order

TA	Technology Name	Description
11.3.4.1	Onboard Simulation-Based Trainers	Enable interactive simulation training that has adaptable simulation fidelity, to match trainee proficiency, is scalable to mission timeline, and provides effectiveness feedback.
11.3.4.2	Integrated Mission Human-in-the-Loop Simulation System	Enables integrated simulations that can be used to evaluate designs and operations, including training.
11.3.4.3	Digital-Human-in-the-Loop Simulation System	Enables integrated human and system simulations to determine human-system performance of designs and operations.



## TA 11.3.5 Exascale Simulation

Currently, exascale simulation development largely relies on legacy applications that are not extensible, use dated language constructs and practices in software design, and are not amenable to coupling codes. The SOA in extreme-scale grid and mesh generation continues to be a primary bottleneck in automating exascale simulation. The dominant concerns center on both cost and time constraints due to human interaction and intervention. Additionally, the technology today provides few standards for representation of surface or solid geometries within computer-aided design (CAD) tools. Many existing CAD geometry definitions are ill suited for discipline analyses due to insufficient accuracy or excessive details. Adaptive mesh refinement (AMR) is maturing for some applications.

Today's SOA in numerical validation predominately involves a single, high-fidelity simulation with a separate post-processing phase for visualization and analysis that relies on databases with disparate standards. Effective visualization software algorithms and innovative information methods like virtual reality are lacking due to the widening gap between input and output and dramatically increasing computational capacity. Comparison of large amounts of experimental and simulation data is mostly carried out through experience and intuition using fairly unsophisticated tools.

### *Technical Capability Objectives and Challenges*

Physics-based exascale modeling and simulation environments consist of several interdependent areas, including a development environment and coupling capabilities, grid and mesh generation, and a physics-based numerical validation capability. Common issues include the lack of interfaces with appropriate level of refinement, lack of a common infrastructure among different physics operators, lack of multi-language support and assurance of future support, and lack of extensibility for larger or future problems.

Many of the technologies discussed throughout TA 11 and the other technology roadmaps explicitly or implicitly enumerate the need for exascale computing. Although exascale computing promises the ability to execute simulations at unprecedented rates, traditional algorithms are not suited to take full advantage of the capabilities for exascale, as discussed in TA 11.1.2. Three extreme-scale technologies are needed, including new approaches for modeling software that fully exploits the HPC environment, tools for grid generation and adaptive mesh refinement, and methods to combine various sources of data for validation.

### *Benefits of Technology*

A modeling and simulation environment providing exascale performance is essential for development of solutions to NASA's most challenging problems. Simply stated, without these HPC-related capabilities, most of the other simulation-related goals in TA 11 and other roadmaps will not be achievable. The standardized use of frameworks, toolkits, and parallel libraries provide a multi-resolution programming model that minimizes concerns of the underlying hardware and separates them from the development of algorithms supporting research. This exascale environment will facilitate the development of innovative numerical methods through improved error estimation techniques, comprehensive uncertainty propagation techniques, more sophisticated stochastic and Bayesian approaches, and overall reduction of risk.

**Table 17. TA 11.3.5 Technology Candidates – not in priority order**

TA	Technology Name	Description
11.3.5.1	Extreme-Scale Software for Modeling and Simulation	Extends research to increasingly complex simulations, such as scientific prediction, engineering design, and policy making, through an integrated development environment such as the co-design process, domain specific languages, parallel toolkits, frameworks, and libraries, for effective use of exascale systems.
11.3.5.2	Extreme-Scale Geometry and Grid Generation Environments	Enables researchers to rapidly create complex, scalable geometry models for exascale systems, and the ability to use automated adaptive mesh refinement (AMR) in production-level, extreme-scale codes.

Table 17. TA 11.3.5 Technology Candidates – not in priority order - Continued

TA	Technology Name	Description
11.3.5.3	Extreme-Scale Numerical Validation Environment	Enables the fusion of observational and experimental data with advanced simulation. The ability to dynamically, in-situ, query and integrate high-fidelity simulation data with lower-fidelity data reduces overall risk in aerospace system design.

### TA 11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods

The treatment of uncertainty in model-based representations of aerospace systems has historically focused on using random sampling together with simulation to assess a given design for a set of assumed uncertainties. The approach, commonly referred to as Monte Carlo analysis, has been successfully applied to many systems and has the heritage necessary to serve as the baseline tool for the bulk of uncertainty quantification used within NASA.

Monte Carlo has some core fundamental limitations. One limitation is that the computational burden becomes prohibitive for very low probability events. This computational burden makes it unsuitable for design, as most design procedures are based on some type of search mechanism that requires repeated function evaluations, each requiring a separate Monte Carlo analysis. A more significant limitation of Monte Carlo is that it requires probability density functions (PDF) to be defined for all uncertainties. Adequate prescription of a PDF-based uncertainty model requires a large amount of data. In many cases, sufficient data are not available and engineering judgment must be employed, admitting gross subjectivity into the uncertainty quantification.

A separate, but largely unaddressed, issue is the lack of systematic methods and tools for accommodating epistemic uncertainty—uncertainty due to lack of knowledge. The current approach for dealing with epistemic uncertainty is to either perform nested Monte Carlo simulations similar to the design problem at various realizations of the epistemic uncertainty, or to simply treat the epistemic uncertainty as a random uncertain parameter. Neither represents a viable way to handle epistemic uncertainty. The former suffers from excessive computational expense while the latter yields an uncertainty quantification that does not properly represent the true nature of the variability.

#### **Technical Capability Objectives and Challenges**

Uncertainty quantification (UQ) is the process of identifying, classifying, modeling, and propagating all forms of uncertainty present in a system, with the objectives of understanding their impact on system performance, robustness, reliability, and safety. NASA missions often involve the development of new vehicles and systems that must be designed to operate in harsh domains with a wide array of operating conditions. These missions involve high-consequence and safety-critical systems for which quantitative data are either very sparse or prohibitively expensive to collect. Limited heritage data may exist, but is also usually sparse and may not be directly applicable to the system of interest, making UQ extremely challenging.

Effective UQ begins at the conceptual design phase and continues into the analysis and design cycles as the refinement of the models and the fidelity of the tools increase. UQ strategies must provide objective information needed to support evaluation of the effects of uncertainty and will provide engineers, crew, and other decision makers with the critical information needed to support resource utilization decisions, risk mitigation strategies, and other information needed to increase the probability of mission success.



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Technologies in this area will be instrumental in the pursuit of engineering solutions that, for a given state of knowledge, rigorously and consistently quantify the effects of uncertainty.

### ***Benefits of Technology***

NASA has long understood the importance of assessing the impact of fundamental uncertainties on mission risk and system reliability. Historically, NASA has used safety and knockdown factors based on complex sets of historical engineering data dating as far back as the Apollo era to safeguard against uncertainty. Typically, these procedures are applied at the discipline level and then rolled up to the system level to provide an overall measure of immunity to the unknowns inherent in the system. More recently, NASA has begun to move to a more probabilistic-based approach; however, both safety factor-based approaches and the more current probabilistic-based approaches have fundamental limitations that in some applications may result in false assessments of mission margins and risks.

At the core of the new technologies needed for UQ will be new mathematical descriptions of uncertainty that are consistent with the true state of knowledge of the system. The software tools will implement new efficient algorithms and software tools to facilitate deployment of near-term and future missions to reduce costs and improve reliability and robustness. Design methods will also be developed to provide systematic treatment of uncertainties from the conceptual design phase through the final design phase. The benefits of these technologies will be dramatically improved capabilities to accurately and efficiently assess the true state of uncertainty, enabling design policies that can overcome uncertainty while meeting mission performance and reliability goals without imposing undue conservatism.

**Table 18. TA 11.3.6 Technology Candidates – not in priority order**

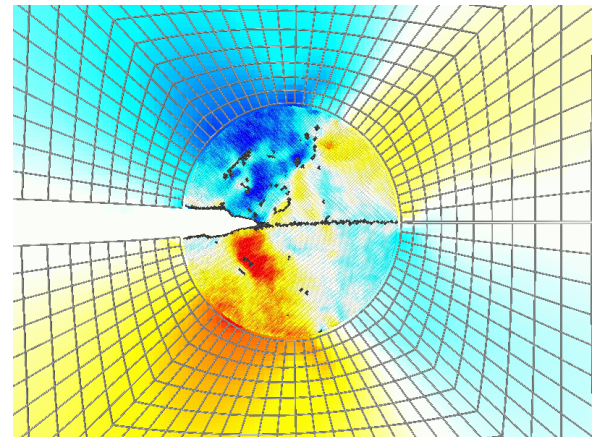
TA	Technology Name	Description
11.3.6.1	Robust System Uncertainty Modeling Toolset	Facilitates the proper quantification of uncertainties in system models, differentiating between inherent variability and lack of knowledge uncertainties.
11.3.6.2	Probabilistic Risk Assessment (PRA) Toolset	Delivers efficient and accurate assessments of system risk in the presence of probabilistic uncertainties.
11.3.6.3	Aleatory and Epistemic Uncertainty Assessment Toolset	Provides uncertainty quantification tools consistent with the current state of knowledge of the system.
11.3.6.4	Toolset for Global Sensitivity Analysis of Uncertain Systems	Facilitates the identification of dominant effects contributing to the performance or robustness degradation for systems subject to probabilistic and non-probabilistic uncertainties.
11.3.6.5	Software Toolset for Robust Design in the Presence of Uncertainty	Provides methods and tools to robustly design multidisciplinary complex systems where all forms of uncertainties are present.
11.3.6.6	Surrogate Models for Uncertainty Quantification	Facilitates the utilization of simplified and computationally-efficient models to replace high-fidelity and computationally-intensive computer models.

### **TA 11.3.7 Multiscale, Multiphysics, and Multifidelity Simulation**

The SOA for multiscale and multiphysics analyses consists of methods that can bridge dimensional scales and/or couple different physical processes to simulate a broad spectrum of important scientific problems. Multiscale methods have been developed to represent the physics of fundamental processes that operate over different length and time scales and are typically linked through homogenization of governing physical parameters. Multiphysics methods have been formulated to improve the fidelity of solutions to difficult problems that involve coupling between different physical representations. These problems are typically nonlinear and time-dependent, and can involve multiple dimensional scales that require multiscale methods to be included in the overall algorithmic procedure. These computational methods yield solutions possessing greater fidelity than simulations performed within a single dimensional scale or those that neglect coupling between dominant physical processes.



Limitations of these analytical methodologies exist in both the range of length and time scales that can be bridged, the coupling range, and in the fidelity of solutions obtainable for systems incorporating coupled physical processes, the coupling fidelity. The spectrum of important technology areas is broad and includes topics as varied as the design and optimization of new materials and novel structures, coupling electricity and magnetism with hydrodynamics to study plasmas and magnetohydrodynamic (MHD) propulsion, and the investigation of chemical reaction with transport in combustion and subsurface flows. Overcoming current limitations in performing more accurate simulations will enable NASA to better understand various governing physical processes and thereby enhance the technologies needed to successfully meet the challenges of future NASA earth-bound and extraterrestrial missions.



**Multiscale Methods**

### ***Technical Capability Objectives and Challenges***

Concurrent multiscale methods enable higher fidelity simulations at all length scales, as well as seamless coupling between different physical representations. In theory, they can couple physical representations as diverse as continuum mechanics and ab initio quantum mechanics. Challenges include the development of concise mathematical bases for determining well-posed problems; determination of error propagation across length scales to quantify required fidelity; and quantification of the effect of uncertainty at all length scales, including the effect of numerical noise or fluctuations in the solutions.

Like concurrent methods, sequential multiscale methods enable higher fidelity simulations at all length scales and coupling between different physical representations. However, sequential multiscale methods enable rigorous homogenization of lower length-scale response for later use in higher length-scale simulations. The challenges for sequential multiscale methods are the same as those for concurrent methods.

The potential impacts of multiphysics technologies are varied and span the breadth of the NASA mission portfolio. Objectives for extreme environment simulations include revolutionizing the multiphysics analysis capabilities for structural materials, multifunctional materials, and fluids subjected to various extreme flux conditions and environments. For example, high-fidelity models are needed to predict damage produced by heavy ions traveling at relativistic velocities; chemical stability of high-temperature materials in combustion applications; and degradation of power systems over extended time scales. Prediction of the response of these systems in extreme environments over long time scales requires coupled analyses of the interactions at subatomic, atomic, molecular, and microstructural length scales.

### ***Benefits of Technology***

The benefits of multiscale and multiphysics analysis methods underpin many aspects of future NASA missions through more robust and informative predictions of system response. Increasing the span of dimensional scales and fidelity of predictions will improve the understanding, design, and optimization of physical systems that possess a hierarchical interdependence of physical processes. The simulations will guide the development of lighter and more durable structural materials; higher performing materials for fuel cells, nuclear reactors, batteries, and solar cells; and new multifunctional materials that combine these functions. The simulations also have application to understanding reactive flows found within engines and surrounding airframes at hypersonic speeds.

Table 19. TA 11.3.7 Technology Candidates – not in priority order

TA	Technology Name	Description
11.3.7.1	Sequential Multiscale Analysis Toolset	Enables the capability to understand, design, and optimize material and structural systems with hierarchical interdependence of underlying physical processes.
11.3.7.2	Concurrent Multiscale Analysis Toolset	Enables the capability to understand, design, and optimize material and structural systems with hierarchical interdependence of underlying physical processes.
11.3.7.3	Energetic Extreme Flux Analysis Toolset	Provides simulations of physical processes involving extreme energetic flux, including photons and high-energy particles that can cause damage to materials, electronics, and other devices over long time scales.
11.3.7.4	Chemically Extreme Environment Analysis Toolset	Provides simulations of physical processes involving extreme chemical environments; for example, chemically reactive environments that can cause damage to materials and devices over long time scales.
11.3.7.5	Thermomechanically Extreme Environment Analysis Toolset	Provides simulations of physical processes involving extreme thermomechanical environments; for example, extreme pressure and stress, strain and strain rate, and high and low temperature that can cause damage to materials and devices over long time scales.
11.3.7.6	Electro-Magnetic Extreme Analysis Toolset	Provides simulations of physical processes involving extreme magnetic environments that can cause damage to materials and devices over long time scales.

## TA 11.3.8 Verification and Validation

Rigorous methods for verification and validation (V&V) are needed to ensure the accuracy and reproducibility of emerging capabilities for modeling and simulation. However, verification of computer software models has historically been an extremely labor intensive, heuristic, and costly effort. In some cases, the tools being used to verify the simulation software are entirely inadequate. Another major concern is that verification and validation tools are not being used uniformly across all disciplines, leading to deficiencies in advanced multi-discipline modeling and simulation efforts such as simulation of unsteady or dynamic events.

Future missions will require significant scaling up of current methods for verification and validation, including those needed for verification of automated operations software, verification for adaptive avionics, validation of physics-based simulations, and validation of flight system software.

### *Technical Capability Objectives and Challenges*

The technologies discussed here assure that simulation models match specifications and assumptions employed in their development. The extremely time consuming and costly engineering effort that is spent on V&V of new simulations and other software motivates development of these technologies. Current usage of V&V limited primarily to steady-state analyses is inconsistent across disciplines. Development and implementation into unsteady and dynamic simulations is also severely lacking. Given the growing dependence across all technical disciplines and projects on more sophisticated modeling and simulation environments, the need for V&V becomes even more crucial and immediate.

### *Benefits of Technology*

As the reliance on computer-based modeling and simulation grows due to reduced access to experimental data, the risks associated with unverified and unvalidated software will pose a tremendous risk to all physics-based simulations and projects. Conversely, development and implementation of robust V&V methods will reduce overall project risk, enable quantification of confidence in the simulations, and decrease time required to make critical decisions while reducing overall project costs.

Table 20. TA 11.3.8 Technology Candidates – not in priority order

TA	Technology Name	Description
11.3.8.1	Model Verification Frameworks	Provide capabilities for quantifying the level of agreement between the predicted numerical solutions for a suboptimal discretization/fidelity setting and the solution corresponding to an optimal one.
11.3.8.2	Model Validation Frameworks	Provide rigorous tools to validate physics-based simulation models across a broad range of operating conditions.



## TA 11.4: Information Processing

Information Processing is an increasingly important area across the entire mission and science data lifecycle and requires new technologies to address NASA's emerging Big Data challenges. The data lifecycle, which spans flight computing, ground-based systems, data analysis, and data archives, motivates development of a new computational infrastructure for capturing, processing, managing, distributing, and analyzing data. Current capabilities for information processing and technology are limited at numerous points across the data lifecycle and will be overwhelmed by the increasing size, speed, and heterogeneity of data expected from future missions and ground processing.

Onboard flight systems currently provide limited capabilities to capture, triage, and reduce data. Bandwidth limitations restrict the amount of data that can be transmitted to Earth, limiting the amount of data that can be collected and returned. Current ground-based systems can process about 2 terabyte (TB)/day and must scale in order to support an increasingly vast network of observational instruments. Currently, cyber infrastructures process, manage, and archive about 15 to 20 petabytes of data across all science missions, much of which is collected and archived in distributed repositories. Traditional approaches to scientific research and data analysis are performed independently, with limited computational support or use of intelligent data understanding algorithms, to support data-driven approaches in scientific discovery. Additionally, cyber security approaches across this entire data lifecycle are ad hoc.

### *Sub-Goals*

The increase in the volume, variety, and velocity of data across the mission, engineering, and science data lifecycle, from data acquired by remote sensing instruments to scientific analysis on the ground, are primary goals of this TA. These goals will require new technologies and new paradigms that will impact the way that NASA designs and executes its missions. Additionally, information processing has far-reaching implications in specific aspects of climate modeling, simulation, data analysis, onboard computing, ground-based operations, and other NASA-unique functions.

Within the science, engineering, and mission data lifecycle, new approaches must be undertaken that will move computational capabilities as close as possible to the location where the data is collected. As more capable instruments are developed and deployed, new computational capabilities to address the data deluge must be put in place across the data lifecycle. Intelligent algorithms that are able to quickly triage this data onboard and on the ground will be required in order to process the increase in data. Semantic technologies that improve the understanding of the data are also critical across the data lifecycle.

Ontological models that can be used to support definition, inference, and data interoperability, particularly across systems and environments, will be necessary. New methods for collaboration by diverse and distributed teams in science and engineering will be important and will enable analysis of highly distributed data. Crosscutting cyber infrastructures that can scale to support increasing requirements in computation, storage, data management, and archive across the data lifecycle will be necessary, particularly as data volumes and computational demands move towards exascale computing. New human-machine interactions will enable rapid visualization and understanding of massive, exabyte data to support scientific inference and engineering decisions. Finally, new technologies will ensure that NASA's data are secure from worldwide cyber-enabled threats throughout the entire data lifecycle.

**Table 21. Summary of Level 11.4 Sub-Goals, Objectives, Challenges, and Benefits**

Level 1		
11.0 Modeling, Simulation, Information Technology, and Processing	Goals:	Develop computing, modeling and simulation, and information technologies that are the basis of new solution paradigms across the breadth of NASA's missions. Enable the NASA mission through development of virtual technologies that increase our understanding and mastery of the physical world.
Level 2		
11.4 Information Processing	Sub-Goals:	Develop software frameworks and toolsets that efficiently and reliably manage greatly increased volume, variety, and velocity of data across the science, engineering and mission data lifecycle while maintaining security of data. Enable advanced missions, effective remote and human-system collaboration, and greater system and crew autonomy through advanced software.
Level 3		
11.4.1 Science, Engineering, and Mission Data Lifecycle	Objectives:	Develop a comprehensive, scalable data architecture that effectively manages the entire data lifecycle, from planning to collection to use and storage.
	Challenges:	Advancing NASA's software technologies to keep pace with mission demands for rapidly increasing scale and complexity of data generation, triage, compression, transport, processing, prioritization, archiving, mining/visualization, and security.
	Benefits:	Maximizes value by making effective tradeoffs in data capture, generation, processing, management, and transport across the data lifecycle from planning to onboard collection and computing to ground-based analysis and storage.
11.4.2 Intelligent Data Understanding	Objectives:	Increase the information content of data downlinked from a space-based observation instrument. Enable intelligent spacecraft reaction to observed data in a dynamic environment. Provide multi-spacecraft collaborative event detection, analysis, and response.
	Challenges:	Effective computational mechanisms for identification of data having high information content. Prioritization of the transmission of data according to its information content.
	Benefits:	Provides cost savings by performing trades between intelligent software and expensive hardware. Increases mission science return by integrating complementary information. Enables distant exploration missions either by assisting crews with semi-autonomous systems or by supporting fully autonomous missions.
11.4.3 Semantic Technologies	Objectives:	Automated ontology from observation data and model output. Semantic bridging: complex interpolation and extrapolation across multiple data sources to produce the information needed, even during anomalies.
	Challenges:	Properly and accurately linking data from a wide range of sources without altering its original structure and purpose. Development of text and numerical tools for automated characterization of data, ideally at its origin, in terms of its generation, authenticity, validation, error ranges, and boundary conditions.
	Benefits:	Delivers increased efficiency, accuracy, and consistency for processing data of all types. Supports machine reasoning on dynamic data, enabling autonomous missions in complex environments. Enables reuse of mission and science data beyond the original purpose, increasing data value.

Table 21. Summary of Level 11.4 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3	
11.4.4 Collaborative Science and Engineering	Objectives: New tools and collaboration environments to support design and analysis for distributed teams and data.
	Challenges: An immersive experience that integrates NASA science and engineering data, addressing cyber security, visual resolution, and interaction richness. Appropriate ways to visualize very different knowledge representations at different levels of abstraction.
	Benefits: Enables distributed, real-time science and engineering, engages a diversity of contributors across multiple organizations, and supports integrated data analysis and multidisciplinary solutions. Supports collaboration and teaming by both scientists and engineers through new visualization capabilities.
11.4.5 Advanced Mission Systems	Objectives: Automated tools for mission planning, risk analysis, and value assessment. Rapidly re-plan missions in response to changing conditions, emergent problems, or new opportunities. Conduct distributed mission management leveraging full interactivity with all appropriate data.
	Challenges: Increase the clarity and completeness decision options presented to mission planners, mission control, crews, and autonomous systems. Reduce mission simulation time, increase the number of alternatives that can be evaluated, automatically generate alternatives in multiple dimensions, and consider goal definition and valuation during the simulations.
	Benefits: Provides rapid determination of optimal initial mission profile and refinement of that profile as conditions change during the mission. Provides mission planning and execution systems that coordinate with other such systems, without requiring human, ground-based, oversight.
11.4.6 Cyber Infrastructure	Objectives: Provide scalable data storage, analysis, management, distribution, assurance, archiving, and preservation.
	Challenges: Meet the rapidly growing requirements from NASA missions for high-capacity computing, data management and storage, and networking services. Extensibility and flexibility for adoption across many NASA missions, without significant redevelopment.
	Benefits: Ensures computing storage, processing, data management, and archiving can substantially scale to meet mission requirements, and provide greater flexibility for workflow innovation such as automation and reuse across the data lifecycle.
11.4.7 Human-System Integration	Objectives: Provide comprehensive, human-centered, mobile mission operations in extreme environments. Develop intuitive interfaces for access to and representation of mission and science data.
	Challenges: Comprehensive mission operations that take a human-centered approach, and effectively distribute the workload between crew and automation. Interfaces that reflect human operator capabilities and limitations.
	Benefits: Increases crew autonomy necessary for crewed deep space missions where ground support is limited. Enhances deep space mission safety by more quickly and clearly providing critical information to crew.



Table 21. Summary of Level 11.4 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3	
11.4.8 Cyber Security	Objectives: Ensure that NASA information systems and data are secure throughout the entire mission and science data lifecycle, allowing efficient access by authorized users while eliminating unauthorized access.
	Challenges: Flexibility for rapid security updates and application across mission and infrastructure information systems. Mine distributed security-relevant Big Data in real-time to quickly detect and triage anomalous behavior. Achieve high assurance user identification and authentication for automated workflows that may span NASA and public systems.
	Benefits: Enhances security of NASA information and data systems are more secure throughout their lifecycle. Provides rapid identification of vulnerabilities or cyber-attacks that require human or automated mitigation action, including detection of new threats without having a pre-defined signature; the ability to track mobile and fixed information systems for recovery of lost or stolen assets; and the ability to transparently run workflows across internal and external systems such as public clouds, for on-demand and secure augmentation of information resources.

### TA 11.4.1 Science, Engineering, and Mission Data Lifecycle

The data-intensive nature of NASA science and exploration missions increases, there is a need to consider the data lifecycle from the point of collection all the way to the application and use of the data. Considerations across the entire lifecycle need to be made in order to support scalability and use of the data. Furthermore, missions may require that data reduction and intelligent triage be done on the data itself across the lifecycle to identify which data should be captured and archived. Additionally, common information models should be developed and defined in order to ensure that consistent definitions of the data are applied so that the data can be accurately managed, discovered, and used.

Throughout the entire lifecycle, data are not “at rest,” but rather, are discoverable, accessible, and usable to update plans, support local operations, and enable science. As a result, a well-architected data system that spans onboard data capture through ground-based operations and data analysis must be in place to enable scalability at multiple points across the data lifecycle.

#### **Technical Capability Objectives and Challenges**

As NASA’s science, aerospace, and exploration missions become increasingly data intensive, a critical goal to support these missions is to develop a comprehensive, scalable data architecture that effectively manages the entire data lifecycle, from planning to collection, use, and storage. For example, intelligent data reduction and triage across the data lifecycle supports efficient use of limited transmission bandwidth, computational resources, and data storage. In addition, common information models will support manual and automated data discovery, management, and use. Critical development challenges of the data lifecycle involve advancing NASA’s software technologies to keep pace with mission demands for rapidly-increasing scale and complexity of data generation, triage, compression, transport, processing, prioritization, archiving, mining and visualization, and security.

#### **Benefits of Technology**

The primary benefit of a comprehensive, scalable Big Data architecture is that it allows NASA to extract maximum value from its missions by making effective tradeoffs in data capture, generation, processing, management, and transport across the data lifecycle—from planning to onboard collection and computing, ground-based analysis, and storage. This architectural model enables the Agency to make strategic decisions

and technology developments regarding the capability to capture and generate more data with better instruments and computing and the capacity to effectively manage and utilize that data with an end-to-end, scalable data architecture.

**Table 22. TA 11.4.1 Technology Candidates – not in priority order**

TA	Technology Name	Description
11.4.1.1	Reference Information System Architecture Frameworks	Provide reference information system architectures for the end-to-end science, engineering, and mission data lifecycle.
11.4.1.2	Distributed Information Architecture Frameworks	Provide reference information architectures to define data across the end-to-end engineering, science, and mission data lifecycle.
11.4.1.3	Information Modeling Frameworks	Provide tools for the development of complex information models to explicitly describe the information architecture across missions, science, and operations.
11.4.1.4	Onboard Data Capture and Triage Methodologies	Apply novel machine learning capabilities onboard to support data reduction, model-based compression, and triage of massive data sets.
11.4.1.5	Real-time Data Triage and Data Reduction Methodologies	Apply novel machine learning capabilities in ground data processing systems to support data reduction and triage of massive data sets.
11.4.1.6	Scalable Data Processing Frameworks	Provide scalable software processing frameworks for processing scientific, engineering, and mission data sets.
11.4.1.7	Massive Engineering and Science Data Analysis Methodologies	Provide scalable infrastructures for analysis of massive data.
11.4.1.8	Remote Data Access Framework	Provides access to and sharing of distributed data sources in a secure environment.
11.4.1.9	Massive Data Movement Services	Develop new technologies for the movement of massive, multi-petabyte data over the network.
11.4.1.10	Large-Scale Data Dissemination Environments	Enable scaling data infrastructures, including software, computation, and networks, that are required to support large-scale data dissemination.
11.4.1.11	Toolset for Massive Model Data	Makes data and information transparent, scalable, and usable when infusing multiple large and diverse datasets into complex models.

## TA 11.4.2 Intelligent Data Understanding

Modern spacecraft can acquire much more data than can be downloaded to Earth. Onboard data analysis offers a means of mitigating the issue by summarizing data and enabling the ability to download a subset containing the most valuable portion of the collected data. Onboard intelligent data understanding (IDU) includes the ability to analyze data, detect interesting events, and take onboard intelligent action based on the onboard content and the results of offline intelligent data understanding. Implementation on NASA spacecraft has already resulted in some notable successes in science event detection and response. These include planning and executing follow-up observations of volcanic eruptions, floods, forest fires, sea-ice break-up, and other surface events, and more recently, tracking dust devils and identifying rocks with specific properties on the surface of Mars from rovers. However, the application of IDU algorithms to the development of systematic approaches for analyzing massive data is still fairly limited. Efforts have been made to develop approaches for data fusion and automating capabilities for pattern recognition, detection, and classification in observational data. However, many of these are currently performed on an ad hoc basis.

Offline IDU can take advantage of ground-based HPC, complement onboard IDU, and utilize models and massive amounts of data from measurements and simulations to produce information and knowledge for use by humans and vehicle systems. This knowledge can be in the form of descriptions of anomalies, clusters of normal data, models of data generation, and others. As data scales, the integration of IDU capabilities with scalable computing infrastructures will be critical to ensure that data analysis can keep pace.

### **Technical Capability Objectives and Challenges**

IDU includes a variety of capabilities, such as situational awareness, data mining for target identification, and triggering rapid response. IDU at the sensor enables automatic data reduction to improve information return on a limited downlink channel. This permits collecting data at the capacity of an instrument rather than preselecting the time and location for observations. IDU permits extended monitoring of an environment for rare events without overburdening downloads. The capability enables the capture and immediate follow up of short-lived events, which is not possible with traditional spacecraft paradigms. Also, the ability to analyze data and immediately use this information onboard can enable reaction in a dynamic environment, a capability that may improve not only information collection but also spacecraft safety, including reaction to unanticipated hazards. This capability enables operations in uncertain and rapidly-changing environments where an adequately rapid feedback loop with ground operators is not possible.

One of the main IDU challenges is to develop effective computational mechanisms for identification of data having high information content. This may involve recognizing features or events that have been pre-specified as being interesting or indicative of novel events. Depending on their application, detectors typically vary from being general purpose to being feature- or instrument-specific, with each having its own advantages and disadvantages. A third category of event detection focuses exclusively on novel or anomalous events, including automated analysis of Raman or fluorescence spectra, visual or near infrared spectroscopy, and detection and mapping of image features and textures.

Upon detection or summary of data, other development challenges focus on the decisions that must be made onboard regarding prioritization of the transmission of data according to its information content. There are a number of approaches for prioritizing data, from pre-specified priorities to the use of machine learning methods based on principles of experimental design and active learning.

Other long-term challenges include development of models needed to support both the prioritization of data and the identification of unexpected trends and individual events, automation of data prioritization based on conflicting science objectives, and development of sophisticated scientific interest metrics. Long-term objectives include integration of onboard data understanding as part of the baseline mission capability for spacecraft, that is, designed and planned throughout the mission lifecycle. Eventually, multi-spacecraft collaborative event detection, analysis, and response, will be enabled by distributed onboard IDU.

### **Benefits of Technology**

When fully integrated in future missions, IDU capabilities will enable realization of cost savings by performing trades between intelligent software and expensive hardware. They will increase the science return of individual missions by integrating complementary information and will enable distant exploration missions by assisting crews with semi-autonomous systems or by designing fully autonomous missions when time latency will not permit remote decisions to guide real-time actions.

**Table 23. TA 11.4.2 Technology Candidates – not in priority order**

TA	Technology Name	Description
11.4.2.1	Intelligent Data Collection and Prioritization Toolset	Provides a means to reduce the size of the data, such as removing clouds and corrupted data, prioritizing data based on content, or collecting complementary data for value-added information.
11.4.2.2	Event Detection and Intelligent Action Toolset	Provides computational mechanisms to identify high-information content data, either pre-specified, novel, or anomalous, including multi-spacecraft collaborative event detection, and to make an autonomous or assisted onboard decision as a result of data analysis.
11.4.2.3	Data on Demand Toolset	Enables users and models to task sensors and leverage sensor webs to develop "on-demand" products.



Table 23. TA 11.4.2 Technology Candidates – not in priority order - Continued

TA	Technology Name	Description
11.4.2.4	Intelligent Data Search and Mining Toolset	Develops search services and engines for massive, distributed data holdings; enables the application of different searching rules/schemes that learn from past searches; and develop “agents” to find and create the most relevant products. It includes rich queries, including fact-based, free-text searches, web-service based indexing as well as anomaly/novelty detection, where the system suggests items of interest to the user without the user necessarily prescribing the information being sought.
11.4.2.5	Data Fusion Toolset	Combines data from multiple sources, including remote sensing, in-situ, and models in order to make inferences that might otherwise not be possible with single data sources, or in order to improve the uncertainty characteristics of these inferences, over what might be achieved with single data sources.
11.4.2.6	Information Representation Standards for Persistent Data	Provide an extensible, evolvable human and machine readable information representation that is key to rapid and persistent understanding of science and engineering phenomena.

### TA 11.4.3 Semantic Technologies

There is a wide range of maturity levels in current semantic technologies. Many are essentially hand-manipulated processes as surrogates for more powerful technologies, some have evolved to a prototype or proof of concept that shows a much broader applicability, while others are emerging into mature capabilities that can be adopted by current operating systems supporting flight missions. This latter category usually supports ground processing of science and engineering data from flight missions and other data sources. Much of the data are from legacy sources and are needed for long time-series analyses. Numeric values may be from simulations or from experimental, observational, or measurement data.

These technologies support development of highly automated, flexible capabilities for discovery, retrieval, and understanding of output from sensors and other sources, including text and numerical data. This accelerated understanding will be essential both to anticipating mission conditions and to handling unforeseen opportunities and problems. Current technology challenges include the need to process large volumes of data and provide rapid delivery of output from instruments, sensors, and models. NASA should leverage previous work from other government agencies and industry. Additionally, some very demanding needs will be met by technologies expected to be available from the intelligence community over the next few years.

#### *Technical Capability Objectives and Challenges*

Semantic technologies are an enabler for many of the other information technology capabilities that have been identified throughout TA 11. Although information management systems are a built-in response to specific requirements for individual missions, NASA’s ability to reuse the related data for purposes other than originally intended is completely dependent upon high quality, structured metadata being generated simultaneous to the measurement data or model output. Manual development of these metadata is slow, inaccurate, and extremely labor intensive. Automating the process of characterizing measurements, observations, and model output to produce metadata will improve the usability of datasets throughout NASA’s mission portfolio.

Two essential capabilities are needed from semantic technologies, including the ability to properly and accurately link data from a wide range of sources without altering its original structure and purpose, and the development of text and numerical tools needed to permit the characterization of the data in terms of its generation, authenticity, validation, error ranges, and boundary conditions. Some of these requirements are unique to NASA; others are likely to be met by applying the work of external collaborators or partnering with external collaborators.

### ***Benefits of Technology***

The benefits of semantic technologies include significantly increased efficiency, accuracy, and consistency for processing data of all types. It provides substantial benefits in mission planning, decision-making, design development, verifications, and operations and addresses three of NASA's pervasive computing-related issues. First, the rapidly-growing volumes of diverse data from remote sensing and model output cannot be triaged, evaluated, analyzed, or used without the use of improved automation and machine reasoning. Second, the complexity and speed of response in autonomous and automated operations, particularly those remote from Earth, is far too demanding for pre-determined programming or man-in-loop decision making at the detail level and requires the computing systems to perform machine reasoning. Third, reconfiguration of missions to respond to unexpected conditions or opportunities requires machines that can respond with only high level, or no, human direction.

Exploitation of emerging machine reasoning and decision-making requires computation that uses precisely-defined, but complex, inputs and situational definitions derived using semantic technologies. For example, complex space systems accrue a significant number of maintenance data and problem reports that are currently stored in unstructured text forms or even in handwritten form. The lack of common structure, semantics, and indexing often prevents discovery of systemic problems. However, recently-maturing capabilities in text-mining, non-obvious relationship analysis, non-linguistic programming, and related methods can be leveraged to meet NASA's needs. Similarly, NASA's role in earth science, particularly measuring climate change, requires access to long time-series of data, including poorly-characterized legacy data. Automation of a capability to mine legacy data and create appropriate metadata with relevant error estimates and provenance information would yield valuable data to extend this time series.

Additionally, increases in capacity of the National Airspace System (NAS) require increased automation in air operations centers, cockpits, and on the ground. Processing data from a variety of different sensors requires tools that enable high-speed computing to link these data together, validate the linkage, and recommend adjustments to the calculated trajectory of aircraft. Semantic bridging capabilities are also needed to swap out inputs and make adjustments to the calculations based on the quality and latency of the data.

**Table 24. TA 11.4.3 Technology Candidates – not in priority order**

TA	Technology Name	Description
11.4.3.1	Semantic Enabler for Data (Text, Binary, and Databases)	Ingests data of all types and produces a data model and a precision ontology; improves the quality of any existing metadata, including provenance and quality of the source document; and disambiguates words in the context of the document, database, or file and visualizes the results.
11.4.3.2	Ultra Large-Scale Visualization and Incremental Toolset	Enables and automates analysis of ultra-large-scale datasets and visualizes the results in the context of the knowledge domain.
11.4.3.3	Semantic Bridge Framework	Enables the alignment of two or more data sources based on their respective ontological descriptions to achieve semantic interoperability and facilitates calculations to be properly made using data from each dataset.
11.4.3.4	Analysis of Competing Hypotheses (ACH) Framework	Generates multiple hypotheses starting from a seed postulate to produce a range of candidate hypotheses.

### **TA 11.4.4 Collaborative Science and Engineering**

NASA's workforce, computing facilities, and mission data are distributed across the Agency, motivating the need for increased synchronous and asynchronous collaboration throughout the NASA mission portfolio and throughout project lifecycles. Asynchronous collaboration has been recently dominated by electronic mail or document interchange via the Internet. Synchronous collaboration usually consists of periodic teleconferences

and videoconferences that are used to exchange updates of progress previously conducted “off-line” by members of the team. Access to data can be difficult and there is limited support for concurrent design, particularly for distributed teams. Scientific data analysis is becoming more collaborative, but the tools, data, and infrastructure often dictate a more independent approach. These independent approaches are becoming more visible as the size and distribution of people, computing, and data continue to increase.

Progress has been made in the areas of shared immersive environments, simulation data interface standards, cached and shared data, knowledge representation, and meta-data management. However, these tools and efforts need to be explicitly developed with the objective of providing a crosscutting, multi-organizational collaborative science and engineering capability for NASA.

### ***Technical Capability Objectives and Challenges***

Collaborative technology environments will enable distributed teams with disparate expertise and resources, including those of partner agencies and contractors, to work in a more unified and more efficient manner than is currently possible. Such capabilities require infrastructures that integrate people, tools, and information and will impact all phases of science and engineering from the initial proposal to the final report. The capability will support development of multidisciplinary solutions and new understanding of scientific phenomena, and discovery of the inter-relationships between phenomena to an extent that would otherwise not be possible. One part of this capability, immersive sight, sound, and touch virtual reality, will likely be commercially available within the next 20 years and will enable real-time, continuous virtual collaboration.

Development challenges include providing an immersive or virtual reality experience that integrates NASA science and engineering data, addressing cyber security issues to enable multi-center and multi-organization collaboration, providing visual resolution and interaction richness while avoiding information overload and clutter, and facilitating the efficient composition of related code development efforts. More specific challenges include finding appropriate ways to visualize very different knowledge representations at different levels of abstraction, including natural language or logic or equations to support requirements, diagrams to support design, state or flow diagrams to support implementation, and dynamic behavior to support test and operations.

### ***Benefits of Technology***

The technologies in collaborative science and engineering will enable geographically-dispersed members of science and engineering teams to come together for real-time collaboration in an integrated environment where the tools, data, and people span multiple institutions. These technologies will provide NASA’s engineers with capabilities for more concurrent engineering and NASA’s scientists with capabilities that support integrated data analysis across highly distributed environments. Additionally, new visualization capabilities will support collaboration and teaming by both scientists and engineers.

**Table 25. TA 11.4.4 Technology Candidates – not in priority order**

TA	Technology Name	Description
11.4.4.1	Immersive Data Explorer	Provides tools to support exploration of complex science and engineering data sets using immersive virtual reality technology.
11.4.4.2	Distributed Collaborative Engineering Frameworks	Provide integrated tools to support engineering collaboration across distributed teams, including teams of tens or hundreds of people.
11.4.4.3	Distributed Collaborative Science Data Analysis Frameworks	Enable data, computation, and services to be brought together to support distributed data analysis in collaborative environments for science.



## TA 11.4.5 Advanced Mission Systems

Advanced mission systems have primarily taken a focus on mission planning, support, and the presentation of near real-time analysis of mission progress. Autonomous, semi-autonomous, and automated capabilities can only be successful if the tools to plan, re-plan, and analyze progress on missions are available to the people who need to manage and oversee the missions. Those planners, managers, and monitors will likely be in the form of dispersed teams requiring sophisticated information sharing, collaboration, and conferencing capabilities.

To support multiple cycles of mission planning by distributed teams, this section focuses on integration of decision-making tools for efficiently dealing with unforeseen circumstances, in order to eliminate emergent problems and capitalize on new opportunities. Advanced mission systems are needed that can rapidly analyze, synthesize, and present those emergent circumstances and appropriate response suggestions in a manner that facilitates informed decision-making by the mission team. Over the past decade, relevant capabilities have begun to emerge at low technology readiness level (TRL) from work funded by NASA, other government agencies, research institutions, and international organizations. To enable missions, NASA must mature the specific advanced mission system technologies described in this section.

### ***Technical Capability Objectives and Challenges***

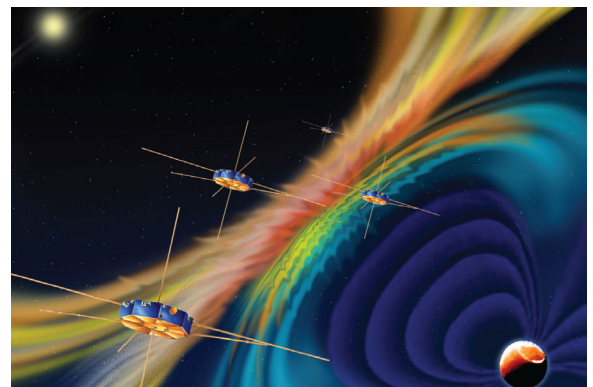
The objectives of advanced mission systems are threefold and span development of baseline mission plans, refinement of the baseline, and collaboration by members of the mission management team. During baseline planning, NASA needs automated tools to mathematically model mission objectives and goals, plot optional mission paths, calculate the potential for mission success, and interactively determine the relative value of the mission. After the baseline plan has been developed, NASA needs the ability to rapidly re-plan missions and estimate the value of alternative approaches or realizations of optional goals when conditions change, problems arise, or new opportunities present themselves. Additionally, a geographically-dispersed mission management team must be able to collaborate and conference with all appropriate data and options, displayed on a variety of interfaces.

Although several early advanced mission systems are in use today by NASA, they are generally limited in scope and reusability, are not rigorous, and often require subjective value judgments by operators who have limited information. Platforms that need these capabilities include Earth-based unpiloted airborne systems, human/machine spaceflight missions, and completely automated systems that operate at sufficient distance from Earth so that communications latency prevents real-time decision-making and control. Technical challenges include the need to reduce mission simulation time, increase the number of alternatives that can be evaluated, automatically generate alternatives in multiple dimensions, and consider goal definition and valuation during the simulations. In many aspects, these technologies are analogous to technologies leading to the Digital Twin for vehicle certification and sustainment, as discussed in TA 11.3.3.

### ***Benefits of Technology***

These technologies will enable both rapid determination of optimal initial mission profile and refinement of that profile as conditions change during the mission. The benefits can be illustrated using adaptive planning and multi-agent planning as examples.

*Adaptive Planning* – Long-duration space systems must address changing environments, degrading hardware, and evolving mission goals. Their control strategies and search strategies must enable adaptive refinement as the mission changes. Scaling to more challenging and unknown operational



**Advanced Mission Systems**

environments will require development and validation of methods for adaptive model and search algorithm updating, including machine learning.

*Multi-Agent Planning, Distributed, Self-Organizing Systems* – Mission planning and execution systems that coordinate with other such systems without requiring human, ground-based oversight, will be ultimately needed. Swarms of exploration spacecraft working together can be coordinated and used effectively if the necessary mission planning and re-planning tools are available.

**Table 26. TA 11.4.5 Technology Candidates – not in priority order**

TA	Technology Name	Description
11.4.5.1	Mission Planner/Monitor	Selects goals for missions from database or manual pre-formatted input, schedules mission segments with detailed activities, and monitors performance and conditions, adjusting plan as necessary.
11.4.5.2	Adaptive Systems Framework	Manages a set of interacting or interdependent entities, real or abstract, forming an integrated whole that together are able to respond to environmental changes or changes in the interacting parts.
11.4.5.3	Multi-Agent Master Framework	Manages over 2,500 remote agents of various sizes and designs, including initiation, assignment, coordination, monitoring, and termination of assignment.
11.4.5.4	High Fidelity Spacecraft Simulator	Monitors system conditions and simulates the remainder of the mission plan to determine probability of success and any points of inflection where decisions can increase or reduce risks.

## TA 11.4.6 Cyber Infrastructure

Scalable Cyber Infrastructures, following a disciplined architectural approach, are rapidly increasing in importance across all NASA elements, including science, exploration, and operations, where the need to capture and use the data to support NASA's goals requires having an infrastructure that will support the data management needs of the Agency. This is particularly true as future data requirements mandate cyber infrastructure technologies to support exascale computing.

The data-intensive computing needed to support Big Data requires the implementation of cyber infrastructures that are explicitly developed to support the lifecycle of data, including its capture, generation, management, archiving, distribution, and analysis. These cyber infrastructures must be architected following a principled approach where the underlying computing services are decoupled to support scalability and distribution within and across NASA centers and partners.

### **Technical Capability Objectives and Challenges**

The objective of NASA's cyber infrastructure technology development is to provide much more scalable approaches for data storage, analysis, management, distribution, assurance, archiving, and preservation. The challenge is that these technologies must be extensible and flexible enough for easy adoption across many NASA missions, without significant redevelopment effort.

### **Benefits of Technology**

Cyber infrastructure is the foundation for scalability and distributed mission contribution using information processing and technology, particularly as the amount of data collected, processed, managed, distributed, analyzed and archived far exceeds current capabilities. A robust cyber infrastructure will benefit NASA by ensuring that computing capabilities, storage, processing, data management, and archiving can substantially scale to meet mission requirements and provide greater flexibility for workflow innovation, such as automation and reuse, across the data lifecycle. These technologies will become increasingly important as exabyte data and exascale computing become commonplace.

Table 27. TA 11.4.6 Technology Candidates – not in priority order

TA	Technology Name	Description
11.4.6.1	On-Demand, Multi-Mission Data Storage and Computation	Provides scalable storage and computing available on demand across projects, including both internal and external, or hybrid clouds at center and NASA levels.
11.4.6.2	Scalable Data Management Frameworks	Extensible, scalable data management frameworks that can take advantage of massive storage and computing resources.
11.4.6.3	Scalable Data Archives Systems	Support scalable archives that can capture, manage, distribute, and preserve massive data sets, both engineering and science.
11.4.6.4	High Performance Networking	Provide terabit data networks to handle movement of massive datasets, particularly those for scientific research.

## TA 11.4.7 Human-System Interaction

Although increasing computational technology has changed the roles of humans in a wide variety of tasks, vehicle and ground displays and controls have evolved slowly. Tasks have changed from inner loop control to supervision. Although the amount and quality of available information has increased, the way in which information is presented to the operator has become dangerously outdated. Hence, new methods must be developed to meet the information needs and capabilities of the operators in a wide variety of systems and tasks—from managing inventory on an exploration system to managing the health of a multiple-vehicle mission.

For example, the current control stations for UAS resemble the displays and controls of a cockpit, even though the tasks have changed. To safely transition from several people controlling one UAS to one person controlling several, the operator-control system interfaces must be reassessed and redesigned.

### *Technical Capability Objectives and Challenges*

For human-system interaction, objectives include developing technologies to provide comprehensive mission operations functionality on mobile devices in extreme environments like space, and achieving a human-centered experience for the user. Mobile mission operations allow space mission crews to effectively and efficiently view and interact with mission operation functions in extreme, constrained, or distributed environments. A challenge is to provide an intelligent system that works effectively with crew, such as efficiently distributing the task workload between crew and automation. A human-centered design approach to system interfaces should be employed to maximize usability, user acceptability, and user comfort, when applicable, of information systems. Other development challenges include developing technologies that provide comprehensive mission operations and that also take a human-centered approach to ensure clear understanding of human operator capabilities and limitations and efficiently enable interactions with the interface while accommodating these capabilities and limitations. These technologies complement the robotics and autonomy related technologies in TA 4.4 Human-System Interaction.

### *Benefits of Technology*

Improved human-system interaction technologies will allow for an increase in crew autonomy and will be necessary for future crewed deep-space missions, where ground support is limited. Better technologies to assist humans in integrating mission operations data will increase the number of connected data sources and lower information retrieval times for critical items, such as mission faults and hazards, supporting enhanced safety of deep-space missions.



Table 28. TA 11.4.7 Technology Candidates – not in priority order

TA	Technology Name	Description
11.4.7.1	Mobile Mission Operation Toolset	Allows space mission crews to effectively and efficiently view and interact with mission operation functions in extreme, constrained, or distributed environments using mobile devices.
11.4.7.2	Crew Autonomy Mission Operation System	Allows space mission crews to effectively and efficiently conduct mission operation functions without continuous connection to and control by mission control.
11.4.7.3	Rich Light-Weight Web-Based Mission Interface	Allows for easier code deployment and maintainability as well as allows mission operations to be performed on any commodity browser.
11.4.7.4	Enhanced Certifiable Unmanned Aircraft System Ground Station	Maximizes human automation teaming, operator situation awareness, and supervisory control for nominal and contingent operations.
11.4.7.5	Smart Object Integration	Allows humans to effectively interact with and control smart objects and robotic equipment.
11.4.7.6	Assistive tool for Heterogeneous Data Integration	Allows integration of heterogeneous data sources to enable querying and linking data.
11.4.7.7	Hyperwall	Enables analysis and visualization of high-resolution, high-density, petascale NASA data.

## TA 11.4.8 Cyber Security

Cyber security is an enabling technology that ensures that the integrity, confidentiality, and availability of NASA systems are not compromised by cyber attacks. In the current operational environment, existing cyber security technology has not kept pace with the rapid evolution of information technologies, including cloud computing, and their interface to existing NASA systems. It has also not kept pace with the constantly-changing threat environment, including attacks from foreign governments. To identify new and emerging threats, cyber security technology must be rapidly improved in several areas, including security situational awareness and anomaly detection.

### *Technical Capability Objectives and Challenges*

NASA has a responsibility to protect Agency-unique data and information systems from essentially continual cyber attack. The overall objectives of technologies in the cyber security area is therefore to ensure that NASA information systems and data are secure throughout the entire mission and science data lifecycle, allowing efficient access by authorized users while eliminating unauthorized access. Development challenges in creating these technologies include achieving the flexibility for rapid updates and broad application needed to keep pace with innovation in information technology, mining the vast amount of distributed security-relevant Big Data in real time to quickly detect and triage anomalous behavior while minimizing false positives and false-negatives, efficiently tracking NASA information systems, and achieving high-assurance user identification and authentication for automated workflows that may span NASA and public systems and that continue after the user logs off.

### *Benefits of Technology*

Successful development and implementation of this technology will ensure that cyber security is an integral part of the information system design, from conception to operations and maintenance to disposal, so that NASA systems are more secure throughout their lifecycle. It will also ensure that security decisions made in earlier stages of the development process can and will be carried through the development phases, enabling more flexible and comprehensive “designed-in” security, rather than “bolt-on” security as an afterthought. Specific benefits of these technologies include rapid identification of vulnerabilities or cyber attacks that requires human or automated mitigation action, including detection of new threats without having a pre-defined signature; the ability to track NASA mobile and fixed information systems for recovery of lost or stolen assets; and the ability to transparently run NASA workflows across internal and external systems, such as public clouds, for on-demand and secure augmentation of NASA information resources.

Table 29. TA 11.4.8 Technology Candidates – not in priority order

TA	Technology Name	Description
11.4.8.1	Cyber Security and Information Assurance Framework	Provides the process and tools to ensure that best security practices are applied throughout the mission data life cycle.
11.4.8.2	Cyber Security Situational Assessment Environment	Uses the confluence of multiple security relevant datasets, such as intrusion detection, flows, log, vulnerability scans, known vulnerabilities, domain name server inquiries, and asset characteristics to identify when there is an attack or probe that warrants action by a security analyst or automated program to counter this threat.
11.4.8.3	User/Asset Geographic Tracking System	Couples the identification of all relevant users, mobile devices, and security assets with their geographical location.
11.4.8.4	Anomaly Detection System	Characterizes normal human and system behavior and then identifies any behavior that deviates from the norm by some delta that could be set by the users.
11.4.8.5	Secure Cloud Bursting Infrastructure	Enables workflows to transfer seamlessly between a physical data center and a cloud.

# Appendix

## *Acronyms*

ACH	Analysis of Competing Hypotheses
ADP	Advanced Diagnostics and Prognostics Adaptive
ADU	Model Updating
AI	Artificial Intelligence
AMR	Adaptive Mesh Refinement
API	Application Programming Interface
BEM	Boundary Element Methods
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAIB	Columbia Accident Investigation Board
CFD	Computational Fluid Dynamics
COTS	Commercial-Off-the-Shelf (hardware or software)
DIS	Distributed Interactive Simulation
DRM	Design Reference Mission
DSES	Distributed Space Exploration Simulation Distributed
DSM	Spacecraft Mission
EDL	Entry, Descent, and Landing
EO-1	Earth Observing 1
ESMA	Earth Science Modeling and Assimilation
EVA	ExtraVehicular Activities
FOV	Fields Of View
FSW	Flight SoftWare
GPU	Graphical Processing Unit
HLA	High-Level Architecture
HPC	High-Performance Computing
HPS	High-Performance Simulations
HW/SW	HardWare/SoftWare
I/O	Input/Output
IDU	Intelligent Data Understanding
IR	InfraRed
IT	Information Technology
ISS	International Space Station
LAN	Local Area Network
LEO	Low-Earth Orbit
LIS	Land Information System
M&S	Modeling and Simulation
MBSE	Model-Based Systems Engineering
MDM	Multi-Domain Modeling
MHD	MagnetoHydroDynamic



MODIS	MODerate resolution Imaging Spectroradiometer
MTBF	Mean Time Between Failure
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NEA	Near-Earth Asteroid
NEX	NASA Earth Exchange
NextGen	Next Generation (air traffic management or national airspace system)
NIC	Network Interface Card
OCT	Office of the Chief Technologist
OSSE	Observing System Simulation Experiments
OSTPV	Onboard Short Term Plan Viewer
PDF	Probability Density Function
PDM	Product Data Management
PLM	Product Lifecycle Management
PRA	Probabilistic Risk Assessment
RDF	Resource Description Framework, a standard
RDM	Robust Decision-Making
RHBD	Radiation-Hardened-By-Design
RMS	Root Mean Square
ROA	Resource Oriented Architecture
SLIM	System-Level Integrated Modeling
SOA	State Of the Art
SOC	Security Operations Center
STEM	Science, Technology, Engineering, and Math
STIP	Strategic Technology Investment Plan
SysML	Systems Modeling Language
TA	Technology Area
TABS	Technology Area Breakdown Structure
TRL	Technology Readiness Level
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
UML	Unified Modeling Language
UQ	Uncertainty Quantification
VR	Virtual Reality
V&V	Verification and Validation
WAN	Wide Area Network
XML	eXtensible Markup Language

## Abbreviations and Units

Abbreviation	Definition
%	Percent
DOF	Degrees of Freedom
FLOPS	Floating Point Operations per Second
g	Unit of acceleration, normalized to Earth surface gravity
GB	GigaByte
Gb	Gigabits
Gbps	Gigabits per Second
GFLOPS	GigaFLOPS
GOPS	Billion (Giga) Operations per Second
km	Kilometers
kW	Kilowatt
m	Meters
MB	MegaByte
Mbp	Megabit
Mbps	Megabits per Second
min	Minutes
MIPS	Million Instructions per Second
MOPS	Million Operations per Second
MSLOC	Million Source Lines of Code
mW	MilliWatts
PB	PetaByte
PFLOPS	PetaFLOPS
POD	Probability of Detection
qubits	Quantum Bits
Rad	Unit of Absorbed Radiation Dose
s or sec	Seconds
TB	TeraByte
Tbps	Terabits per Second
V	Volts
W	Watts

## Contributors

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### TECHNOLOGY AREA ROADMAP DEVELOPMENT TEAM

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**Edward H. Glaessgen**

TA 11 Chair  
NASA, Langley Research Center

**Bryan Biegel**

TA 11 Co-Chair  
NASA, Ames Research Center

**Faith Chandler**

Director, Strategic Integration, OCT  
NASA, Headquarters

**Dan Crichton**

NASA, Jet Propulsion Laboratory

**Jacqueline LeMoigne**

NASA, Goddard Space Flight Center

**Michael Little**

NASA, Langley Research Center

**Cynthia Null**

NASA, Langley Research Center

**Willard Peters**

NASA, Headquarters

**Jonathan B. Ransom**

NASA, Langley Research Center

**Lui Wang**

NASA, Johnson Space Center

---

### OTHER CONTRIBUTORS

---

**Tracy Bierman**

NASA, Kennedy Space Center

**Jeff Cerro**

NASA, Langley Research Center

**Thomas Clune**

NASA, Goddard Space Flight Center

**Michael Conroy**

NASA, Kennedy Space Center

**Edwin Z. Crues**

NASA, Johnson Space Center

**Richard Doyle**

NASA, Jet Propulsion Laboratory

**Dana Hammond**

NASA, Langley Research Center

**Matthew Handy**

NASA, Goddard Space Flight Center

**Tom Hinke**

NASA, Ames Research Center

**Sean Kenny**

NASA, Langley Research Center

**Dennis Lawler**

NASA, Johnson Space Center

**Daniel Mandl**

NASA, Goddard Space Flight Center

**Carie Mullins**

The Tauri Group

**Richard Ross**

NASA, Langley Research Center

**Erik Saether**

NASA, Langley Research Center

**W. Phil Webster**

NASA, Goddard Space Flight Center

**Alan Zide**

NASA, Headquarters



## Technology Candidate Snapshots

### 11.1 Computing 11.1.1 Flight Computing

#### 11.1.1.1 Radiation-Hardened General Purpose Flight Processor

##### TECHNOLOGY

**Technology Description:** Enables general-purpose onboard processing in the space radiation environment using a combination of traditional parts-level hardening, rad-hard-by-design (RHBD) techniques, and architectural support for software-based fault tolerance techniques.

**Technology Challenge:** Address power dissipation at the hardware level to enable power scaling.

**Technology State of the Art:** Space qualifiable radiation-hardened-by-design (RHBD) 49-core processor via 7x7 tiled multi-core architecture, developed for a government agency.

##### Parameter, Value:

Computational throughput: 44 GOPS;  
Power: 19 W;  
Power Scalability: none;  
Architectural support for software-based fault-tolerance: none.

##### TRL

3

**Technology Performance Goal:** Significantly advance computational performance beyond the radiation-hardened single core and quad core RISC processors available in the commercial sector. Provide architectural support to dynamically trade performance, energy management, and fault tolerance.

##### Parameter, Value:

Computational throughput: 24 GOPS / 10 GFLOPS  
Power: 7 W;  
Power Scalability: < 1 W  
Architectural support for software-based fault-tolerance: yes (such as, voting, graceful degradation).

##### TRL

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.3.7 Multiscale, Multiphysics, and Multifidelity Simulation

##### CAPABILITY

**Needed Capability:** High-performance, space-qualified flight processing.

**Capability Description:** Provides high-performance, radiation-tolerant, space-qualified, general-purpose flight computing. Includes the ability to continuously trade computational performance, energy management, and fault tolerance. Incorporates power scaling, and support for a range of software-based fault tolerance techniques.

**Capability State of the Art:** Radiation-hardened single core processor available in the commercial sector.

##### Parameter, Value:

Computational throughput: 400 MOPS;  
Power: 5 W;  
Power scalability: none;  
Architectural support for software-based fault tolerance: none

**Capability Performance Goal:** Increase number of operations by at least two orders of magnitude to support future onboard computer-intensive functions and system demands. Enable fine-grained power scaling. Support a range of software-based fault tolerance methods.

##### Parameter, Value:

Computational throughput: 24 GOPS / 10 GFLOPS; Power: 7 W;  
Power scalability: < 1 W;  
Architectural support for software-based fault-tolerance: yes (such as, voting, graceful degradation)

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Discovery: Later Discovery Program	Enabling	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.1 Computing  
11.1.1 Flight Computing

## 11.1.1.2 Radiation-Hardened High-Capacity Memory

## TECHNOLOGY

**Technology Description:** Enables volatile and non-volatile, radiation-hardened memory management for flight computing using a combination of traditional parts-level hardening, rad-hard-by-design (RHBD) techniques, and architectural support for software-based fault tolerance techniques.

**Technology Challenge:** Address power management and mitigate radiation induced single event effects.

**Technology State of the Art:** Limited onboard memory management and capability.

**Parameter, Value:**

Non-volatile capacity: 64 Mb;  
Core voltage: 3.3 V;  
Data transfer rate: 20 MB/sec;  
Power: 0.6 W;  
Volatile capacity: 16 Mb;  
Core voltage: 3.3 V;  
Data transfer rate: 50 MB/sec

**TRL**

3

**Technology Performance Goal:** Use of radiation-hardened memory management onboard that supports requirements for reliable, low-power use. Highly scalable storage to support complex onboard flight software.

**Parameter, Value:**

Non-volatile capacity: 1 Gb;  
Core voltage: 1.8 V;  
Data transfer rate: 500 MB/sec;  
Power: 0.3 W;  
Volatile capacity: 1 Gb;  
Core voltage: 1.5V;  
Data transfer rate: 6400 MB/sec

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.3.7 Multiscale, Multiphysics, and Multifidelity Simulation

## CAPABILITY

**Needed Capability:** Flight memory management.

**Capability Description:** Provides massive radiation-hardened, high-capacity, low-power, high-speed, and volatile/non-volatile memories.

**Capability State of the Art:** Memory management has limited offerings for radiation-tolerant environments. Projects use a combination of limited RAD-based availability and commercial-off-the-shelf (COTS)-based solutions that limit scalability as well as reliability and power consumption. This engenders risk to missions that depend on components that must operate in harsh environments.

**Parameter, Value:**

Non-volatile capacity: 64 Mb;  
Core voltage: 3.3 V;  
Data transfer rate: 20 MB/sec;  
Power: 0.6 W;  
Volatile capacity: 16 Mb;  
Core voltage: 3.3 V;  
Data transfer rate: 50 MB/sec

**Capability Performance Goal:** Substantially scale memory management demands for onboard high-performance computing.

**Parameter, Value:**

Non-volatile capacity: 1 Gb;  
Core voltage: 1.8 V;  
Data transfer rate: 500 MB/sec;  
Power: 0.3 W;  
Volatile capacity: 1 Gb;  
Core voltage: 1.5 V;  
Data transfer Rate: 6400 MB/sec

**Technology Needed for the Following NASA Mission Class and Design Reference Mission**

Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Enabling	2027	2027	2021	5 years
Enhancing	2027	2027	2021	5 years
Enhancing	2027	2027	2021	5 years
Enabling	2033	--	2027	5 years
Enhancing	--	2022*	2019	5 years
Enhancing	--	2023*	2020	5 years
Enabling	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.1 Computing  
11.1.1 Flight Computing

## 11.1.1.3 High Performance Flight Software

## TECHNOLOGY

**Technology Description:** Enables onboard, high performance autonomy and data processing processing taking advantage of flight processor and memory management advances in flight computing.

**Technology Challenge:** Increased autonomy and data processing onboard.

**Technology State of the Art:** Highly-scalable onboard flight software leveraging the computing environment including processing and memory management. Verification and validation by use of static analyzers. Fault tolerance at subsystem level via second string fail over and safe mode with ad hoc subsystem level erroneous behavior detection.

**Parameter, Value:**

Probability of code error per 1,000 lines of code : high

**TRL**

3

**Technology Performance Goal:** Deployment of much more capable flight software onboard that can leverage more capable processor and memory management capabilities. Improvement in state-based software architecture approaches, including efficient support for multicore and many core processors. 100% of code verified and validated by dynamic analysis.

**Parameter, Value:**

Probability of code error per 1,000 lines of code: low

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1.1 Radiation-hardened General Purpose Flight Processor, 11.1.1.2 Radiation-hardened High-Capacity Memory.

## CAPABILITY

**Needed Capability:** High performance flight software.

**Capability Description:** Provides highly-capable flight computing that supports reconfigurable spacecraft and versatile missions where onboard computation directly supports missions requiring a characterization phase at the target (such as small body proximity ops, atmospheric mobility) to refine environmental models, operations concepts, spacecraft configuration and mission design as needed.

**Capability State of the Art:** Limited techniques onboard due to limitations of scalability. Minimal capability for rapid and effective validation and verification (V&V). Minimal capability for efficient fault tolerance. Minimal capability for safety and security.

**Parameter, Value:**

Probability of code error per 1,000 lines of code: high

**Capability Performance Goal:** Enable substantially improved capabilities for onboard autonomy and data processing. Enable architectures supporting highly reliable composable systems comprised of modules of varying reliability mission criticality. 100% of code verified and validated by dynamic analysis.

**Parameter, Value:**

Probability of code error per 1,000 lines of code: low

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enabling	--	2023*	2020	5 years
Discovery: Later Discovery Program	Enabling	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.1 Computing  
11.1.1 Flight Computing

## 11.1.1.4 Low Power Embedded Computer

## TECHNOLOGY

**Technology Description:** Enables low-power processor for embedded processing within small systems incorporating low-power processor designs and provide architectural support for power scalability.

**Technology Challenge:** Improving power reduction and radiation hardening is a challenge.

**Technology State of the Art:** Commercial sector instruction set architecture embeddable processors implemented in a deep submicron process (45 nano meter or below), not radiation hardened, can achieve over 200 MIPS at under 2 mW.

**Parameter, Value:**

Processor speed, MIPS: 200 at under 2 mW.

## TRL

3

**Technology Performance Goal:** Radiation-hardened embedded processor.

**Parameter, Value:**

RadHard processor speed, MIPS: 200 at under 100 mW.

## TRL

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.3.7 Multiscale, Multiphysics, and Multifidelity Simulation

## CAPABILITY

**Needed Capability:** Flight embedded computing.

**Capability Description:** Provides for size, weight, and power efficient processing that can be embedded into subsystems, miniaturized instruments, and CubeSats/smallsats.

**Capability State of the Art:** Current approaches are to use either low-power discrete processors or processor IP cores embedded within field programmable gate arrays (FPGAs) available in the commercial sector

**Parameter, Value:**

Processor speed, MIPS: Up to 99 at 1.2 W;

Processor speed, MIPS: 20 at 0.5 W.

**Capability Performance Goal:** Support for embedded processors/computing, not necessarily radiation hardened, for subsystems, instruments, sensors, and CubeSats/smallsats.

**Parameter, Value:**

Processor speed, MIPS: 200 at under 2 mW.

## Technology Needed for the Following NASA Mission Class and Design Reference Mission

Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Enabling	2027	2027	2021	5 years
Enabling	2027	2027	2021	5 years
Enabling	2027	2027	2021	5 years
Enabling	2033	--	2027	5 years
Enabling	2033	--	2027	5 years
Enabling	2033	--	2027	5 years

11.1 Computing  
11.1.1 Flight Computing

### 11.1.1.5 High Speed Onboard Networks

#### TECHNOLOGY

**Technology Description:** Enables onboard, high-speed networks for sensor data.

**Technology Challenge:** Radiation hardening is a challenge.

**Technology State of the Art:** Serial RapidIO, Gigabit ethernet (1000 Base-T).

**Parameter, Value:**

Data transfer rate: 10 Gbps (Serial RapidIO); Data transfer rate: 1 Gbps (1000 Base-T).

**TRL**

3

**Technology Performance Goal:** Component technology to implement multigigabit onboard network conforming to next generation space interconnect standard.

**Parameter, Value:**

Data transfer rate: 10 Gbps.

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.3.7 Multiscale, Multiphysics, and Multifidelity Simulation

#### CAPABILITY

**Needed Capability:** Flight onboard networking.

**Capability Description:** Provides onboard networks that can meet emerging needs to handle high-speed sensor data.

**Capability State of the Art:** Current approaches utilize either a derivative standard of IEEE 1355 or a time triggered gigabit-ethernet.

**Parameter, Value:**

Data transfer rate: 2-400 Mbps (IEEE 1355 derivative);  
Data transfer rate: 1 Gbps maximum (time triggered).

**Capability Performance Goal:** Support for onboard data communications within the flight system.

**Parameter, Value:**

Data transfer rate: 10 Gbps (Serial RapidIO);  
Data transfer rate: 1 Gbps maximum (1000 Base-T).

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

11.1 Computing  
11.1.2 Ground Computing

## 11.1.2.1 Exascale Supercomputer

## TECHNOLOGY

**Technology Description:** Provides peak computational capability of  $\geq 1$  exaFLOPS,  $10^{18}$  floating point operations per second, for exascale performance of NASA computations, with excellent energy efficiency and reliability, to support NASA's exponentially growing high-end computational needs.

**Technology Challenge:** NASA must continue to work closely with vendors and the community to develop exascale interconnects that operate reliably despite massive data transfer requirements across the supercomputer, and must assure that NASA applications run efficiently on the system.

**Technology State of the Art:** Commercial sector supplied supercomputer at another government agency sustained 14.4 petaFLOPS (PFLOPS =  $10^{15}$  floating point operations per second) on a fluid dynamics simulation.

**Parameter, Value:**

Sustained application performance: 14.4 PF.

MTBF: unknown (probably on the order of 1 hour).

LINPACK Energy Efficiency: 2.2 GFLOPS/Watt.

TRL

6

**Technology Performance Goal:** 1,000x increase in sustained processing performance for large modeling and simulation (M&S) applications in 10 years, within facility power limits and with 10X longer mean time between failures (MTBF).

**Parameter, Value:**

Sustained application performance: 50 PFLOPS;

MTBF: 100 hours;

LINPACK Energy Efficiency: 400 GFLOPS/Watt.

TRL

9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:**

Exascale computing research being conducted by other federal agencies and academia.

## CAPABILITY

**Needed Capability:** Exascale supercomputing.

**Capability Description:** Enables exascale M&S and exascale data analysis for a broad range of NASA computational applications at 1000x processing speed and 10x reliability compared to current M&S, within the energy capacity of NASA supercomputing facilities.

**Capability State of the Art:** NASA's 200,000-core, 4.5 PFLOPS, 4 mega watt Pleiades supercomputer supports up to 70,000 core computations on NASA M&S applications, averaging about 10 hours MTBF requiring application restart.

**Parameter, Value:**

Sustained application performance: 0.15 PFLOPS;

MTBF: 10 hours;

LINPACK Energy Efficiency: 0.8 GFLOPS/Watt.

**Capability Performance Goal:** 1,000x increase in sustained processing performance for large M&S applications in 10 years, within facility power limits and with 10x longer MTBF.

**Parameter, Value:**

Sustained application performance: 150 PFLOPS

(1,000x); MTBF: 100 hours (10x);

LINPACK Energy Efficiency: 400 GFLOPS/Watt (500x).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enhancing	--	2035*	2030	15 years
Solar Terrestrial Probes: Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI)	Enhancing	--	2032	2030	10 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	10 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	10 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.1 Computing  
11.1.2 Ground Computing

### 11.1.2.2 Automated Exascale Software Development Toolset

#### TECHNOLOGY

**Technology Description:** Provides automated, exascale application performance monitoring, analysis, tuning, and scaling.

**Technology Challenge:** Automating general-purpose software development tools, scaling them to millions of processors and threads, support for energy-efficient exascale architectures (such as with graphical processing units (GPUs) or many integrated cores), and higher level of abstraction (such as data reduction, automated handling of routine code performance tuning tasks); high-performance standards and libraries for computational accelerators.

**Technology State of the Art:** Autoparallelizing compiler for shared-memory computers.

**Parameter, Value:**

Sustained application performance: 0.15 PFLOPS

**TRL**

4

**Technology Performance Goal:** 1,000x improvement in sustained processing for large modeling and simulation (M&S) applications in 10 years, without hand tuning.

**Parameter, Value:**

Sustained application performance: 150 PFLOPS

**TRL**

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2.1 Exascale Supercomputer

#### CAPABILITY

**Needed Capability:** Efficient exascale software development.

**Capability Description:** Facilitates rapid development, modification, porting, and optimization of exascale application software.

**Capability State of the Art:** Currently, high-performance computing (HPC) application software takes an expert to develop and optimize, the process is labor-intensive, and the tools offer little automation of routine tasks, especially for the most energy-efficient processors, including GPUs and many integrated cores accelerators.

**Parameter, Value:**

Sustained application performance: 0.05 PFLOPS

**Capability Performance Goal:** 1,000x improvement in sustained processing for large M&S applications in 10 years, achieved with tool-based parallelization and performance tuning of the application code, without significant hand tuning.

**Parameter, Value:**

Sustained application performance: 50 PFLOPS

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enhancing	--	2035*	2030	15 years
Solar Terrestrial Probes: Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI)	Enhancing	--	2032	2030	10 years
Solar Terrestrial Probes: Dynamical Neutral Atmosphere Ionosphere Coupling (DYNAMIC)	Enhancing	--	2025	2021	10 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	10 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	10 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.1 Computing  
11.1.2 Ground Computing

## 11.1.2.3 Exascale Supercomputer File System

## TECHNOLOGY

**Technology Description:** Provides online data storage capacity of  $\geq 1$  exabyte, enabling data storage for exascale modeling and simulation (M&S) and data analysis, with sufficient performance and reliability to maintain productivity for a broad array of NASA applications.

**Technology Challenge:** NASA must continue to work closely with vendors and the community to scale the file system to reliably handle the large-scale data storage and input/output (I/O) rates needed. Technology is needed to make the storage system more self-optimizing and self-correcting.

**Technology State of the Art:** NASA operates a 20 petabyte parallel distributed file system for the Pleiades supercomputer.

**Parameter, Value:**

File system capacity: 20 PB;

File system I/O rate: 15 GB/s.

**TRL**

9

**Technology Performance Goal:** 100x increase in data storage capacity and I/O rate in 10 years, with only 2x increase in power use, and no decrease in mean time between failures (MTBF).

**Parameter, Value:**

File system capacity: 2,000 PB (100x); File system I/O rate: 1,500 GB/s (100x).

**TRL**

9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Exascale supercomputing data storage.

**Capability Description:** Provides online data storage and I/O for exascale M&S and exascale data analysis for a broad range of NASA computational applications at 100x file system size, and equivalent reliability compared to current file systems, within the energy capacity of NASA facilities.

**Capability State of the Art:** NASA operates a 20 petabyte parallel-distributed file system for the Pleiades supercomputer.

**Parameter, Value:**

File system capacity: 20 PB;

File system I/O rate: 15 GB/s.

**Capability Performance Goal:** 100x increase in data storage capacity and I/O rate in 10 years, with only 2x increase in power use, and no decrease in MTBF.

**Parameter, Value:**

File system capacity: 2,000 PB (100x);

File system I/O rate: 1,500 GB/s (100x).

## Technology Needed for the Following NASA Mission Class and Design Reference Mission

Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Enhancing	2033	--	2027	10 years
Enhancing	2033	--	2027	10 years
Enhancing	--	2035*	2030	15 years
Enhancing	--	2032	2030	10 years
Enhancing	--	2025	2021	10 years
Enhancing	--	--	2035	10 years
Enhancing	--	--	2025	10 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.1 Computing  
11.1.2 Ground Computing

## 11.1.2.4 Quantum Computer

## TECHNOLOGY

**Technology Description:** Utilizes quantum effects such as superposition and entanglement to enable the solution of certain computational problems, like optimization or pattern recognition, where an exhaustive search of all possibilities or computations by a conventional computer would be infeasible.

**Technology Challenge:** There is currently no known approach to maintain coherence of more than a few qubits; identification and implementation of several real science data processing applications.

**Technology State of the Art:** 7-qubit quantum computer.

**Technology Performance Goal:** Reliable operation of a fully-entangled 1,024-qubit quantum computer.

**Parameter, Value:**

TRL

Number of qubits that can be entangled: 7;  
Two-qubit gate fidelity: > 99%.

3

**Parameter, Value:**

TRL

Number of qubits that can be entangled: 1,024;  
Two-qubit gate fidelity: > 99%.

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Quantum computing.

**Capability Description:** Enables solution of certain computational problems (such as optimization or pattern recognition) where an exhaustive search of all possibilities or computations by a conventional computer would be infeasible.

**Capability State of the Art:** NASA operates a 2 quantum computer, with 512 qubits that are sparsely interconnected outside of clusters of 8. This system is able to solve small, discrete optimization problems in a time similar to conventional computers.

**Capability Performance Goal:** Ability to optimize full day of rover or astronaut activities in near real time.

**Parameter, Value:**

Number of qubits that can be entangled: 0  
Two-qubit gate fidelity: N/A.

**Parameter, Value:**

Number of qubits that can be entangled:  
1,024 Two-qubit gate fidelity: > 99%.

**Technology Needed for the Following NASA Mission Class and Design Reference Mission**

Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Enhancing	2033	--	2027	10 years
Enhancing	--	2035*	2035	20 years
Enhancing	--	2035*	2035	20 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.1 Computing  
11.1.2 Ground Computing

## 11.1.2.5 Public Cloud Supercomputer

## TECHNOLOGY

**Technology Description:** Provides additional resources for NASA supercomputer users, such as for mission-critical computing in an emergency.

**Technology Challenge:** Efficient and reliable methods for packaging entire computational tasks (including environment, codes, and data) for the cloud, shipping this to and from the cloud. Implementing adequate information technology (IT) security is also essential.

**Technology State of the Art:** Huge public clouds exist, such as those operated by the commercial sector, which can do computing on demand. However, a significant effort (days to months) is required to arrange computing and set up the cloud environment, and the computing.

**Technology Performance Goal:** Provide a 50% augmentation to NASA's supercomputing capacity, with only a 10% increase in application turn-around time.

**Parameter, Value:**

Surge capacity: 10% of NASA supercomputing

Ratio of cloud to NASA turn-around time: 600

**TRL**

6

**Parameter, Value:**

Surge capacity: 50% of NASA supercomputing

(2,500x) Ratio of cloud to NASA turn-around time: 1

**TRL**

9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Cloud supercomputing.

**Capability Description:** Enables NASA to dynamically expand its supercomputing resources by drawing on available computing capacity outside of NASA's supercomputing center.

**Capability State of the Art:** In 2014, the NASA Advanced Supercomputing facility ran a surge computing experiment, to run a small parallel computation on a 4-node internal cloud system. Total turn-around time for the cloud was ~10 minutes compared to about 1 second on NASA's Pleiades supercomputer.

**Capability Performance Goal:** For surge computing to be useful, it must provide a significant augmentation to NASA's supercomputing capacity, and with only a small increase in application turn-around time.

**Parameter, Value:**

Surge capacity: 0.02% of NASA supercomputing

Ratio of cloud to NASA turn-around time: 600

**Parameter, Value:**

Surge capacity: 50% of NASA supercomputing

Ratio of cloud to NASA turn-around time: 1

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enhancing	--	2035*	2030	5 years
Solar Terrestrial Probes: Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI)	Enhancing	--	2032	2030	5 years
Solar Terrestrial Probes: Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)	Enhancing	--	2025	2021	5 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	5 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.1 Computing  
11.1.2 Ground Computing

## 11.1.2.6 Cognitive Computer

## TECHNOLOGY

**Technology Description:** Provides efficient, adaptable brain-like computing, using synthetic neurons and synapses, programmed by learning from instances, to sense, predict, and reason.

**Technology Challenge:** Adaptation of NASA applications to this technology, including training the systems.

**Technology State of the Art:** In August 2011, the commercial sector demonstrated a building block of a novel brain-inspired chip architecture based on a scalable, interconnected, configurable network of “neurosynaptic cores” that brought memory, processors, and communication into close proximity, to emulate the brain’s computing efficiency, size, and power usage.

**Parameter, Value:**

Number of artificial neurons: 256

Number of artificial synapses: 256,000

Power usage: 10-100 W.

**TRL**

4

**Technology Performance Goal:** Cognitive computing for mining and analyzing large amounts of disparate data (“Big Data”) or processing complex data during a mission in near real time.

**Parameter, Value:**

Number of artificial neurons: 10 billion Number of

artificial synapses: 100 trillion

Power usage: 1 kW.

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Cognitive computing.

**Capability Description:** Provides brain-like computing, using synthetic neurons and synapses, programmed by learning from instances, to sense, predict, and reason.

**Capability State of the Art:** The commercial sector has developed an artificially intelligent computer that can answer questions posed in natural language. It competed and won in a competition setting against the best human competitors. During the competition, it was not connected to the Internet, but utilized a large set of structured and unstructured knowledge that it learned over several years. It used a combination of machine learning, statistical analysis, and natural language processing.

**Parameter, Value:**

Number of neurons: 0;

Number of synapses: 0;

Power usage: 200 kW

**Capability Performance Goal:** Develop a highly capable cognitive system at least 10% the size of the human brain, with no more than 10x the power usage.

**Parameter, Value:**

Number of neurons: 10 billion;

Number of synapses: 100 trillion;

Power usage: 1 kW

## Technology Needed for the Following NASA Mission Class and Design Reference Mission

Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Enhancing	2033	--	2027	10 years
Enhancing	2033	--	2027	10 years
Enhancing	--	2035*	2030	15 years
Enhancing	--	2030*	2025	10 years
Enhancing	--	2032	2030	10 years
Enhancing	--	--	2035	10 years
Enhancing	--	--	2025	10 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.1 Computing  
11.1.2 Ground Computing

### 11.1.2.7 High Performance Data Analytics Platform

#### TECHNOLOGY

**Technology Description:** Provides a computing and storage environment optimized for high-performance data analytics, supporting interactive exploration and analysis with petabyte-scale observational and computed data sets.

**Technology Challenge:** Optimized integration of high-performance computing, distributed storage, high-performance networking, parallel analytics software, an application programming interface (API), and workflow automation into a seamless environment that enables distributed, interactive petabyte-scale analytics.

**Technology State of the Art:** Data is downloaded from various sources to the local computer, where commercial and custom software perform interactive data analysis.

**Technology Performance Goal:** Data is analyzed where it is stored, with multi-site analysis done through high-speed data streaming between sites, supported by automated workflow tools that include real-time user interaction with data visualization.

**Parameter, Value:**

Maximum size of interactive data analytics: 1 TB;  
Time for first results from petascale analysis: 1 week.

**TRL**

9

**Parameter, Value:**

Maximum size of interactive data analytics: 1 PB;  
Time for first results from petascale analysis: 1 minute.

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2.1 Exascale Supercomputer, 11.1.2.3, Exascale Supercomputing File System

#### CAPABILITY

**Needed Capability:** High-performance data analytics platform.

**Capability Description:** A high-performance computing and storage platform with the ability to create a custom-working environment for scientists (a user experience similar to their workstation) to analyze large-scale data sets (terabyte to petabyte). In addition, the platform will have the ability to enable server-side processing of extreme data sets through the use of APIs specifically designed for distributed data analytics.

**Capability State of the Art:** High performance computing environments that are rigid and designed for large parallel jobs that create streaming data sets. File systems are designed for streaming data and not agile enough to effectively handle the requirements of large-scale data analysis. User workstations with various operating systems, memory, networking, and software packages.

**Capability Performance Goal:** Data is analyzed where it is stored, with multi-site analysis done through high-speed data streaming between sites, supported by automated workflow tools that include real-time user interaction with data visualization.

**Parameter, Value:**

Maximum size of interactive data analytics: 1 TB

**Parameter, Value:**

Maximum size of interactive data analytics: 1 PB

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enhancing	--	2024*	2020	5 years
Earth Systematic Missions: Global Atmosphere Composition Mission (GACM)	Enhancing	--	2024*	2019	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.2 Modeling  
11.2.1 Software Modeling and Model  
Checking

### 11.2.1.1 Hybrid Model Checking

#### TECHNOLOGY

**Technology Description:** Automates symbolic analysis of discrete and continuous variables governing a system, along all the paths linking different states of a system.

**Technology Challenge:** Technology challenges include mapping models of physical systems to hybrid representations, performing sound abstractions automatically, and scaling core algorithms.

**Technology State of the Art:** A language for specifying hybrid systems and a tool that performs hybrid abstraction is capable of hybrid model checking of mass-spring-damper with software controller. Checking of simple transmission controller requires significant manual guidance.

**Technology Performance Goal:** Model checking of full description of vehicle or mission.

**Parameter, Value:**

Number of continuous variables: 15  
Differential Equations of physical system: 20.

**TRL**

1

**Parameter, Value:**

Number of continuous variables: 1,000  
Differential Equations of physical system: 10,000.

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

#### CAPABILITY

**Needed Capability:** Cyber-physical system formal verification.

**Capability Description:** Provides formal verification toolset for integrated models of physical (vehicle) systems and embedded software control.

**Capability State of the Art:** Pattern-based static analysis for software only.

**Capability Performance Goal:** Software defects per size of embedded software system.

**Parameter, Value:**

Defects per Million Source Lines of Code (MSLOC): 200

**Parameter, Value:**

Defects per Million Source Lines of Code (MSLOC): < 10

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years

11.2 Modeling  
11.2.1 Software Modeling and Model  
Checking

### 11.2.1.2 Automated Software Testing Environment

#### TECHNOLOGY

**Technology Description:** Provides automated generation of tests and corresponding coverage analysis for specified coverage criteria.

**Technology Challenge:** Technology challenges include maturing coverage criteria to enable meaningful testing, automating generation of tests, and evaluating results with respect to matured coverage criteria.

**Technology State of the Art:** Symbolic PathFinder software analysis tool combining symbolic execution with model checking for automated test case generation and error detection in Java bytecode programs.

**Parameter, Value:**

Test coverage for limited coverage criteria: 90%

TRL

4

**Technology Performance Goal:** Complete test coverage of embedded software systems.

**Parameter, Value:**

Test coverage of software for extended coverage criteria: 99.9%

TRL

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

#### CAPABILITY

**Needed Capability:** Automated software verification.

**Capability Description:** Enables automation of labor-intensive aspects of software testing, including test suite generation, test execution, and data mining of test results.

**Capability State of the Art:** Test conductor (similar to automation in crew vehicles under development at NASA).

**Parameter, Value:**

Test coverage of Level A software per human man-month of testing: 70%;

Test cost: > \$500M for 1 millions source lines of code (MSLOC).

**Capability Performance Goal:** Complete test coverage of embedded software systems.

**Parameter, Value:**

Percent coverage to specified coverage criteria: > 99.9%

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years

11.2 Modeling  
11.2.1 Software Modeling and Model  
Checking

### 11.2.1.3 Software Development Environment with Program Synthesis

#### TECHNOLOGY

**Technology Description:** Provides automated reasoning and knowledge representation for software generation in space applications.

**Technology Challenge:** Augmenting generation capabilities to ensure correctness by construction is a challenge.

**Technology State of the Art:** Current commercially-available automatic code generation does not guarantee semantic preservation.

**Technology Performance Goal:** Semantically-based correct-by-construction automated program generation automating expert knowledge.

**Parameter, Value:**

Cost of 1 million source lines of code (MSLOC) of generated code for spaceflight hardware: \$1B.

**TRL**

3

**Parameter, Value:**

Cost of 1 MSLOC of generated code for spaceflight hardware: \$100M.

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

#### CAPABILITY

**Needed Capability:** Automated software generation.

**Capability Description:** Enables a semi-automated software development environment, incorporating fail-safe architecture, requirements management, and automated program synthesis.

**Capability State of the Art:** Commercial sector modeling environments and visual development environment for using graphical models to generate software applications.

**Capability Performance Goal:** Semantically-based automated program generation automating expert knowledge.

**Parameter, Value:**

Cost of 1 MSLOC of generated code for spaceflight hardware: \$1B.

**Parameter, Value:**

Cost of 1 MSLOC of generated code for spaceflight hardware: \$100M.

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years



11.2 Modeling  
11.2.2 Integrated Hardware and  
Software Modeling

11.2.2.1 Hardware/Software (HW/SW) Interface Modeling  
Specification Language

### TECHNOLOGY

**Technology Description:** Provides a formal specification language to enable automatic generation of integrated hardware and software artifacts.

**Technology Challenge:** Use of different HW/SW interface representations in different engineering disciplines makes knowledge representation difficult. Ontology-aware system engineering tools must support a network of distributed HW/SW systems (cyberphysical systems).

**Technology State of the Art:** Commercial sector and open source frameworks for creation of applications based on resource description framework (RDF), an ontology editor and knowledge acquisition system, and ontology languages (such as ontology web language).

**Technology Performance Goal:** Able to specify almost all system design HW/SW interface artifacts with the specification language.

**Parameter, Value:**

Percent of HW/SW system interface artifacts specified by specification language: 10%.

**TRL**

2

**Parameter, Value:**

Percent of HW/SW system interface artifacts specified by specification language: 100%.

**TRL**

9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** HW/SW interface modeling specification language.

**Capability Description:** Create a formal specification language to enable automatic generation of integrated hardware and software artifacts.

**Capability State of the Art:** Current crew vehicle development uses flight software (FSW), commercial sector modeling environments, and visual development environments for graphical models to develop integrated hardware and software models; however, no formal modeling specification language was developed.

**Capability Performance Goal:** Able to specify almost all system design HW/SW interface artifacts with the specification language.

**Parameter, Value:**

Percent of HW/SW system interface artifacts specified by specification language: 10%.

**Parameter, Value:**

Percent of HW/SW system interface artifacts specified by specification language: 100%.

### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years
Solar Terrestrial Probes: Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)	Enhancing	--	2025	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	3 years
Transition to Low-Carbon Propulsion: Initial Introduction of Alternative Propulsion Systems	Enhancing	--	--	2035	9 years

11.2 Modeling  
11.2.2 Integrated Hardware and  
Software Modeling

11.2.2.2 Intelligent Hardware and Software Interface Reasoning  
Framework

### TECHNOLOGY

**Technology Description:** Provides automated tools to intelligently support human designers in producing integrated hardware/software (HW/SW) interface design models such as those for interface requirements, implementations; includes constraint checking, test plan generation, support of automated test execution, and reuse of standard library models of hardware and software interfaces.

**Technology Challenge:** Huge and diverse set of rules and scope/complexity of engineering design options are challenges.

**Technology State of the Art:** Semantic web services and an artificial intelligence project that attempts to assemble a comprehensive ontology and knowledge base of everyday common sense knowledge, with the goal of enabling artificial intelligence (AI) applications to perform human-like reasoning.

**Parameter, Value:**

Number of design or analysis cycles per system development phase: 2x

TRL

2

**Technology Performance Goal:** Able to improve integrated HW/SW modeling productivity by a factor of 5.

**Parameter, Value:**

Number of design or analysis cycles per system development phase: 5x

TRL

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Intelligent HW/SW interface reasoning framework.

**Capability Description:** Provides automated tools to intelligently support human designers in producing integrated HW/SW interface design models (such as, interface requirements, implementations); includes constraint checking, test plan generation, support of automated test execution, and reuse of standard library models of hardware and software interfaces.

**Capability State of the Art:** SOA reasoning system in support of space operations based on NASA-developed aerospace ontology interpreting textual input (including natural language) to extract and track information regarding safety related operation events.

**Parameter, Value:**

Number of design or analysis cycles per system development phase: 1x (baseline).

**Capability Performance Goal:** Able to improve integrated HW/SW modeling productivity by a factor of 5.

**Parameter, Value:**

Number of design or analysis cycles per system development phase: 5x.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years
Solar Terrestrial Probes: Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)	Enhancing	--	2025	2021	5 years
Solar Terrestrial Probes: Interstellar Mapping and Acceleration Probe (IMAP)	Enhancing	--	2022	2019	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	3 years
Transition to Low-Carbon Propulsion: Initial Introduction of Alternative Propulsion Systems	Enhancing	--	--	2035	9 years

11.2 Modeling  
11.2.2 Integrated Hardware and  
Software Modeling

### 11.2.2.3 Automated Design Specification Knowledge Capture System

#### TECHNOLOGY

**Technology Description:** Provides an automated design specification knowledge capture system to combine design knowledge from a multitude of space hardware and software systems into an integrated system representation.

**Technology Challenge:** Huge and diverse set of rules and scope/complexity of engineering design options are challenges.

**Technology State of the Art:** State of the art design tools capture less than 10% of the design artifacts.

**Parameter, Value:**

Percent of design artifacts generated from the knowledge capture system: 10%

TRL

2

**Technology Performance Goal:** Generate almost all design artifacts from the knowledge capture system.

**Parameter, Value:**

Percent of design artifacts generated from the knowledge capture system: 100%

TRL

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

#### CAPABILITY

**Needed Capability:** Automated design specification knowledge capture.

**Capability Description:** Provides an automated design specification knowledge capture system to combine design knowledge from a multitude of space hardware and software systems into an integrated system representation.

**Capability State of the Art:** Translation tool between computer-aided design (CAD) model to systems modeling language (SysML) model to support integrated hardware/software modeling analysis; NASA-developed SysML Plug-in for exploration.

**Parameter, Value:**

Percent of design artifacts generated from the knowledge capture system: no data available.

**Capability Performance Goal:** Generate almost all design artifacts from the knowledge capture system.

**Parameter, Value:**

Percent of design artifacts generated from the knowledge capture system: 100%

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years
Solar Terrestrial Probes: Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)	Enhancing	--	2025	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2017	3 years
Transition to Low-Carbon Propulsion: Initial Introduction of Alternative Propulsion Systems	Enhancing	--	--	2035	9 years



11.2 Modeling  
11.2.3 Human-System Performance  
Modeling

### 11.2.3.1 Integrated Human-Systems Models

#### TECHNOLOGY

**Technology Description:** Estimate human-system performance for concept, design, and operational validation and verification.

**Technology Challenge:** Increase the fidelity and validity of human-system model predictions without increasing the cost to develop the models. Extend models to domains beyond piloting.

**Technology State of the Art:** Models exist for analysis of human-system performance for certain piloting tasks, with limited performance parameters.

**Parameter, Value:**

Percentage of target mission models that include validated human-system performance models: 10-20%

**TRL**

3

**Technology Performance Goal:** Evaluation of designs for manufacturing, integration, maintenance, and operations, decreasing cost of redesign, collateral damage, and mission risk.

**Parameter, Value:**

Percentage of target mission models that include validated human-system performance models: 90%

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.2.3.2 Human Digital Twin; 11.2.3.3 Toolset for Automated Task Generation for Human-System Modeling (for efficient use); 11.3.5.2 Extreme-scale Software for Modeling and Simulation.

#### CAPABILITY

**Needed Capability:** Human-systems modeling to enable verification of mission design, operations, and mission planning.

**Capability Description:** Infuse human-performance/capability (medical, physical, sensory, perceptual, cognitive, team) models into all vehicle and habitat designs and associated operations concepts.

**Capability State of the Art:** Modeling prototypes exist for certain ground-based human-system interactions, at various levels of complexity for a limited number of tasks in 1-g.

**Parameter, Value:**

Percentage of target mission models that include validated human-system performance models: 10%

**Capability Performance Goal:** Increase human capabilities within system models; extend models (operations, maintenance; increase capability for aeronautics; extend to exploration).

**Parameter, Value:**

Percentage of target mission models that include validated human-system performance models: 90%

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Safe, Efficient Growth in Global Operations: Improved Efficiency and Hazard Reduction within NextGen Operational Domains	Enabling	--	--	2025	5 years
Enable Assured Machine Autonomy For Aviation: Human-machine Teaming in Key Applications	Enabling	--	--	2035	5 years

11.2 Modeling  
11.2.3 Human-System Performance  
Modeling

### 11.2.3.2 Human Digital Twin

#### TECHNOLOGY

**Technology Description:** Provides predictive models of human performance at multiple levels of complexity for individuals as well as groups, for a wide range of tasks, under a wide variety of mission-relevant shaping factors.

**Technology Challenge:** Integrating performance and health modeling in different performance domains (medical, physical, cognitive, social) into a validated multi-scale model for exploration environments and tasks is a challenge.

**Technology State of the Art:** Domain- and task-specific models in 1-g environment for simple performance parameters.

**Parameter, Value:**

Percentage of human performance domains with validated models for environments and mission tasks: 10%

**TRL**

3

**Technology Performance Goal:** Models with the complexity and fidelity to represent human agents in complex mission environments.

**Parameter, Value:**

Percentage of human performance domains with validated models for environments and mission tasks: 90%

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.2.3.3 Toolset for Automated Task Generation for Human-System Modeling (for efficient use); 11.3.5.2 Extreme-scale Software for Modeling and Simulation.

#### CAPABILITY

**Needed Capability:** Human performance modeling.

**Capability Description:** Enables multi-scale simulation of an individual/team that uses the best available medical, physical, cognitive, and team capability models to predict human task performance and health.

**Capability State of the Art:** Modeling prototypes exist for many human performance parameters for 1-g. Medical models exist at varying levels of fidelity and integration.

**Parameter, Value:**

Percentage of human performance domains with validated models for relevant natural and induced environments and mission tasks: 10%

**Capability Performance Goal:** The Human Digital Twin should be able to predict a bounded range of performance and behaviors when introduced into a simulated scenario.

**Parameter, Value:**

Percentage of human performance domains with validated models for relevant natural and induced environments and mission tasks: 90%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	7 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Strategic Missions: Mars 2020	Enabling	--	2020	2017	2 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	4 years
Safe, Efficient Growth in Global Operations: Improved Efficiency and Hazard Reduction within NextGen Operational Domains	Enabling	--	--	2025	5 years
Enable Assured Machine Autonomy For Aviation: Human-machine Teaming in Key Applications	Enabling	--	--	2035	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.2 Modeling  
11.2.3 Human-System Performance  
Modeling

### 11.2.3.3 Toolset for Automated Task Generation for Human-System Modeling

#### TECHNOLOGY

**Technology Description:** Provides ability to unobtrusively capture, measure, and analyze task performance to feed into human and human-system modeling technologies.

**Technology Challenge:** Integrating data capture and analysis methods, with generation of mission and task scenarios is a challenge.

**Technology State of the Art:** Motion capture technology exists that can drive a digital human in a modeling environment to perform exact physical actions. Taking individual actions and creating new tasks is time-consuming. Capture of other human actions (vision, cognitive, communication) is severely limited.

**Parameter, Value:**

Time to create validated task description model: 100 – 2,000 hours

**TRL**

2

**Technology Performance Goal:** Enhance the ability to mine the data from human-in-loop simulations and other observations of human performance tasks, to enable effective modeling of human performance in system-modeling tools; 4x reduction in time to create validated task description model.

**Parameter, Value:**

Time to create validated task description model: 25 – 500 hours

**TRL**

9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

#### CAPABILITY

**Needed Capability:** Task behavior generation.

**Capability Description:** Enables automated collection of real world activities at an appropriate level of fidelity to accurately and realistically represent the human, the tasks, and the environments of operation context.

**Capability State of the Art:** Human modeling and human-system modeling technology requires generation of normative models by experts to link human perceptual, motor, and cognitive acts to create detailed task descriptions.

**Parameter, Value:**

Time to create validated task description model: 100 – 2,000 hours.

**Capability Performance Goal:** Automated data capture and mining tools that create descriptions of human tasks from multi-media sources, task performance, task procedures, operational concepts, requirements, and other design documents.

**Parameter, Value:**

Time to create validated task description model: 25 – 500 hours.

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Safe, Efficient Growth in Global Operations: Improved Efficiency and Hazard Reduction within NextGen Operational Domains	Enhancing	--	--	2025	5 years
Real-Time System-Wide Safety Assurance: An Integrated Safety Assurance System Enabling Continuous System-Wide Safety Monitoring	Enhancing	--	--	2035	5 years
Enable Assured Machine Autonomy for Aviation: Human-machine Teaming in Key Applications	Enhancing	--	--	2035	5 years



11.2 Modeling  
11.2.4 Science Modeling

## 11.2.4.1 Fortran Compatible and Interoperable Parallel Libraries

## TECHNOLOGY

**Technology Description:** Enable the many legacy models to take advantage of newly available data and other models, and to improve their capabilities.

**Technology Challenge:** Sustain and constantly evolve parallel computational libraries and standards to become compatible with all types of scientific models, and state of the art (SOA) high performance computing (HPC) architectures. Improve the interoperability of FORTRAN codes with C and other languages.

**Technology State of the Art:** Partial implementation on hardware accelerators. Note: The emergence of graphical processing units (GPUs) and multi-integrated cores will make the current parallel libraries obsolete, at least for large applications. Existing partial interoperability of Fortran and C++ in an object-oriented environment.

**Technology Performance Goal:** All appropriate legacy science models able to run on all available and appropriate state of the art HPC systems.

**Parameter, Value:**

Percentage of appropriate legacy science models that run on state of the art HPC systems: 50%

TRL

4

**Parameter, Value:**

Percentage of appropriate legacy science models that run on state of the art HPC systems: 100%

TRL

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing

## CAPABILITY

**Needed Capability:** Sustaining and improving legacy science models.

**Capability Description:** Significantly increases the speed, takes advantage of newly available data and other models, and runs on state of the art HPC systems.

**Capability State of the Art:** Recent Fortran versions are supported at different levels. Current use of a suite of data structures and routines for the scalable (parallel) solution of scientific applications modeled by partial differential equations; partial interoperability of Fortran and C; distributed parallelism in F2008 (co-array Fortran) and an extension of the C programming language designed for high-performance computing on large-scale parallel machines.

**Capability Performance Goal:** All legacy science models are able to run on all available SOA HPC systems for various Fortran versions and with full interoperability with other languages, newly available data, and other models.

**Parameter, Value:**

Percentage of appropriate legacy science models that run on state of the art HPC systems: 50%

**Parameter, Value:**

Percentage of appropriate legacy science models that run on state of the art HPC systems: 100%

## Technology Needed for the Following NASA Mission Class and Design Reference Mission

Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Enhancing	--	2024*	2020	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.2 Modeling  
11.2.4 Science Modeling

11.2.4.2 High Performance Processor Toolset for Science Modeling

### TECHNOLOGY

**Technology Description:** Facilitates retrospective analyses, or reanalyses, that integrate a variety of observing systems with numerical models that run on high-performance computing (HPC) systems.

**Technology Challenge:** Data processing requirements for climate models can be considerable. The challenge is to provide programming tools with ease of use for all types of users.

**Technology State of the Art:** Retrospective analyses will eventually produce more than 150 terabytes (tera = trillion) of value-added earth science data. Integration of hardware accelerators with high performance computers. A commercial sector supercomputer has enabled other government agency applications to scale to 1.5 million cores and 14 petaFLOPS (PFLOPS) sustained.

**Technology Performance Goal:** Science models able to run on all available and appropriate state of the art (SOA) HPC systems; using a programming paradigm where users are not aware of the underlying hardware.

**Parameter, Value:**

Percentage of appropriate science models that run on state of the art HPC systems: 50%

**TRL**

4

**Parameter, Value:**

Percentage of appropriate science models that run on state of the art HPC systems: 100%

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing

### CAPABILITY

**Needed Capability:** Increased use of HPC for science modeling.

**Capability Description:** Enables high-fidelity numerical simulation, using a supercomputer by taking full advantage of new HPC technology, such as improved parallel input/output (I/O) and optimal trade-offs between memory, I/O and processor utilization, and enables climate models to ingest increasing amounts of observations that make these NASA models more accurate.

**Capability State of the Art:** Retrospective analyses ingests more than 50 billion observations over the Earth observing system satellite era. A comprehensive ocean modeling code integrates models from many disciplines, and it has achieved the largest computational scale of any science code within NASA, running at 35,000 cores. However, it takes a tremendous effort to get the code to run at this scale.

**Capability Performance Goal:** Science models are able to run on all available SOA HPC systems and take full advantage of SOA capabilities.

**Parameter, Value:**

Percentage of appropriate science models that run on state of the art HPC systems: 50%

**Parameter, Value:**

Percentage of appropriate science models that run on state of the art HPC systems: 100%

### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enhancing	--	2024*	2020	6 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.2 Modeling  
11.2.4 Science Modeling

## 11.2.4.3 Quality Metrics for Science Data

## TECHNOLOGY

**Technology Description:** Encode dataset variable characteristics and related quality to derive inter-comparison rules between datasets and ensure accurate and reliable scientific results.

**Technology Challenge:** Definition of relevant domain ontologies is a challenge.

**Technology State of the Art:** Portal providing interoperable access, tools, and contextual guidance to scientists and value-added organizations in using remotely sensed atmospheric composition data.

**Technology Performance Goal:** Develop semantic advisor describing data provenance and data quality to help researchers make valid data comparisons and draw quantitative conclusions on specific analysis.

**Parameter, Value:**

Percentage of extensible markup language (XML) encoded representations: 20%

TRL

4

**Parameter, Value:**

Percentage of XML encoded representations: 100%

TRL

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Data provenance.

**Capability Description:** Encodes and/or annotates data and information such that it can be understood later by other teams and applications.

**Capability State of the Art:** Entity state data, some meta-information of relevant simulation information.

**Capability Performance Goal:** All data annotated with all information needed to use and replicate products.

**Parameter, Value:**

Percentage of XML encoded representations: 20%

**Parameter, Value:**

Percentage of XML encoded representations: 100%

## Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enhancing	--	2024*	2020	6 years
Earth Systematic Missions: Geostationary Coastal and Air Pollution Events (GEO-CAPE)	Enhancing	--	2024*	2019	5 years
Earth Systematic Missions: Global Atmosphere Composition Mission (GACM)	Enhancing	--	2024*	2019	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.2 Modeling  
11.2.4 Science Modeling

11.2.4.4 Toolset for Concurrent Data Diagnostics and Acquisition  
for Science Modeling

### TECHNOLOGY

**Technology Description:** Optimizes the application of the models by identifying model uncertainties, relating them to data gaps, and visualizing intermediate results.

**Technology Challenge:** Being able to handle the complexity of the models is a challenge that requires tight integration of science domain knowledge.

**Technology State of the Art:** Technology for seamlessly integrating advanced multiscale modeling visualizations and supercomputing to inter-compare satellite observations and model simulations.

**Parameter, Value:**

Percentage of models being interactive: 5%

TRL

5

**Technology Performance Goal:** Seamless acquisition and integration of new data while running models.

**Parameter, Value:**

Percentage of models being interactive: 100%

TRL

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing, 11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods.

### CAPABILITY

**Needed Capability:** Interactive models.

**Capability Description:** Integrate knowledge and information from new data and modeling results in a seamless and real-time fashion.

**Capability State of the Art:** None operational.

**Parameter, Value:**

Percentage of models being interactive: 0%

**Capability Performance Goal:** All models have the ability to ingest new data, to show intermediate results, and to modify internal variables in real-time.

**Parameter, Value:**

Percentage of models being interactive: 100%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enhancing	--	2024*	2020	6 years
Earth Systematic Missions: Precision and All-Weather Temperature and Humidity (PATH)	Enhancing	--	2024*	2019	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.2 Modeling  
11.2.4 Science Modeling

## 11.2.4.5 Software Infrastructure for Sensor Webs

## TECHNOLOGY

**Technology Description:** Enables data and information acquisition, fusion, and integration in an interoperable fashion, for real-time data utilization and societal benefits

**Technology Challenge:** Interoperability, standards, and data accessibility are challenges.

**Technology State of the Art:** Technologies that connect prediction and forecasting disaster models to the sensor web, allowing daily coverage of specifically-targeted areas.

**Parameter, Value:**

Temporal resolution: daily

Spatial resolution: 30 m

## TRL

5

**Technology Performance Goal:** Daily or hourly complementary and coordinated full coverage at a few meters resolution, via routine integration of sensor web technologies for discovering, acquiring, analyzing, and integrating multi-source data and data products.

**Parameter, Value:**

Temporal resolution: hourly

Spatial resolution: 3 m

## TRL

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2.1 Exascale Supercomputer, 11.1.2.3 Exascale Supercomputing File System, 11.1.2.7 High Performance Data Analytics Platform, 11.4.2 Intelligent Data Understanding.

## CAPABILITY

**Needed Capability:** Sensor webs and virtual observatories for real-time data utilization and societal benefits.

**Capability Description:** Develop complex data environments allowing real-time ingestion of space sciences data from a variety of NASA missions and providing tools for scientists to access and analyze the data, and enable the evolution of distributed sensors and components into autonomous, unified networks (webs) of sensors.

**Capability State of the Art:** Earth Observing 1 (EO-1) experiments for disaster management, such as, floods and earthquakes.

**Parameter, Value:**

Temporal resolution: 8 days

Spatial resolution: 30 m

**Capability Performance Goal:** Daily or hourly complementary and coordinated full coverage at a few meters resolution.

**Parameter, Value:**

Temporal resolution: hourly

Spatial resolution: 3 m

## Technology Needed for the Following NASA Mission Class and Design Reference Mission

Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Enhancing	--	2024*	2019	5 years
Enhancing	--	2024*	2019	5 years
Enhancing	--	2030*	2025	10 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.2 Modeling  
11.2.5 Frameworks, Languages,  
Tools, and Standards

### 11.2.5.1 Library of Reusable NASA-Related System Models

#### TECHNOLOGY

**Technology Description:** Enables sharing across NASA centers and supports all NASA exploration mission products and process production.

**Technology Challenge:** Complexity of building up a reusable library that can be easily shared among different diverse sets of NASA missions.

**Technology State of the Art:** Example: NASA analog missions during FY 2011 and FY 2012 system modeling language (SysML) using plugin software input files production exploration augmentation module designs.

**Parameter, Value:**

Number of designs or analysis cycles per system development phase: 2x  
Systems design and development time per development phase: 2x.

**TRL**

2

**Technology Performance Goal:** Increase the number of design and analysis cycles per system development phase while decreasing overall design and development time.

**Parameter, Value:**

Number of design or analysis cycles per system development phase: 5x Decrease systems design and development time per development phase: 4x.

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.2.1 Software Modeling and Model Checking

#### CAPABILITY

**Needed Capability:** Library of reusable system models.

**Capability Description:** Create a library of SysML and unified modeling language (UML) models that is under flexible configuration management control and is shared across all NASA centers and supports all NASA exploration mission products and process production.

**Capability State of the Art:** NASA crew vehicle software design using UML; Constellation training facility Rhapsody system.

**Parameter, Value:**

Number of designs or analysis cycles per system development phase: no data available  
Systems design and development time per development phase: no data available

**Capability Performance Goal:** Increase the number of design and analysis cycles per system development phase while decreasing overall design and development time.

**Parameter, Value:**

Increase in number of design or analysis cycles per system development phase: 5x  
Decrease systems design and development time per development phase: 4x.

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years
Solar Terrestrial Probes: Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)	Enhancing	--	2025	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	3 years
Transition to Low-Carbon Propulsion: Initial Introduction of Alternative Propulsion Systems	Enhancing	--	--	2035	9 years



11.2 Modeling  
11.2.5 Frameworks, Languages,  
Tools, and Standards

## 11.2.5.2 Profiles for Spacecraft, Space Robotics, and Space Habitats

### TECHNOLOGY

**Technology Description:** Creates NASA system profiles to support system engineers and can support auto generation of design artifacts and guide downstream engineering work.

**Technology Challenge:** Developing and formalizing a diverse set of NASA missions and domains into a small set of reusable profiles that are inter-related and shared among all NASA centers is a challenge.

**Technology State of the Art:** Example: Architecture analysis and design language; unified modeling language (UML) profile for schedulability performance and time; UML profile for other agency architecture frameworks.

**Parameter, Value:**

Number of designs or analysis cycles per system development phase: 2x Systems design and development time per development phase: 2x.

TRL

2

**Technology Performance Goal:** Increase the number of design and analysis cycles per system development phase while decreasing overall design and development time.

**Parameter, Value:**

Increase in number of design or analysis cycles per system development phase: 5x  
Decrease systems design and development time per development phase: 4x.

TRL

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Profiles for spacecraft, space robotics, and space habitats.

**Capability Description:** Create NASA space system profiles to systems engineers for designing future space systems.

**Capability State of the Art:** No profiles for spacecraft, space robotics, and space habitats use in relevant environment.

**Parameter, Value:**

Number of designs or analysis cycles per system development phase: no data available  
Systems design and development time per development phase: no data available.

**Capability Performance Goal:** Increase the number of design and analysis cycles per system development phase while decreasing overall design and development time.

**Parameter, Value:**

Increase in number of design or analysis cycles per system development phase: 5X  
Decrease systems design and development time per development phase: 4X.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years
Solar Terrestrial Probes: Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)	Enhancing	--	2025	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2017	3 years
Transition to Low-Carbon Propulsion: Initial Introduction of Alternative Propulsion Systems	Enhancing	--	--	2035	9 years

11.2 Modeling  
11.2.5 Frameworks, Languages,  
Tools, and Standards

### 11.2.5.3 Robust Mission Requirements Modeling

#### TECHNOLOGY

**Technology Description:** Provides a comprehensive set of aerospace and NASA specific requirement and process models that can be shared with all NASA mission programs and projects. These models are linked and traced to all development artifacts. Also, these requirement models can be tailored to fit the needs for specific missions context.

**Technology Challenge:** Modeling requirements to maximize traceability and interchange among system development tools, and to link project requirements to operational products of a project is a challenge.

**Technology State of the Art:** Example: Project to evaluate technology such as NASA crew vehicle avionics subsystem modeling of core design reference mission (DRM).

**Parameter, Value:**

Number of designs or analysis cycles per system development phase: 2x Systems design and development time per development phase: 2x.

**TRL**

3

**Technology Performance Goal:** Increase the number of design and analysis cycles per system development phase while decreasing overall design and development time.

**Parameter, Value:**

Increase in number of design or analysis cycles per system development phase: 5x  
Decrease systems design and development time per development phase: 4x.

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

#### CAPABILITY

**Needed Capability:** Requirements modeling.

**Capability Description:** Enable sharing, tracing, and linking of the requirement models to the system artifacts. Also, these requirement models can be tailored to fit the needs for a specific mission's context.

**Capability State of the Art:** NASA crew vehicle avionics subsystem modeling of core mission DRM; exploration augmentation module system requirements and functional modeling.

**Parameter, Value:**

Number of designs or analysis cycles per system development phase: no data available  
Systems design and development time per development phase: no data available.

**Capability Performance Goal:** Increase the number of design and analysis cycles per system development phase while decreasing overall design and development time.

**Parameter, Value:**

Increase in number of design or analysis cycles per system development phase: 5x  
Decrease systems design and development time per development phase: 4x.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years
Solar Terrestrial Probes: Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)	Enhancing	--	2025	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	3 years
Transition to Low-Carbon Propulsion: Initial Introduction of Alternative Propulsion Systems	Enhancing	--	--	2035	9 years

11.2 Modeling  
11.2.5 Frameworks, Languages,  
Tools, and Standards

### 11.2.5.4 Executable Models

#### TECHNOLOGY

**Technology Description:** Define the execution semantics and a complete library of executable models that have precise and unambiguous semantics, shared across NASA centers, and support all NASA exploration mission products and process production.

**Technology Challenge:** Complexity of the building up a reusable library of executable models that can be easily shared among a diverse set of NASA missions.

**Technology State of the Art:** Example: executable models for generating flight software (FSW) using commercial modeling systems, guidance navigation and control, and FSW from proprietary source code to C++ for various NASA programs. The executable models are mostly created at the individual system and subsystems levels.

**Technology Performance Goal:** Increase the number of the auto-coded executables from the models.

**Parameter, Value:**

Percent of auto coded executables from the models:  
5%

**TRL**

3

**Parameter, Value:**

Increase number of the auto coded executables from  
models: 95%

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

#### CAPABILITY

**Needed Capability:** Executable models and model components that define their own execution semantics and support translation to multiple computer architectures to enhance and manage software complexity.

**Capability Description:** Define the execution semantics of the relevant elements of the models.

**Capability State of the Art:** Auto code generation from proprietary source code to C++ code for various NASA programs.

**Capability Performance Goal:** Increase number of the auto coded executables from models.

**Parameter, Value:**

Percent of auto coded executables from the models: 5%

**Parameter, Value:**

Increase number of the auto coded executables from the models: 95%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years
Solar Terrestrial Probes: Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)	Enhancing	--	2025	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2017	3 years
Transition to Low-Carbon Propulsion: Initial Introduction of Alternative Propulsion Systems	Enhancing	--	--	2035	9 years



11.2 Modeling  
11.2.6 Analysis Tools for Mission Design

### 11.2.6.1 Science Performance Evaluation Toolset for Distributed Missions

#### TECHNOLOGY

**Technology Description:** Performs trade space analysis as a function of the multiple variables that define distributed missions. A distributed spacecraft mission (DSM) is defined here as a mission that involves multiple spacecraft to achieve one or more common goals.

**Technology Challenge:** Integrating multiple mission aspects and multiple science domains, as well as tying mission design to cost and risk factors is a challenge. This technology will optimize NASA's mission portfolio while maximizing science return.

**Technology State of the Art:** Ad-hoc tools based on commercial-off-the-shelf (COTS) systems.

**Technology Performance Goal:** General access open source tools with user-friendly interface that are able to trade mission designs based on multiple variables.

**Parameter, Value:**

Number of variables traded simultaneously: 2 or 3

TRL

4

**Parameter, Value:**

Number of variables traded simultaneously: 10

TRL

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.3.3 Simulation-Based Systems Engineering

#### CAPABILITY

**Needed Capability:** Science constellation design tools.

**Capability Description:** Optimize the design of DSMs based on design variables and on science objectives determining performance and cost.

**Capability State of the Art:** This capability current has no SOA.

**Capability Performance Goal:** Being able to trade mission design based on multiple variables (number of satellites, number and types of orbits, altitudes, fields of view (FOVs), spatial and temporal coverage, etc.) simultaneously.

**Parameter, Value:**

Number of variables traded simultaneously: Not available

**Parameter, Value:**

Number of variables traded simultaneously: 10 or more

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years
Living with a Star: Geospace Dynamics Constellation (GDC)	Enhancing	--	2030	2019	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.2 Modeling  
11.2.6 Analysis Tools for Mission Design

### 11.2.6.2 Toolset for Cost Analysis of Complex Missions

#### TECHNOLOGY

**Technology Description:** Generalizes and extends current models; develops new models to accurately estimate the cost of complex missions and mission campaigns, including, but not limited to constellations of nanosats, CubeSats, and minisats, taking into account learning curve parameters.

**Technology Challenge:** Fidelity of the models: there is currently no past data to rely on. This capability will enable NASA to optimize mission portfolios while maximizing return on investment.

**Technology State of the Art:** Small satellite cost model for 20 to 1,000 kilograms. Picosatellite cost model for 1 to 15 kilograms, as well as other government agency models for 20 to 500 kilograms.

**Parameter, Value:**

Number of variables traded simultaneously: 2 or 3

TRL

4

**Technology Performance Goal:** General and sustainable cost models that are able to trade constellation mission designs based on multiple variables.

**Parameter, Value:**

Number of variables traded simultaneously: 10

TRL

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.3.3 Simulation-Based Systems Engineering

#### CAPABILITY

**Needed Capability:** Complex mission and mission campaign design.

**Capability Description:** Optimizes the design of distributed spacecraft missions (DSMs) based on design variables and on science objectives determining performance and cost.

**Capability State of the Art:** There is no standard cost-to-copy database or learning curve model established for multiple satellites. NASA prescribes an 85% learning curve.

**Parameter, Value:**

Number of variables traded simultaneously: not available.

**Capability Performance Goal:** Being able to trade mission design based on multiple variables simultaneously while minimizing cost and risk.

**Parameter, Value:**

Number of variables traded simultaneously: 10 or more.

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years
Living with a Star: Geospace Dynamics Constellation (GDC)	Enabling	--	2030	2019	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.2 Modeling  
11.2.6 Analysis Tools for Mission Design

### 11.2.6.3 Toolset for Cost Risk Analysis of Complex Missions

#### TECHNOLOGY

**Technology Description:** Develops new analysis models to accurately estimate the risk of complex missions.

**Technology Challenge:** Little data availability, feedback credibility, limitations on risk quantification, and unavailability of methods for large cost growth. Unmitigated technical risk was identified as the biggest factor in cost overruns, such as risks attributed to inadequate systems engineering, aggressive adoption of commercial standards for military applications, lack of process controls or domain knowledge, and reduction in acquisition workforce due to budget cuts. This capability will enable NASA to optimize mission portfolios while maximizing the return on investment.

**Technology State of the Art:** Quantitative cost risk methods include deterministic (such as historical analogies and cost growth factors) and probabilistic (such as error propagation, methods of moments, and Monte Carlo simulation) methods.

**Technology Performance Goal:** General and sustainable risk models that are able to trade mission designs based on multiple variables.

**Parameter, Value:**

Number of mission design variables traded simultaneously: 2 or 3

TRL

3

**Parameter, Value:**

Number of mission design variables traded simultaneously: 10

TRL

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.3.3 Simulation-Based Systems Engineering

#### CAPABILITY

**Needed Capability:** Complex mission design.

**Capability Description:** Optimizes the design of distributed spacecraft missions (DSMs) based on design variables and science objectives determining performance and cost.

**Capability State of the Art:** Use of multiple independent experts, providing at a minimum upper, lower, and most-likely values for cost elements under consideration, fitting a triangle distribution to these three numbers and using the upper and lower values to bound the risk probability.

**Capability Performance Goal:** Being able to trade mission design based on multiple variables simultaneously, while minimizing cost and risk.

**Parameter, Value:**

Number of mission design variables traded simultaneously: not available.

**Parameter, Value:**

Number of mission design variables traded simultaneously: 10 or more.

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years
Living with a Star: Geospace Dynamics Constellation (GDC)	Enhancing	--	2030	2019	5 years



11.2 Modeling  
11.2.6 Analysis Tools for Mission Design

### 11.2.6.4 Observing System Simulation Experiments (OSSE) Framework and Component Library

#### TECHNOLOGY

**Technology Description:** Develops the OSSE workflow environment and capabilities by integrating OSSEs with the middleware and software libraries, and multi-disciplinary model integration.

**Technology Challenge:** Defining interoperability needs and standards is a challenge. This technology will enable NASA to optimize mission portfolios while maximizing science return.

**Technology State of the Art:** Very few reusable components are currently available. A few were developed for individual projects, such as land information system (LIS) OSSEs.

**Parameter, Value:**

Decrease in model uncertainty: 2x

**TRL**

2

**Technology Performance Goal:** Develop testbed or simulation capabilities that can be re-used, such as low-cost simulations, testbeds, and data storage/networking capabilities, as well as standards and formats for data and datasets exchanges.

**Parameter, Value:**

Decrease in model uncertainty: 5x

**TRL**

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.3.3 Simulation-Based Systems Engineering, 11.4.5 Advanced Mission Systems

#### CAPABILITY

**Needed Capability:** Observing system simulation experiments.

**Capability Description:** Quantitatively assess the impact of proposed scientific observations using a computational system.

**Capability State of the Art:** Independent OSSEs are being developed on a case-by-case basis.

**Parameter, Value:**

Decrease in model uncertainty: 2x

**Capability Performance Goal:** Decrease model uncertainty using mission simulation and evaluation framework.

**Parameter, Value:**

Decrease in model uncertainty: 5x

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Global Atmosphere Composition Mission (GACM)	Enhancing	--	2024*	2019	5 years
Solar Wind Measurements	Enhancing	--	On-going*	--	7 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

### 11.3 Simulation

#### 11.3.1 Distributed Simulation

### 11.3.1.1 Immersive Environments for Distributed Simulation of NASA Systems

#### TECHNOLOGY

**Technology Description:** Enables real-time collaborative interaction between space system simulations located at different centers or even agencies to analyze mission architectures.

**Technology Challenge:** Managing standard and model exchange; managing time sync, latency issues, performance, and verification; and controlling the performance of resource distribution are challenges.

**Technology State of the Art:** Distributed space exploration simulation (DSES) project.

**Parameter, Value:**

Percentage of target real world environment simulated: 10% of target

Scenario duration: 1 hour.

**TRL**

4

**Technology Performance Goal:** Fidelity of simulation to target systems is near 100%.

**Parameter, Value:**

Percentage of target real world environment simulated: 100%

Scenario duration: 3 hours.

**TRL**

9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.4.8 Cyber Security

#### CAPABILITY

**Needed Capability:** Large-scale, shared, and secure, immersive environments.

**Capability Description:** Enable collaborative interaction between space system simulations located at different centers or even agencies to analyze mission architectures.

**Capability State of the Art:** Distributed interactive simulation (DIS) experiment of rendezvous docking scenario between the ISS and an international transfer vehicle.

**Parameter, Value:**

Percentage of target real world environment simulated: 10% of target

Scenario duration: 1 hour.

**Capability Performance Goal:** Fidelity of simulation to target systems is near to 100%.

**Parameter, Value:**

Percentage of target real world environment simulated: 100% of target

Scenario duration: 3 hours.

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	4 years
Innovation in Commercial Supersonic Aircraft: Supersonic Overland Certification Standard Based on Acceptable Sonic Boom Noise	Enhancing	--	--	2025	5 years

11.3 Simulation  
11.3.1 Distributed Simulation

### 11.3.1.2 High-Speed Computer Networks

#### TECHNOLOGY

**Technology Description:** Enable advances in network technology specifically to support distributed simulation for moving, sharing, and allowing secure interaction with large data sets.

**Technology Challenge:** Increase bandwidth and intelligent data exchange to maximize overall distributed system performance.

**Technology State of the Art:** Distributed space exploration simulation (DSES) project.

**Parameter, Value:**

Percentage of target real world environment simulated:  
10% of target

Scenario duration: 1 hour.

TRL

4

**Technology Performance Goal:** Fidelity of simulation to target systems is near 100%.

**Parameter, Value:**

Percentage of target real world environment simulated:  
100%

Scenario duration: 3 hours.

TRL

9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.4.8 Cyber Security

#### CAPABILITY

**Needed Capability:** High-speed computer networks.

**Capability Description:** Create high-speed computer networks to move, share, and allow secure interaction with large data sets.

**Capability State of the Art:** Distributed interactive simulation (DIS) experiment of rendezvous docking scenario between the International Space Station (ISS) and an international transfer vehicle.

**Parameter, Value:**

Percentage of target real world environment simulated: 10%  
Scenario duration: 1 hour.

**Capability Performance Goal:** Fidelity of simulation to target systems is near to 100%.

**Parameter, Value:**

Percentage of target real world environment simulated: 100%  
Scenario duration: 3 hours.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2017	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	4 years
Innovation in Commercial Supersonic Aircraft: Supersonic Overland Certification Standard Based on Acceptable Sonic Boom Noise	Enhancing	--	--	2025	5 years



11.3 Simulation  
11.3.1 Distributed Simulation

11.3.1.3 Standardized NASA Simulation Interoperability Infrastructure

## TECHNOLOGY

**Technology Description:** Facilitate the development of large-scale distributed simulations and support the large-scale integration of multi-disciplinary simulation elements for integrated systems analysis and design.

**Technology Challenge:** There are existing technologies that can be applied to solving challenges of security and across-the-wire compatibility. The difficulty is in determining and deploying a consensus standard across the Agency.

**Technology State of the Art:** Interoperability systems that provide better support for object-oriented data representations and across-the-wire transport protocol standards. They also provide better configurability, security, and reliability.

**Parameter, Value:**

Level of compliance with IEEE 11516: 20%

**TRL**

6

**Technology Performance Goal:** Full compliance and implementation of the Interoperability Infrastructure based on the IEEE 11516 standard.

**Parameter, Value:**

Level of compliance with IEEE 11516: 100%

**TRL**

9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.4.8 Cyber Security

## CAPABILITY

**Needed Capability:** Standardized space simulation interoperability infrastructure.

**Capability Description:** Facilitate the development of large-scale distributed simulations and support the large-scale integration of multi-disciplinary simulation elements for integrated systems analysis and design.

**Capability State of the Art:** The IEEE1516-2010, high-level architecture (HLA) evolved standard for simulation interoperability is in active use in industrial, academic, and government application. NASA and another government agency are using HLA in supporting space and air systems related modeling and simulation activities.

**Parameter, Value:**

Level of compliance with IEEE 11516: 20%

**Capability Performance Goal:** Full compliance and implementation of the interoperability infrastructure based on the IEEE 11516 standard.

**Parameter, Value:**

Level of compliance with IEEE 11516: 100%

## Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	4 years

11.3 Simulation  
11.3.1 Distributed Simulation

### 11.3.1.4 Standardized NASA Simulation Data Exchange Standard

#### TECHNOLOGY

**Technology Description:** Provides a data exchange standard that supports air- and space-based simulation and defines the principal state representations, reference frames, units, etc. required for meaningful interoperability between distributed simulation elements.

**Technology Challenge:** An extensive common set of coordinate systems needs to be adopted; data exchange protocols, units, and representations need to be defined. Significant information storage, retrieval, and exchange infrastructure needs to be developed, deployed, and maintained.

**Technology State of the Art:** NASA-sponsored standard for data representations and data exchange. Provides definition of reference frames, units, data representations, naming standards, and data exchange standards.

**Parameter, Value:**

Completeness of the data exchange standard: 20%

**TRL**

6

**Technology Performance Goal:** Full compliance and implementation of the data exchange standards for NASA distributed simulation systems.

**Parameter, Value:**

Completeness of the data exchange standard: 100%

**TRL**

9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.2.5 Frameworks, Languages, Tools and Standards

#### CAPABILITY

**Needed Capability:** Space simulation data exchange standard.

**Capability Description:** Provides a data exchange standard that supports air- and space-based simulation and defines the principal state representations, reference frames, units, etc. required for meaningful interoperability between distributed simulation elements.

**Capability State of the Art:** There are numerous data exchange standards and defacto standards used at various levels for data exchange between technical aeronautics and space simulations. These include comma separated values, extensible markup language (XML), heirarchical data format, Proto Buffers, figure of merit modules etc. Unfortunately, the data representations and content of these vary significantly.

**Parameter, Value:**

Completeness of the data exchange standard: 20%

**Capability Performance Goal:** Full compliance and implementation of the data exchange standards for NASA distributed simulation systems.

**Parameter, Value:**

Completeness of the data exchange standard: 100%

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2017	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	4 years
Innovation in Commercial Supersonic Aircraft: Supersonic Overland Certification Standard Based on Acceptable Sonic Boom Noise	Enhancing	--	--	2025	5 years

### 11.3 Simulation

#### 11.3.1 Distributed Simulation

### 11.3.1.5 Cross-Domain Simulation Toolset and Integration Framework

#### TECHNOLOGY

**Technology Description:** Creates a coordinated and managed collection of models, simulations, and applications for aircraft and spacecraft modeling. This will include models of the principal domain-specific elements that compose a complex aircraft or spacecraft system.

**Technology Challenge:** An extensive common set of coordinate systems need to be adopted, and data exchange protocols, units, and representations need to be defined. Significant information storage, retrieval, and exchange infrastructure needs to be developed, deployed, and maintained.

**Technology State of the Art:** Advanced data exchange standards will provide standards for coordinate frames, data transport unit standards, system identification nomenclature, data representations, etc. This will enable the reliable exchange of data between projects and specifically between simulation disciplines and components.

**Parameter, Value:**

Percent of cross-domain simulations built using the integrated framework: 5%

**TRL**

6

**Technology Performance Goal:** Almost all of NASA's cross-domain simulation using the integrated framework.

**Parameter, Value:**

Percent of cross-domain simulations built using the integrated framework: 95%

**TRL**

9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.2.5 Frameworks, Languages, Tools and Standards

#### CAPABILITY

**Needed Capability:** Cross-domain simulation toolset and integration framework.

**Capability Description:** Create a coordinated and managed collection of models, simulations, and applications for aircraft and spacecraft modeling. This will include models of the principal domain specific elements that compose a complex aircraft or spacecraft system.

**Capability State of the Art:** Numerous domain specific tool sets and simulation frameworks exist. However, there are few cross-domain integrated frameworks. Most of these are closed and proprietary systems. A few coordinating frameworks exist but lack coordinated and integrated tool and model sets. There are also some developing integrated frameworks and model sets.

**Parameter, Value:**

Percent of cross-domain simulations built using the integrated framework: 5%

**Capability Performance Goal:** Almost all of NASA's cross-domain simulation using the integrated framework.

**Parameter, Value:**

Percent of cross-domain simulations built using the integrated framework: 95%

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	4 years
Innovation in Commercial Supersonic Aircraft: Supersonic Overland Certification Standard Based on Acceptable Sonic Boom Noise	Enhancing	--	--	2025	5 years



11.3 Simulation  
11.3.2 Integrated System Lifecycle  
Simulation

### 11.3.2.1 Model and Simulation Interface Specifications

#### TECHNOLOGY

**Technology Description:** Provide capability to stakeholders in lifecycle simulation to ensure accurate and efficient collaboration of analysis objects across a distributed simulation. Systems modeling language (SysML) descriptors of federate behavior and implementing high-level architecture (HLA) code will be created.

**Technology Challenge:** Broadly-applicable model and simulation interfaces require government support, which cuts across an userbase in industry, academia, government, and international participants to build distributed lifecycle engineering analyses. The primary challenge is to ensure proper participation in all technologies of NASA interest for live, virtual, and constructive simulations. In this manner, simulation object behavior can be used effectively by all interested simulation participants. Though defined for operational aspects of some systems, pre-operational lifecycle phase (development) interfaces and NASA-specific technology needs in this area are not yet defined.

**Technology State of the Art:** Examples include: flight dynamics where an industry consensus standard based on the commercial extensible markup language (XML) schema, or industry plug-and-play architecture. NASA requires similar efforts to enable easy collaboration on systems development projects across its enterprise and for the full lifecycle of a product.

**Technology Performance Goal:** Create an evolving, composable NASA simulation capability through modeling and simulation interface specifications in all technologies and disciplines of interest. Permit and encourage all participants to interact equally with NASA simulations. Definition of object data and functional interface specifications is required. A generic, non-code-specific approach also enforces the goal that utilization of a single simulation framework standard is not required.

**Parameter, Value:**

Percent of NASA disciplines and programs with well-defined model schemas: 10%.

**TRL**

6

**Parameter, Value:**

Percent of NASA disciplines and programs with well-defined model schemas: 90%.

**TRL**

9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.3.3 Simulation-Based Systems Engineering

#### CAPABILITY

**Needed Capability:** Modeling and simulation interface specifications, in the form of technology products useful in a model-based systems engineering (MBSE) environment, must be available for collaborative efforts between NASA and all of its potential work and outreach stakeholders. SysML MBSE requirements shall flow in a tightly integrated manner into system and subsystem model functional requirements.

**Capability Description:** A current typical interface product structure is an XML schema for each subject discipline and systems analysis area of interest. NASA must create an evolving, composable simulation capability and permit all players to interact equally with its simulations. Arriving at consensus decisions on schema representations and maintaining those representations in an evolving technology base will be an ongoing task.

**Capability State of the Art:** Used in flight simulator work, system architecture studies, and to design products, but is primarily in a research mode for this capability.

**Capability Performance Goal:** As well as traditional flight simulator model development, these new model definitions will be used by NASA acquisition programs and internal development programs to understand product behavior throughout a products full lifecycle. This work enables development of composable, extensible objects suitable for efficient integration into NASA federated simulations.

**Parameter, Value:**

Percent of NASA disciplines and programs with well-defined model behaviors: 10%

**Parameter, Value:**

Percent of NASA disciplines and programs with well-defined model behaviors: 90%

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – crewed in DRO	Enhancing	2022	2022	2015-2021	2 years
Explorer Class: Explorer missions	Enhancing	--	2023	2020	6 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	8 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	8 years

### 11.3 Simulation

#### 11.3.2 Integrated System Lifecycle Simulation

#### 11.3.2.2 Federated Simulations

##### TECHNOLOGY

**Technology Description:** Quantify product behavior throughout the system lifecycle and to predict operational behavior. Federated simulations enable an enterprise to allow all geographically diverse and computationally non-heterogeneous participants to supply federate models to an enterprise simulation execution.

**Technology Challenge:** Supporting a basic level of federated simulations for near-term product development and operations of existing system architectures is required as an underlying feature of an agency's simulation capability. For organizations that have not used a federated simulation approach, this is an internal technology development. To maintain model implementing frameworks that are current with the state of the art (SOA) in high-speed computing and meet the growing needs of multiscale, multidisciplinary, simulation-based engineering and science requires strong coordination between physics modelers, computational specialists, and MBSE-guided programmatic oversight.

**Technology State of the Art:** Such frameworks as formal discrete event simulation IEEE-1516 HLA, distributed interactive simulation (DIS), and test and training enabling architecture; or computer framework codes like commercial industry's adaptive modeling language.

**Parameter, Value:**

% of NASA programs/projects implementing federation architectures: 10%

**TRL**

6

**Technology Performance Goal:** To extend federated simulation capability from an operations-centric user base to product developers and the full lifecycle of system characterization. To incorporate evolving design tools and techniques such as high-performance computing and Big Data type capabilities as simulations evolve as well.

**Parameter, Value:**

% of NASA programs/projects implementing federation architectures: 50%

**TRL**

9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.4.1 Science, Engineering and Mission Data Lifecycle

##### CAPABILITY

**Needed Capability:** NASA needs to provide a formal implementation of enterprise-level federated simulations for modeling and simulation technology to support lifecycle simulation. The organization's capability in operational federated simulations shall be extended formally into its product development system lifecycle. Simulation-based engineering and science will be integrated into this execution environment. Implementation of different systems will be at the center levels and an integrating tracking and control for cross-center collaboration will be needed at a central point. This baseline system, exposed to the general NASA engineering community, is then available for collaborative reuse and efficient recomposition to support new program analysis requests.

**Capability Description:** The extension of formal discrete event simulation techniques to product development will be accomplished by first implementing the existing SOA. Evolving these simulation capabilities to perform analysis functions of the product development and system analysis disciplines utilizing a hierarchy of fidelity levels will follow. By working with common computational interfaces in design, systems analysis, and operations provides efficient sharing of data between these various aspects of engineering in general.

**Capability State of the Art:** High-level architecture (HLA) used in NASA exploration program, model center used in air systems analysis, adaptive modeling language used for space/launch vehicle concept development, and commercial-off-the-shelf (COTS) software used for exploration architecture studies.

**Parameter, Value:**

% of NASA programs and projects implementing federated architecture collaborations: 10%

**Capability Performance Goal:** NASA distributed collaborative heterogeneous simulations are available to support multi-program, center, industry, academic, and public participating agents in source-proprietary controlled execution environments.

**Parameter, Value:**

% of NASA programs and projects implementing federated architectures: 50%

##### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – crewed in DRO	Enhancing	2022	2022	2015-2021	2 years
Explorer Class: Explorer missions	Enhancing	--	2023	2020	6 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	8 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	8 years

11.3 Simulation  
11.3.2 Integrated System Lifecycle  
Simulation

### 11.3.2.3 Enterprise-Level Modeling and Simulation Repositories

#### TECHNOLOGY

**Technology Description:** Develop enterprise-level technologies for the sharing of model federates and simulation federations across all NASA interested parties.

**Technology Challenge:** A model and simulation repository must be in place that is sufficiently characterized in usage and content such that it is not an arduous task for the user to utilize. Computational and collaborative technologies to share the information must be sufficient to efficiently handle large organizational needs and maintain data configuration control.

**Technology State of the Art:** Enterprise negotiated center-based product data management/product lifecycle management (PDM/PLM) systems. Weak programmatic control of collaboration space and insufficient resources for implementation frustrates users and system developers.

**Technology Performance Goal:** Achieve organizational user satisfaction with the performance of repository systems from functionality and efficiency viewpoints. Incorporate model-based systems engineering (MBSE) technology to define characterizations that better describe model and simulation functionalities to potential users. Requires creation of supporting systems modeling language (SysML) code, example coded implementations of models, and distributed database access routines.

**Parameter, Value:**

User acceptance of repository functionality: 30%

**TRL**

9

**Parameter, Value:**

User acceptance of repository functionality: 90%

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.4.1 Science, Engineering and Mission Data Lifecycle

#### CAPABILITY

**Needed Capability:** A network of center-based model and simulation repositories that are collaborative in nature across the full NASA domain.

**Capability Description:** A NASA network of PDM/PLM systems supported with current technology so that utilization is fast and efficient. Integration with MBSE approaches. As an example, SysML system behavior definitions should be encouraged and potential users trained in the understanding of modeling and simulation capabilities through these then available characterizing techniques.

**Capability State of the Art:** NASA's Windchill used in various NASA projects including past work for NASA exploration program with Agency-wide distribution.

**Capability Performance Goal:** A continually growing library of federates and federations should be available forever for quicker implementation in the next project. NASA employees have easy, organized, and well-documented access to elements, which leads to success in successor programs.

**Parameter, Value:**

User acceptance of repository functionality: 30%

**Parameter, Value:**

User acceptance of repository functionality: 90%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – crewed in DRO	Enhancing	2022	2022	2015-2021	2 years
Explorer Class: Explorer missions	Enhancing	--	2023	2020	5 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	8 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	8 years



11.3 Simulation  
11.3.3 Simulation-Based Systems  
Engineering

### 11.3.3.1 Multi-Domain Modeling (MDM) Frameworks

#### TECHNOLOGY

**Technology Description:** Enables modeling of physical systems, including sensors and measurement points, across multiple domains for modeling of system behavior under nominal and off-nominal conditions.

**Technology Challenge:** Multi-domain modeling should be implemented at the earliest conceptual stages. This is fundamentally different from approaches used today, where domain-specific approaches are developed and matured and then integrated at a later stage.

**Technology State of the Art:** Multi-domain modeling is currently performed using integration and data fusion methods, which combine results from individual, domain-specific models into a comprehensive system-level model. Currently, modeling methods incorporate their own solvers, limiting the ability to tightly integrate models from different domains.

**Technology Performance Goal:** Development of multi-physics modeling capabilities will result in systems of equations with a large number of degrees of freedom. Measurement points are also modeled for comparison between the model and the actual system using sensor measurements, allowing high-fidelity model updates based on sensor measurements. The performance goal is to develop tools that allow users to easily create integrated, realistic multi-physics models of the physical response of systems.

**Parameter, Value:**

Degrees of freedom:  $10^8$

**TRL**

2

**Parameter, Value:**

Degrees of freedom:  $10^{10}$

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing, 11.1.2 Ground Computing, 11.3.5 Exascale Simulation, 11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods, 11.3.7 Multiscale, Multiphysics and Multifidelity Simulation, 11.3.8 Verification and Validation.

#### CAPABILITY

**Needed Capability:** Highly accurate, simulation-based systems engineering technologies are needed to interrogate changing vehicle states under a variety of operational scenarios within a high degree of variability and uncertainty.

**Capability Description:** Ensuring favorable mission outcomes requires the ability to rapidly make critical decisions regarding the design, testing, operation, and maintenance of aerospace vehicles throughout their lifecycles. Simulation-based systems engineering technologies must incorporate an accurate model of the physical vehicle and vehicle components; tools for rapidly and efficiently simulating the vehicle in its operational environment; vehicle state monitoring and model updating to ensure the correlation between the model and the physical system; and a robust decision-making capability despite large uncertainties and a lack of consistent predictions.

**Capability State of the Art:** Individual tools have been developed for modeling, simulation, and health management for vehicle design and maintenance; however, these tools have not been refined and integrated to the level required for effective decision-making.

**Capability Performance Goal:** Models should accurately model the physical behavior of the system and adapt to changing environments and vehicle conditions throughout its lifetime.

**Parameter, Value:**

Probability of detection for faults and damage: 95% ( $2\sigma$ )

**Parameter, Value:**

Probability of detection for faults and damage: 99.99% ( $4\sigma$ )

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – crewed in DRO	Enhancing	2022	2022	2015-2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	4 years
Real-Time System-Wide Safety Assurance: Introduction of Advanced Safety Assurance Tools	Enhancing	--	--	2025	4 years
Enable Assured Machine Autonomy for Aviation: Initial Autonomy Applications	Enhancing	--	--	2025	5 years

11.3 Simulation  
11.3.3 Simulation-Based Systems  
Engineering

### 11.3.3.2 High-Performance Simulations (HPS)

#### TECHNOLOGY

**Technology Description:** Provide highly efficient numerical methods and algorithms for efficient solutions to large systems of equations for simulation models.

**Technology Challenge:** Multi-domain modeling will result in significantly larger and more complex models due to a dramatic increase in degrees of freedom. Solving the modeling equations requires highly-efficient function evaluation algorithms, as well as much greater computing power.

**Technology State of the Art:** Simulation and equation-solving algorithms are being designed specifically for use in high-performance computing environments, using software languages and interfaces that facilitate the use of parallel computing.

**Parameter, Value:**

Function evaluations per second:  $10^8$

**TRL**

3

**Technology Performance Goal:** Solving large systems of equations with large numbers of degrees of freedom will require massively parallel computational capabilities to solve these equations. To be effective, these equations must be solved within minutes – or faster – to support critical missions.

**Parameter, Value:**

Function evaluations per second:  $10^{11}$

**TRL**

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing, 11.1.2 Ground Computing, 11.3.5 Exascale Simulation, 11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods, 11.3.7 Multiscale, Multiphysics, and Multifidelity Simulation, 11.3.8 Verification and Validation.

#### CAPABILITY

**Needed Capability:** Highly accurate, simulation-based systems engineering technologies are needed to interrogate changing vehicle states under a variety of operational scenarios within a high degree of variability and uncertainty.

**Capability Description:** Ensuring favorable mission outcomes requires the ability to rapidly make critical decisions regarding the design, testing, operation, and maintenance of aerospace vehicles throughout their lifecycles. Simulation-based systems engineering technologies must incorporate an accurate model of the physical vehicle and vehicle components; tools for rapidly and efficiently simulating the vehicle in its operational environment; vehicle state monitoring and model updating to ensure the correlation between the model and the physical system; and a robust decision-making capability despite large uncertainties and a lack of consistent predictions.

**Capability State of the Art:** Individual tools have been developed for modeling, simulation, and health management for vehicle design and maintenance; however, these tools have not been refined and integrated to the level required for effective decision-making.

**Parameter, Value:**

Probability of detection for faults and damage: 95% ( $2\sigma$ )

**Capability Performance Goal:** Models should accurately model the physical behavior of the system and adapt to changing environments and vehicle conditions throughout its lifetime.

**Parameter, Value:**

Probability of detection for faults and damage: 99.99% ( $4\sigma$ )

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – crewed in DRO	Enhancing	2022	2022	2015-2021	5 years
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	4 years
Real-Time System-Wide Safety Assurance: Introduction of Advanced Safety Assurance Tools	Enhancing	--	--	2025	4 years
Enable Assured Machine Autonomy for Aviation: Initial Autonomy Applications	Enhancing	--	--	2025	5 years

11.3 Simulation  
11.3.3 Simulation-Based Systems  
Engineering

### 11.3.3.3 Adaptive Model Updating (ADU) Toolset

#### TECHNOLOGY

**Technology Description:** Provides highly integrated vehicle state monitoring and predictive capabilities that accurately monitor the physical behavior of a vehicle or vehicle component, update the multi-domain physics-based model for correlation of the model with the behavior of the physical system, estimate service life, and determine inspection intervals.

**Technology Challenge:** Current in-situ health management requires a large number of sensors to achieve high accuracy, but this is not practical due to weight, cost, and space considerations. Intelligent approaches that assess the health of the vehicle as a whole, utilizing all available data from a limited number of sensors, will be needed to maximize health information for updating the multi-domain physics-based model to correlate the model with the behavior of the physical system. This capability is needed to utilize this model as an effective decision-making tool.

**Technology State of the Art:** State of the technology in-vehicle health management systems assess the integrity and performance of a vehicle at the system and subsystem levels and assesses the ability of the vehicle to operate safely and efficiently within design constraints to achieve mission objectives.

**Parameter, Value:**

Probability of detection for faults and damage: 95%  
(2 $\sigma$ )

**TRL**

4

**Technology Performance Goal:** Multi-domain modeling and simulation will identify likely sources of damage initiation and component faults and failure, facilitate service life inspection, and enable life extension predictions using lightweight and wireless sensor systems. These critical sources must be accurately monitored with high probabilities of detection for damage, faults, and failures.

**Parameter, Value:**

Probability of detection for faults and damage: 99.99%  
(4 $\sigma$ )

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 4.5.1.3: Integrated Vehicle Health Monitoring, 11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods, 11.3.8 Verification and Validation.

#### CAPABILITY

**Needed Capability:** Highly accurate, simulation-based systems engineering technologies are needed to interrogate changing vehicle states under a variety of operational scenarios within a high degree of variability and uncertainty.

**Capability Description:** Ensuring favorable mission outcomes requires the ability to rapidly make critical decisions regarding the design, testing, operation, and maintenance of aerospace vehicles throughout their lifecycles. Simulation-based systems engineering technologies must incorporate an accurate model of the physical vehicle and vehicle components; tools for rapidly and efficiently simulating the vehicle in its operational environment; vehicle state monitoring and model updating to ensure the correlation between the model and the physical system; and a robust decision-making capability despite large uncertainties and a lack of consistent predictions.

**Capability State of the Art:** Individual tools have been developed for modeling, simulation, and health management for vehicle design and maintenance; however, these tools have not been refined and integrated to the level required for effective decision-making.

**Parameter, Value:**

Probability of detection for faults and damage: 68% (1 $\sigma$ )

**Capability Performance Goal:** Models should accurately model the physical behavior of the system and adapt to changing environments and vehicle conditions throughout its lifetime.

**Parameter, Value:**

Probability of detection for faults and damage: 99.99% (4 $\sigma$ )

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – crewed in DRO	Enhancing	2022	2022	2015-2021	5 years
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	4 years
Real-Time System-Wide Safety Assurance: Introduction of Advanced Safety Assurance Tools	Enhancing	--	--	2025	4 years
Enable Assured Machine Autonomy for Aviation: Initial Autonomy Applications	Enhancing	--	--	2025	5 years



11.3 Simulation  
11.3.3 Simulation-Based Systems  
Engineering

### 11.3.3.4 Advanced Diagnostics and Prognostics (ADP) Toolset

#### TECHNOLOGY

**Technology Description:** Provides capability to accurately assess the probability that a fault or failure will impact mission success.

**Technology Challenge:** Developing accurate and integrated models of physical responses and sensor measurement points, correlated with physical sensor measurements, will facilitate fault detection and help isolate the cause of anomalies. However, this will require more complex simulations based not only on models of system behavior, but also on models of sensor measurements at key locations. Modeling both sensor measurements and system behavior will facilitate accurate inverse solutions that identify the cause of system anomalies based on changes in sensor measurements, even for effects which cannot be measured directly.

**Technology State of the Art:** ADP identifies the current level of damage or faults, safety risk, and performance. ADP assesses risk and estimates remaining useful life at the system, subsystem, and component levels.

**Technology Performance Goal:** Accident rates for commercial aviation are less than two fatalities per  $10^8$  flight hours, and mission failure rate for space operations are significantly higher. The goal of ADP is to accurately assess the probability of system/component failure. While accidents and incidents are unlikely, the goal is to accurately identify those that are likely to fail within 1% accuracy.

**Parameter, Value:**

Accuracy of probability of system/ component failure per mission: within 32% (1-1 $\sigma$ )

**TRL**

3

**Parameter, Value:**

Accuracy of probability of system/ component failure per mission: within 1% (1-3 $\sigma$ )

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing, 11.1.2 Ground Computing, 11.3.5 Exascale Simulation, 11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods, 11.3.7 Multiscale, Multiphysics, and Multifidelity Simulation, 11.3.8 Verification and Validation.

#### CAPABILITY

**Needed Capability:** Highly accurate, simulation-based systems engineering technologies are needed to interrogate changing vehicle states under a variety of operational scenarios within a high degree of variability and uncertainty.

**Capability Description:** Ensuring favorable mission outcomes requires the ability to rapidly make critical decisions regarding the design, testing, operation, and maintenance of aerospace vehicles throughout their lifecycles. Simulation-based systems engineering technologies must incorporate an accurate model of the physical vehicle and vehicle components; tools for rapidly and efficiently simulating the vehicle in its operational environment; vehicle state monitoring and model updating to ensure the correlation between the model and the physical system; and a robust decision-making capability despite large uncertainties and a lack of consistent predictions.

**Capability State of the Art:** Individual tools have been developed for modeling, simulation, and health management for vehicle design and maintenance; however, these tools have not been refined and integrated to the level required for effective decision-making.

**Capability Performance Goal:** Models should accurately model the physical behavior of the system and adapt to changing environments and vehicle conditions throughout its lifetime.

**Parameter, Value:**

Probability of detection for faults and damage: 95% (2 $\sigma$ )

**Parameter, Value:**

Probability of detection for faults and damage: 99.99% (4 $\sigma$ )

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – crewed in DRO	Enhancing	2022	2022	2015-2021	5 years
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	4 years
Real-Time System-Wide Safety Assurance: Introduction of Advanced Safety Assurance Tools	Enhancing	--	--	2025	4 years
Enable Assured Machine Autonomy for Aviation: Initial Autonomy Applications	Enhancing	--	--	2025	5 years

### 11.3 Simulation

#### 11.3.3 Simulation-Based Systems Engineering

### 11.3.3.5 Robust Decision-Making (RDM) Framework

#### TECHNOLOGY

**Technology Description:** Provides the ability to evaluate the mission trade space and to make decisions that ensure the maximum probability of mission success using models of uncertainties identified in Section 11.3.6.

**Technology Challenge:** Confidence in mission success requires use of complex models and simulations limited by uncertainties resulting from sensor measurements, environmental factors, modeling assumptions, and computational methods. In addition, complex, multi-domain models will likely result in under-constrained problems. Robust decisions can be achieved using multidomain models and simulations, coupled with continuous health updates, to achieve a “digital twin” for critical decision-making for maximizing mission success.

**Technology State of the Art:** RDM uses an outcome-based approach that works backwards, using multiple scenarios generated from the multi-domain modeling (MDM) and high-performance simulation (HPS) results to identify the model parameters most relevant to the mission’s success, thus providing a robust solution that maximizes the probability of mission success even when the model parameters may be uncertain or unknown.

#### Parameter, Value:

Probability of mission success:  $10^7$  for commercial flights and  $10^2$  for space flights.

#### TRL

2

**Technology Performance Goal:** The goal is to accurately identify the probability of failure so that corrective action can be taken when necessary.

#### Parameter, Value:

Probability of mission success:  $10^9$  commercial flights and  $10^4$  space flights.

#### TRL

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing, 11.1.2 Ground Computing, 11.3.5 Exascale Simulation, 11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods, 11.3.7 Multiscale, Multiphysics, and Multifidelity Simulation, 11.3.8 Verification and Validation.

#### CAPABILITY

**Needed Capability:** Highly accurate, simulation-based systems engineering technologies are needed to interrogate changing vehicle states under a variety of operational scenarios within a high degree of variability and uncertainty.

**Capability Description:** Ensuring favorable mission outcomes requires the ability to rapidly make critical decisions regarding the design, testing, operation, and maintenance of aerospace vehicles throughout their lifecycles. Simulation-based systems engineering technologies must incorporate an accurate model of the physical vehicle and vehicle components; tools for rapidly and efficiently simulating the vehicle in its operational environment; vehicle state monitoring and model updating to ensure the correlation between the model and the physical system; and a robust decision-making capability despite large uncertainties and a lack of consistent predictions.

**Capability State of the Art:** Individual tools have been developed for modeling, simulation, and health management for vehicle design and maintenance; however, these tools have not been refined and integrated to the level required for effective decision-making.

#### Parameter, Value:

Probability of detection for faults and damage: 95% ( $2\sigma$ )

**Capability Performance Goal:** Models should accurately model the physical behavior of the system and adapt to changing environments and vehicle conditions throughout its lifetime.

#### Parameter, Value:

Probability of detection for faults and damage: 99.99% ( $4\sigma$ )

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – crewed in DRO	Enhancing	2022	2022	2015-2021	5 years
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	4 years
Real-Time System-Wide Safety Assurance: Introduction of Advanced Safety Assurance Tools	Enhancing	--	--	2025	4 years
Enable Assured Machine Autonomy for Aviation: Initial Autonomy Applications	Enhancing	--	--	2025	5 years

11.3 Simulation  
11.3.3 Simulation-Based Systems  
Engineering

### 11.3.3.6 Onboard Predictive Physics-Based Vehicle Simulation

#### TECHNOLOGY

**Technology Description:** Provides a reduced-order vehicle simulation capability for space exploration crews using response surface method or other computationally efficient methods for rapid assessment on low-power onboard computer systems.

**Technology Challenge:** Providing a multi-subsystem, physics-based vehicle simulation with sufficient fidelity to allow crew to predict vehicle responses to configuration changes on computational equipment available on exploration spacecraft. Providing adequate processing speed with power and volumetric constraints, determining adequate model fidelities, ability to run flight software on low-power processors, and interfacing to spacecraft systems to acquire vehicle states are all technological challenges.

**Technology State of the Art:** Multi-subsystem, physics-based simulations integrated with flight software on emulated processors are available on multi-core workstation-class machines.

**Parameter, Value:**

Execution of complex multi-subsystem, physics-based simulations with emulated flight processors on 64 core workstation-class machines. No direct spacecraft interfaces included. Simulation configuration is "expert-friendly."

**TRL**

4

**Technology Performance Goal:** The goal is to provide multi-subsystem, physics-based simulations incorporating malfunction processing on laptop-class machines that acquire vehicle state information from a spacecraft bus.

**Parameter, Value:**

Execution of complex, multi-subsystem, physics-based simulations with emulated flight processors on laptop-class machines. Direct acquisition of data required to configure simulation from spacecraft bus. User interfaces sufficient to allow configuration by crew in minutes.

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** TA 4 Automation, TA 7 Habitat Systems, 11.2.3 Human-System Performance Modeling, 11.3.4 Simulation-Based Training and Decision Support Systems, 11.3.3.4 Advanced Diagnostics and Prognostics Toolset, 11.3.3.5 Robust Decision-Making Frameworks.

#### CAPABILITY

**Needed Capability:** Highly accurate, simulation-based systems engineering technologies are needed to interrogate changing vehicle states under a variety of operational scenarios within a high degree of variability and uncertainty.

**Capability Description:** Ensuring favorable mission outcomes requires the ability to rapidly make critical decisions regarding the design, testing, operation, and maintenance of aerospace vehicles throughout their lifecycles. Simulation-based systems engineering technologies must incorporate an accurate model of the physical vehicle and vehicle components; tools for rapidly and efficiently simulating the vehicle in its operational environment; vehicle state monitoring and model updating to ensure the correlation between the model and the physical system; and a robust decision-making capability despite large uncertainties and a lack of consistent predictions.

**Capability State of the Art:** Individual tools have been developed for modeling, simulation, and health management for vehicle design and maintenance; however, these tools have not been refined and integrated to the level required for effective decision-making.

**Parameter, Value:**

Probability of detection for faults and damage: 95%

**Capability Performance Goal:** Models should accurately model the physical behavior of the system and adapt to changing environments and vehicle conditions throughout its lifetime.

**Parameter, Value:**

Probability of detection for faults and damage: 99%

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – crewed in DRO	Enhancing	2022	2022	2015-2021	5 years
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	4 years
Real-Time System-Wide Safety Assurance: Introduction of Advanced Safety Assurance Tools	Enhancing	--	--	2025	4 years
Enable Assured Machine Autonomy for Aviation: Initial Autonomy Applications	Enhancing	--	--	2025	5 years



11.3 Simulation  
11.3.4 Simulation-Based Training and  
Decision Support Systems

### 11.3.4.1 Onboard Simulation-Based Trainers

#### TECHNOLOGY

**Technology Description:** Enable interactive simulation training that has adaptable simulation fidelity to match trainee proficiency, is scalable to mission timeline, and provides effectiveness feedback.

**Technology Challenge:** Provide low-mass, low-volume, low-power, integrated training technology that evaluates training effectiveness for individuals and teams for mission tasks (medical, payload, operations).

**Technology State of the Art:** Ground-based training, including immersive environments for robotics, and high-fidelity mock-ups.

**Technology Performance Goal:** Variable-fidelity, simulation-based, immersive training that adapts to crew proficiency and mission timeline to provide effective and efficient just-in-time team and individual training with performance feedback.

**Parameter, Value:**

**TRL**

Percentage of target tasks that can be effectively trained in-situ to performance criterion (training time and accuracy): 20%

2

Percentage of post-training retention goal: 0%

**Parameter, Value:**

**TRL**

Percentage of target tasks that can be effectively trained to performance criterion (training time and accuracy): 100%

9

Percentage of post-training retention goal: 80%

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing

#### CAPABILITY

**Needed Capability:** Onboard just-in-time training for nominal and contingency mission and payload operations.

**Capability Description:** Trains astronauts to remain proficient for long-duration exploration missions beyond low-Earth orbit (LEO), particularly in robotics, extravehicular activities (EVA), proximity, and surface operations.

**Capability State of the Art:** Ground-based event simulation training exists for all mission tasks, including virtual reality training lab for EVA and robotic manipulator operations.

**Capability Performance Goal:** Training and simulations provide the crew just-in-time training that evaluates and adapts to current crew proficiency for all mission tasks (nominal and off-nominal, including medical, and payload) for both individuals and teams.

**Parameter, Value:**

Percentage of target tasks that can be effectively trained in-situ to performance criterion (based on required time and accuracy): 20%

Percentage of post-training retention goal: 0%

**Parameter, Value:**

Percentage of target tasks that can be effectively trained in-situ to performance criterion (based on required time and accuracy): 100%

Percentage of post-training retention goal: 80%

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Enabling	2027	2027	2021	5 years
Enabling	2027	2027	2021	7 years
Enabling	2033	--	2027	8 years

Exploring Other Worlds: DRM 6 Crewed to NEA

Exploring Other Worlds: DRM 7 Crewed to Lunar Surface

Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)

11.3 Simulation  
11.3.4 Simulation-Based Training and  
Decision Support Systems

### 11.3.4.2 Integrated Mission Human-in-the-Loop Simulation System

#### TECHNOLOGY

**Technology Description:** Enables integrated simulations that can used to evaluate designs and operations, including training.

**Technology Challenge:** Fully integrated mission simulations that are efficient to use, have validated embedded performance measures, and enable variable simulation fidelity.

**Technology State of the Art:** Stand-alone ground-based training, including immersive environments for robotics and high-fidelity mock-ups, are difficult environments to collect performance data critical to design or provide inadequate training feedback.

**Technology Performance Goal:** Variable-fidelity, integrated mission human-in-the-loop simulation that includes measurement of human-system performance.

**Parameter, Value:**

Percentage of target tasks effectively evaluated or trained to performance criterion (training time and task accuracy): 40%

Time to develop simulation: 6-12 weeks.

**TRL**

2

**Parameter, Value:**

Percentage of target tasks effectively evaluated or trained to performance criterion (training time and task accuracy): 100%

Time to develop simulation: 1-3 weeks.

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.2.3.3 Toolset For Automated Task Generation For Human-System Modeling (For Efficient Use)

#### CAPABILITY

**Needed Capability:** Human-in-the-loop training and testing.

**Capability Description:** Provides increased ability for integrated (mission-level) human-in-the-loop simulations.

**Capability State of the Art:** Ground-based event simulation training exists for mission tasks, often not in full mission context.

**Capability Performance Goal:** Multi-scale, multi-agent simulations need to provide integrated simulations with embedded human/system performance measures.

**Parameter, Value:**

Percentage of target tasks effectively evaluated or trained to performance criterion (training time and task accuracy): 40%

Time to develop simulation: 6-12 weeks.

**Parameter, Value:**

Percentage of target tasks effectively evaluated or trained to performance criterion (training time and task accuracy): 100%

Time to develop simulation: 1-3 weeks.

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Safe, Efficient Growth in Global Operations: System-wide Safety, Predictability, and Reliability Through Full NextGen Functionality	Enhancing	--	--	2035	4 years
Enable Assured Machine Autonomy for Aviation: Human-machine Teaming in Key Applications	Enhancing	--	--	2035	4 years

11.3 Simulation  
11.3.4 Simulation-Based Training and  
Decision Support Systems

### 11.3.4.3 Digital-Human-in-the-Loop Simulation System

#### TECHNOLOGY

**Technology Description:** Enables integrated human and system simulations to determine human-system performance of designs and operations.

**Technology Challenge:** Rapid prototyping of human-system performance simulation to reduce design cycle time and evaluate system safety. Simulation architecture that is multi-agent and supports multiple levels of fidelity in system design, tasks descriptions, and extensive human-system performance parameters does not currently exist.

**Technology State of the Art:** Simulation tools exist for a limited number of human performance parameters for individual tasks in a limited mission context.

**Parameter, Value:**

Percentage of validated simulations for target mission tasks: 0%

**TRL**

2

**Technology Performance Goal:** Simulation environment that supports rapid development of simulations, with varying levels of fidelity.

**Parameter, Value:**

Percentage of validated simulations for target mission tasks: 80%

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.2.3.2 Human Digital Twin, 11.2.3.3 Toolset for Automated Task Generation For Human-System Modeling (For Efficient Use).

#### CAPABILITY

**Needed Capability:** Digital-human-in-loop simulation.

**Capability Description:** Provide integrated simulations using digital human models to evaluate and down-select designs, as well as evaluate operations procedures (for mission planning and contingent operation validation).

**Capability State of the Art:** Event-based simulation prototypes exist for certain ground-based human-system interactions, at various levels of complexity for tasks in 1-g.

**Parameter, Value:**

Percentage of validated simulations for target mission tasks: 0%

**Capability Performance Goal:** Multi-scale, multi-agent mission simulations to provide integrated validated simulations of human/system performance predictions.

**Parameter, Value:**

Percentage of validated simulations for target mission task: 80%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years
Safe, Efficient Growth in Global Operations: System-wide Safety, Predictability, and Reliability Through Full NextGen Functionality	Enhancing	--	--	2035	8 years
Real-Time System-Wide Safety Assurance: An Integrated Safety Assurance System Enabling Continuous System-Wide Safety Monitoring	Enhancing	--	--	2035	8 years
Enable Assured Machine Autonomy for Aviation: Human-machine Teaming in Key Applications	Enhancing	--	--	2035	8 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.3 Simulation  
11.3.5 Exascale Simulation

## 11.3.5.1 Extreme-Scale Software for Modeling and Simulation

## TECHNOLOGY

**Technology Description:** Extends research to increasingly complex simulations, such as scientific prediction, engineering design, and policy making, through an integrated development environment such as the co-design process, domain specific languages, parallel toolkits, frameworks, and libraries, for effective use of exascale systems.

**Technology Challenge:** Beyond codification of a discipline, the challenge of extreme-scale software is the tailoring of development environments to rapidly model the behavior of complex systems at multiple levels of software abstraction, balancing performance, numerical accuracy, and sharing/coupling at various discipline levels (such as operator-splitting algorithms) while maintaining effective use of evolving, extreme-scale systems (petascale/exascale).

**Technology State of the Art:** Various frameworks for complex simulations have been developed and refined as a common interest between two specific scientific groups—usually by low-order accuracy, coupled with quick ad hoc schemes.

**Parameter, Value:**

Percent of standard methods: 5%

Percent maturity of coupling methods: 5%

**TRL**

3

**Technology Performance Goal:** Demonstrate a scalable, common development environment that combines accuracy, order of convergence, and coupling methods and considers verification and validation, software lifecycle, and collaborative software.

**Parameter, Value:**

Percent of standard methods: 25%

Percent maturity of coupling methods: 25%

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing

## CAPABILITY

**Needed Capability:** Rapid development and adaptation of physics-based exascale modeling and simulation environments.

**Capability Description:** Enables the transition of modeling and simulation to exascale computing by leveraging extreme-scale development environments, including computational frameworks and toolkits, thereby enabling missions to model increasingly complex problems.

**Capability State of the Art:** The research process currently relies on legacy applications that are not extensible, use dated constructs and practices in software design, and are not amenable to coupling codes (multi-physics, multi-scale, multifidelity).

**Parameter, Value:**

Percent use of standard methods: 2%

Percent maturity of coupling methods: 2%

**Capability Performance Goal:** Increased ability to share common practices and reduce time and cost to transition and develop codes in a parallel (petascale/exascale) development environment.

**Parameter, Value:**

Percent use of standard methods: 20%

Percent maturity of coupling methods: 20%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Innovation in Commercial Supersonic Aircraft: Supersonic Overland Certification Standard Based on Acceptable Sonic Boom Noise	Enhancing	--	--	2025	5 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	10 years
Transition to Low-Carbon Propulsion: Introduction of Low-carbon Fuels for Conventional Engines and Exploration of Alternative Propulsion Systems	Enhancing	--	--	2025	5 years
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enhancing	--	2024*	2020	5 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	5 years
Into the Solar System: DRM 5 Asteroid Redirect – crewed in DRO	Enhancing	2022	2022	2015-2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

### 11.3 Simulation

#### 11.3.5 Exascale Simulation

### 11.3.5.2 Extreme-Scale Geometry and Grid Generation Environments

#### TECHNOLOGY

**Technology Description:** Enables researchers to rapidly create complex, scalable geometry models for exascale systems, and the ability to use automated adaptive mesh refinement (AMR) in production-level, extreme-scale codes.

**Technology Challenge:** The difficulties of deploying scalable AMR are fundamental (such as better error estimates, anisotropic mesh refinement), and logistical (tight computer aided design (CAD) coupling, software efficiency, and complexity). Further, exascale systems require increased automation of reliable extreme-scale meshes from grid generation, where the geometry definitions must have suitable accuracy (water-tight for manufacturing purposes), without non-essential excessive detail.

**Technology State of the Art:** Limited standards for CAD interfaces and access, tighter CAD coupling, and slow adoption of production AMR in discipline codes (such as computational fluid dynamics).

**Parameter, Value:**

Percent use of scalable AMR: 15%

Percent use of scalable mesh generation: 2%

Percent linkage with CAD: 5%.

**TRL**

3

**Technology Performance Goal:** Ability to generate very large scale meshes through tighter CAD automation and coupling; early prototypes of parallel mesh generation. Partnerships and consortiums for defining and adopting AMR and CAD meshing interface methods.

**Parameter, Value:**

Percent use of scalable AMR: 45%

Percent use of scalable mesh generation: 20%

Percent linkage with CAD: 20%.

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing

#### CAPABILITY

**Needed Capability:** Reliable and scalable AMR and mesh generation for exascale modeling and simulation.

**Capability Description:** Enables a scalable meshing generation capability that constructs suitable meshes, then uses AMR throughout the solution process with minimal user intervention.

**Capability State of the Art:** Current practice is a mesh generation phase, followed by adaptive scalable mesh refinement. The initial mesh generation phase dominants with cost and time constraints, and lacks a common representation of surface geometries in CAD tools; many CAD geometry definitions are ill-suited for discipline (such as computational fluid dynamics analyses) due to insufficient accuracy (non-water-tight geometries) or excessive details. Once in production, meshes serve as a basis for AMR, a well established approach being evolved to scale for many cores.

**Parameter, Value:**

Percent use of scalable AMR: 10%;

Percent use of scalable mesh generation: 2%;

Percent linkage with CAD: 5%.

**Capability Performance Goal:** Scale mesh generation and create robust grids for a variety of applications and demonstrate scalable mesh generation with less human interaction. Provide tight CAD coupling and adaptive mesh, large-scale,  $O(10^{12})$ , parallel mesh generation, and a fully automated in-situ mesh generation and adaptive control for extreme-scale, time dependent problems.

**Parameter, Value:**

Percent use of scalable AMR: 25%;

Percent use of scalable mesh generation: 20%;

Percent linkage with CAD: 20%.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	10 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	10 years
Innovation in Commercial Supersonic Aircraft: Supersonic Overland Certification Standard Based on Acceptable Sonic Boom Noise	Enhancing	--	--	2025	5 years
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enhancing	--	2024*	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

## 11.3 Simulation

## 11.3.5 Exascale Simulation

## 11.3.5.3 Extreme-Scale Numerical Validation Environment

## TECHNOLOGY

**Technology Description:** Enables the fusion of observational and experimental data with advanced simulation. The ability to dynamically, in-situ, query and integrate high-fidelity simulation data with lower-fidelity data reduces overall risk in aerospace system design.

**Technology Challenge:** The fusion of observational and experimental data for advanced simulations requires rigorous mathematical models/methods (such as reduced-order model, surrogate models, Kriging methods), extensible framework (tailorable to diverse problems, yet robust and detailed enough for specific applications) and efficient, robust implementations for data assimilation and databases for collaborative validation.

**Technology State of the Art:** Single, high-fidelity simulation, with a separate post-processing process involving databases with disparate standards. In-situ visualization is available, but is environment-specific. Comparison of data requires mathematical approach for quantifying the level of uncertainties. Real-time analysis and visualization are gaining acceptance, but are currently limited.

**Parameter, Value:**

Percent of simulations using in-situ validation: 5%  
Simulation size: 1 to 4 billion point unsteady CFD simulation by 2020,  
20 billion data points by 2025.

**TRL**

3

**Technology Performance Goal:** Create real-time, multifidelity database for various disciplines; establish a large-scale, flexible validation database consisting of a visualization component; a data analysis/management component; and an integration component (mathematical models). Demonstrate in-situ analysis and visualization of simulation and test facility data such as a notional  $10^{10}$  point unsteady computational fluid dynamics (CFD) simulation.

**Parameter, Value:**

Percent of simulations using in-situ validation: 25%  
Simulation size: 5 to 10 billion point unsteady CFD simulation by 2020,  
100 billion data points by 2025.

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing

## CAPABILITY

**Needed Capability:** On-demand, in-situ physics-based numerical validation for exascale simulations and test facilities.

**Capability Description:** Enables an integrated approach combining well-designed ground-based (and perhaps flight) experiments to provide high-quality datasets directly coupled with CFD technology and applications code for verification and validation. The system is both scalable for petascale systems, and on-domain (in-situ).

**Capability State of the Art:** Validation and verification often involves a single, high-fidelity simulation with a separate post-processing process, usually involving databases with disparate standards. Post-processing is the dominant means of visualization and analysis. The engineering process is complicated by a lack of data standards. Comparisons of large amounts of experimental and simulation data are largely carried out through experience and intuition using fairly unsophisticated tools.

**Parameter, Value:**

Percent of simulations using in-situ validation: 1%  
Simulation size: 1 to 2 billion point unsteady CFD simulation by 2020,  
10 billion data points by 2025.

**Capability Performance Goal:** Dynamically validate in-situ simulations with test facility and theory results, while adaptively bridging differences in the engineering domain data representations. Demonstrate open-source visualization toolkits; decoupling input/output (I/O) from the simulation; converting data into a compact intermediate representation, facilitating post-processing visualization.

**Parameter, Value:**

Percent of simulations using in-situ validation: 20%  
Simulation size: 5 to 10 billion point unsteady CFD simulation by 2020, 50 to 100 billion points by 2025.

## Technology Needed for the Following NASA Mission Class and Design Reference Mission

Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Enhancing	--	--	2025	5 years
Enhancing	--	--	2035	10 years
Enhancing	--	--	2025	10 years
Enhancing	--	2024*	2020	5 years
Enhancing	--	2029	2021	5 years
Enhancing	--	2035*	2030	10 years
Enhancing	2027	2027	2021	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.3 Simulation  
11.3.6 Uncertainty Quantification and  
Nondeterministic Simulation Methods

### 11.3.6.1 Robust System Uncertainty Modeling Toolset

#### TECHNOLOGY

**Technology Description:** Facilitates the proper quantification of uncertainties in system models, differentiating between inherent variability and lack of knowledge uncertainties.

**Technology Challenge:** Currently, there is a lack of unified methodologies to accommodate uncertainty characterization and model calibration. The goal of utilizing disparate data adds much complexity.

**Technology State of the Art:** Bayesian inference, maximum likelihood estimation, and empirical prediction models are techniques used to characterize uncertainty. Dissimilar sources of information (experimental-, expert opinion-, and simulation-based) are blended using data fusion techniques.

**Parameter, Value:**

Percent of accurate characterization of uncertainty:  
90%

**TRL**

4

**Technology Performance Goal:** Systematic methods and tools to facilitate rigorous uncertainty characterization using limited and potentially disparate experimental data.

**Parameter, Value:**

Percent of accurate characterization of uncertainty:  
100%

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

#### CAPABILITY

**Needed Capability:** Accurate characterization of model uncertainties.

**Capability Description:** Enables accurate assessment of mission reliability, robustness, and performance in the presence of all forms of uncertainty.

**Capability State of the Art:** Uncertainty characterization is currently done using system identification and other data-driven tools that employ specific assumptions in the form of uncertainties. These assumptions can have a dramatic impact on the correctness of subsequent analysis and design.

**Parameter, Value:**

Percent of accurate characterization of uncertainty: 20%

**Capability Performance Goal:** Tools and methods to dramatically improve the ability to properly quantify uncertainties so that meaningful mission risk and reliability assessments can be performed.

**Parameter, Value:**

Percent of accurate characterization of uncertainty: 100%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	7 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	7 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	10 years
Real-Time System-Wide Safety Assurance: An Integrated Safety Assurance System Enabling Continuous System-Wide Safety Monitoring	Enhancing	--	--	2035	10 years

11.3 Simulation  
11.3.6 Uncertainty Quantification and  
Nondeterministic Simulation Methods

### 11.3.6.2 Probabilistic Risk Assessment (PRA) Toolset

#### TECHNOLOGY

**Technology Description:** Delivers efficient and accurate assessments of system risk in the presence of probabilistic uncertainties.

**Technology Challenge:** Propagation of probabilistic uncertainties to accurately assess low-probability events poses a large computational burden.

**Technology State of the Art:** Monte Carlo analysis, Markov chain Monte Carlo, interval analysis-based techniques, and polynomial chaos are used to propagate random vectors and probability boxes.

**Parameter, Value:**

Efficient PRA methods deployed: 80%

**TRL**

4

**Technology Performance Goal:** Rapid uncertainty propagation for probabilistic models for a diverse class of physics-based simulation models.

**Parameter, Value:**

Efficient PRA methods deployed: 100%

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing

#### CAPABILITY

**Needed Capability:** Probabilistic risk assessment.

**Capability Description:** Efficiently and accurately evaluate risk and reliability predictions resulting from having probabilistic uncertainties in the model's parameters, boundary conditions, and loads.

**Capability State of the Art:** The current baseline tool for PRA is Monte Carlo when using probabilistic definitions of uncertainty. This tool is typically used to assess mean value system response or provide estimates of failure probabilities. Computational costs are burdensome for large system models with small failure probability requirements.

**Parameter, Value:**

Efficient PRA methods deployed: 20%

**Capability Performance Goal:** Methods to efficiently and accurately assess risk using large-order system models subject to probabilistic uncertainties.

**Parameter, Value:**

Efficient PRA methods deployed: 100%

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	7 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	7 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	9 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	9 years
Real-Time System-Wide Safety Assurance: An Integrated Safety Assurance System Enabling Continuous System-Wide Safety Monitoring	Enhancing	--	--	2035	9 years

11.3 Simulation  
11.3.6 Uncertainty Quantification and  
Nondeterministic Simulation Methods

### 11.3.6.3 Aleatory and Epistemic Uncertainty Assessment Toolset

#### TECHNOLOGY

**Technology Description:** Provides uncertainty quantification tools consistent with the current state of knowledge of the system.

**Technology Challenge:** Lack of efficient computational methods to propagate intervals and probability boxes through simulation models.

**Technology State of the Art:** Global optimization, failure domain bounding (parametric safety margins), and randomized algorithms are some of the techniques used in mixed-form uncertainty assessment.

**Parameter, Value:**

Proper handling of mixed uncertainty formulations: 90%

TRL

3

**Technology Performance Goal:** Rapid and accurate uncertainty propagation for mixed-form uncertainties on a diverse class of physics-based simulation models.

**Parameter, Value:**

Proper handling of mixed uncertainty formulations: 100%

TRL

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

#### CAPABILITY

**Needed Capability:** Accurate assessment of mixed aleatory (inherent variability) and epistemic (lack of knowledge) representations of uncertainty.

**Capability Description:** Enables accurate and efficient evaluation of the effects of combined probabilistic and non-probabilistic descriptions of uncertainty on system risk and reliability predictions.

**Capability State of the Art:** Epistemic uncertainties are routinely modeled as either aleatory uniform distributions or as intervals and used in second-order (nested) Monte Carlo simulations. The former leads to false measures of probability and other statistics, while the latter is extremely computationally intensive and therefore not well suited for implementation.

**Parameter, Value:**

Proper handling of mixed uncertainty formulations: 20%

**Capability Performance Goal:** Physics-based models accurately and efficiently accommodate both epistemic and aleatory representations of uncertainty to obtain predictions of component or system-level risk and reliability.

**Parameter, Value:**

Proper handling of mixed uncertainty formulations: 100%

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	7 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	7 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	11 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	11 years
Real-Time System-Wide Safety Assurance: An Integrated Safety Assurance System Enabling Continuous System-Wide Safety Monitoring	Enhancing	--	--	2035	11 years



11.3 Simulation  
11.3.6 Uncertainty Quantification and  
Nondeterministic Simulation Methods

### 11.3.6.4 Toolset for Global Sensitivity Analysis of Uncertain Systems

#### TECHNOLOGY

**Technology Description:** Facilitates the identification of dominant effects contributing to the performance or robustness degradation for systems subject to probabilistic and non-probabilistic uncertainties.

**Technology Challenge:** The combination of uncertainty classes, such as aleatory and epistemic, requires the development of new mathematical tools.

**Technology State of the Art:** Analysis of variance, Morris one-step-at-a-time method, and Sobol methods are statistical methods commonly used for global sensitivity analysis.

**Parameter, Value:**

Identification of dominant parameters across entire parameter space: 90%

TRL

3

**Technology Performance Goal:** Global sensitivity analysis of physics-based simulation models subject to a broad class of uncertainties.

**Parameter, Value:**

Identification of dominant parameters across entire parameter space: 100%

TRL

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.3.6.3 Aleatory and Epistemic Uncertainty Assessment Toolset

#### CAPABILITY

**Needed Capability:** Dominant global effects analysis.

**Capability Description:** Enables global sensitivity analysis of model predictions to the input parameters and uncertainties, as they are free to vary within a prescribed domain.

**Capability State of the Art:** The bulk of current usage involves local deterministic sensitivity analysis at single or possibly multiple points in parameter space. This lacks the ability to capture global behavior, which can lead to unexpected consequences.

**Parameter, Value:**

Identification of dominant parameters across entire parameter space: 10%

**Capability Performance Goal:** A cost effective way to allocate resources in all development phases of mission/vehicle development.

**Parameter, Value:**

Identification of dominant parameters across entire parameter space: 100%

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	7 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	7 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	10 years
Real-Time System-Wide Safety Assurance: An Integrated Safety Assurance System Enabling Continuous System-Wide Safety Monitoring	Enhancing	--	--	2035	10 years

11.3 Simulation  
11.3.6 Uncertainty Quantification and  
Nondeterministic Simulation Methods

### 11.3.6.5 Software Toolset for Robust Design in the Presence of Uncertainty

#### TECHNOLOGY

**Technology Description:** Provides methods and tools to robustly design multidisciplinary complex systems where all forms of uncertainties are present.

**Technology Challenge:** Extreme computational expense associated with probabilistic design and accommodating all forms of uncertainty poses a technical challenge because few methods currently exist.

**Technology State of the Art:** Robust design, reliability-based design optimization, chance constrained, and the scenario approach are some of the techniques used for design optimization.

**Parameter, Value:**

Robustness to multiple classes of uncertainty: 60%

TRL

3

**Technology Performance Goal:** Rapid design methods and tools to robustly synthesize aerospace systems in the presence of uncertainties.

**Parameter, Value:**

Robustness to multiple classes of uncertainty: 100%

TRL

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing, 11.3.5 Exascale Simulation, 11.3.6.3 Aleatory and Epistemic Uncertainty Assessment Toolset.

#### CAPABILITY

**Needed Capability:** Design in the presence of uncertainty.

**Capability Description:** Design strategies that enable the systematic search for engineering solutions that accommodate the effects of uncertainty, including aleatory, epistemic, and model form uncertainties.

**Capability State of the Art:** Current robust design procedures often utilize descriptions of the uncertainties that facilitate tractable mathematical solutions and may not represent the true, or even physically viable, state of knowledge.

**Parameter, Value:**

Robustness to multiple classes of uncertainty: 5%

**Capability Performance Goal:** Multidisciplinary design methods and tools to accommodate all forms of uncertainty.

**Parameter, Value:**

Robustness to multiple classes of uncertainty: 80%

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	7 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	7 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	11 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	11 years
Real-Time System-Wide Safety Assurance: An Integrated Safety Assurance System Enabling Continuous System-Wide Safety Monitoring	Enhancing	--	--	2035	11 years

11.3 Simulation  
11.3.6 Uncertainty Quantification and  
Nondeterministic Simulation Methods

### 11.3.6.6 Surrogate Models for Uncertainty Quantification

#### TECHNOLOGY

**Technology Description:** Facilitates the utilization of simplified and computationally-efficient models to replace high-fidelity and computationally-intensive computer models.

**Technology Challenge:** Most surrogate modelling methods have very little heritage on NASA programs and would require extensive investment to move up in technology readiness level (TRL). This is even more the case when uncertainty is considered.

**Technology State of the Art:** Empirical prediction models can be used to describe model-form uncertainty and discretization/ numerical error of observations subject to measurement noise.

**Parameter, Value:**

Speed increase over physics-based models: 100x

TRL

4

**Technology Performance Goal:** Surrogate models that can robustly capture the effects of uncertainty on system response quantities.

**Parameter, Value:**

Speed increase over physics-based models: 1,000x

TRL

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.3.6.5 Software Toolset for Robust Design in the Presence of Uncertainty, 11.4.2 Intelligent Data Understanding, 11.4.3 Semantic Technologies.

#### CAPABILITY

**Needed Capability:** Accurate surrogate models for uncertainty quantification.

**Capability Description:** Robustly account for the effects of model-form uncertainty when compared to either high-fidelity predictions or observations of the physical system.

**Capability State of the Art:** Polynomial functions, radial basis functions, Taylor and Fourier series, and Kriging approximations used to capture the response of computationally-expensive models across narrow regions in the application domain.

**Parameter, Value:**

Speed increase over physics-based models: 10x

**Capability Performance Goal:** Ultra-efficient and accurate surrogate models validated across the entire operational domain.

**Parameter, Value:**

Speed increase over physics-based models: 1,000x

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	7 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	7 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	8 years
Real-Time System-Wide Safety Assurance: An Integrated Safety Assurance System Enabling Continuous System-Wide Safety Monitoring	Enhancing	--	--	2035	8 years



11.3 Simulation  
11.3.7 Multiscale, Multiphysics, and  
Multifidelity Simulation

### 11.3.7.1 Sequential Multiscale Analysis Toolset

#### TECHNOLOGY

**Technology Description:** Enables the capability to understand, design, and optimize material and structural systems with hierarchical interdependence of underlying physical processes.

**Technology Challenge:** Development of more concise mathematical bases for obtaining well-posed models, determination of error measures at each length scale to control fidelity, and quantification of the effect of uncertainty at all length scales and the effect of noise or fluctuations in the solutions.

**Technology State of the Art:** Model coupling is performed using small-scale physical experiments and limited model fidelity and range of dimensional linkage, yielding a predictive capability more qualitative than quantitative.

**Parameter, Value:**

Coupling order: 9  
Coupling accuracy: 20%

**TRL**

3

**Technology Performance Goal:** Require extended range of dimensional coupling, rigorously-defined homogenization in determining parameters used to sequentially link analyses, and increased fidelity at each length scale.

**Parameter, Value:**

Coupling order: 12  
Coupling accuracy: 1%

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing, 11.3.5 Exascale Simulation, 11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods, 11.3.8 Verification and Validation.

#### CAPABILITY

**Needed Capability:** Simulation of coupled physical processes by transferring high-fidelity information across a range of length scales.

**Capability Description:** Enables analyses to represent system response at different length and time scales using best-physics simulation methods.

**Capability State of the Art:** Simulations are performed using a sequence of existing analytical models with dimensional scales varying from atomistic to continuum.

**Parameter, Value:**

Coupling order: 9  
Coupling accuracy: 20%

**Capability Performance Goal:** Need increases in fidelity and in the range of length scales over which sequential multiscale analysis can be performed, to include subatomic ab initio simulations.

**Parameter, Value:**

Coupling order: 12  
Coupling accuracy: 1%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	7 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	10 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	10 years

11.3 Simulation  
11.3.7 Multiscale, Multiphysics, and  
Multifidelity Simulation

### 11.3.7.2 Concurrent Multiscale Analysis Toolset

#### TECHNOLOGY

**Technology Description:** Enables the capability to understand, design, and optimize material and structural systems with hierarchical interdependence of underlying physical processes.

**Technology Challenge:** Current requirements to enhance the technology include the development of more concise mathematical bases for obtaining well-posed models, determination of error measures at each length scale to control fidelity, and quantification of the effect of uncertainty at all length scales and the effect of noise or fluctuations in the solutions.

**Technology State of the Art:** Model coupling is performed using small-scale physical experiments and limited model fidelity and range of dimensional linkage, yielding a predictive capability more qualitative than quantitative.

**Parameter, Value:**

Coupling order: 9  
Coupling accuracy: 20%

**TRL**

3

**Technology Performance Goal:** Require high fidelity simulations over all length scales, seamless coupling between different physical models, and an increase in coupling order to include ab initio simulations.

**Parameter, Value:**

Coupling order: 12  
Coupling accuracy: 1%

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing, 11.3.5 Exascale Simulation, 11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods, 11.3.8 Verification and Validation.

#### CAPABILITY

**Needed Capability:** Simulation of coupled physical processes by transferring high-fidelity information across a range of length scales.

**Capability Description:** Enable analyses to represent system response at different length and time scales using best-physics simulation methods.

**Capability State of the Art:** Concurrent simulations performed using existing analytical models with dimensional scales varying from atomistic to continuum dimensional scales.

**Parameter, Value:**

Coupling order: 9  
Coupling accuracy: 20%

**Capability Performance Goal:** Require increases in fidelity and the range of length scales over which concurrent multiscale analysis can be performed, to include subatomic ab initio simulations.

**Parameter, Value:**

Coupling order: 12  
Coupling accuracy: 1%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	7 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	10 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	10 years

11.3 Simulation  
11.3.7 Multiscale, Multiphysics, and  
Multifidelity Simulation

### 11.3.7.3 Energetic Extreme Flux Analysis Toolset

#### TECHNOLOGY

**Technology Description:** Provides simulations of physical processes involving extreme energetic flux, including photons and high-energy particles that can cause damage to materials, electronics, and other devices over long time scales.

**Technology Challenge:** Require improved physical bases for nucleonic interaction/fragmentation models to better predict accumulated nanoscale damage and application of self-healing processes.

**Technology State of the Art:** Modeling methods exist to predict material's intrinsic properties for new and existing materials exposed to extreme environments. Tools have been developed that allow the observation of initial atomic-scale damage. Small-capacity algorithms, such as density functional theory for electronic structure and excitations and molecular dynamics for dynamic atomic interactions, are available.

**Parameter, Value:**

Current fidelity factor of technology: 6

**TRL**

3

**Technology Performance Goal:** Require prediction of damage produced by swift heavy ions traveling at relativistic velocities passing through materials. Better models are needed for the design of even stronger and more durable materials that operate in extreme flux environments, such as shielding for satellites and space probes.

**Parameter, Value:**

Increase in fidelity factor: 9

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing, 11.3.5 Exascale Simulation, 11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods, 11.3.8 Verification and Validation.

#### CAPABILITY

**Needed Capability:** Require high-fidelity methods for accurately performing coupled multiphysics simulations pertaining to extreme flux environments.

**Capability Description:** Enable modeling of materials in extreme energetic particle and photon flux environments that include nuclear fission and fusion reactors, long-lived radiation waste forms, photovoltaic systems, solar collectors, laser applications, and nanoscale electronics for computers and communication. Early failure and degradation is the primary constraint limiting material and structural performance in these environments.

**Capability State of the Art:** Current analyses use measurements of high-energy particles and photons and apply assumed empirical material damage models to assess the effect on load carrying ability and service life.

**Parameter, Value:**

Fidelity factor: 6 (Fidelity factor is defined as the range of length scales over which flux can be accurately simulated)

**Capability Performance Goal:** Prediction of intrinsic properties to simulate new and existing materials exposed to extreme environments.

**Parameter, Value:**

Fidelity factor: 9

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	7 years
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	10 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	10 years



11.3 Simulation  
11.3.7 Multiscale, Multiphysics, and  
Multifidelity Simulation

### 11.3.7.4 Chemically Extreme Environment Analysis Toolset

#### TECHNOLOGY

**Technology Description:** Provides simulations of physical processes involving extreme chemical environments; for example, chemically reactive environments that can cause damage to materials and devices over long time scales.

**Technology Challenge:** Require enhanced analytical methods to better understand the fundamental chemical reactions that cause degradation of materials in extreme environments.

**Technology State of the Art:** Basic material properties and actual combustion environments can be quantified. Test rigs are used to determine degradation mechanisms for materials at high temperatures.

**Parameter, Value:**

Coupling factor of technology: 6

**TRL**

3

**Technology Performance Goal:** Need better analytical models for the design of stronger and more durable materials and more reliable devices. The chemical stability of high-temperature materials must be known for use in the extreme environments of combustion applications.

**Parameter, Value:**

Coupling factor of technology: 9

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing, 11.3.5 Exascale Simulation, 11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods, 11.3.8 Verification and Validation.

#### CAPABILITY

**Needed Capability:** Require high-fidelity methods for accurately performing coupled multiphysics simulations pertaining to extreme chemical environments.

**Capability Description:** Modeling chemically reactive extreme environments pertaining to advanced power systems, such as fuel cells, nuclear reactors, and batteries. Requires an understanding of the fundamental processes involved in the degradation of materials in extreme chemical environments.

**Capability State of the Art:** Current modeling methods exist to computationally predict lifetimes of existing materials exposed to extreme environments.

**Parameter, Value:**

Coupling factor of capability: 6

**Capability Performance Goal:** Require improved, high-fidelity models to better predict lifetimes of new and existing materials exposed to extreme chemical environments.

**Parameter, Value:**

Coupling factor of capability: 9

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	7 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	7 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	4 years
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	10 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	5 years

11.3 Simulation  
11.3.7 Multiscale, Multiphysics, and  
Multifidelity Simulation

### 11.3.7.5 Thermomechanically Extreme Environment Analysis Toolset

#### TECHNOLOGY

**Technology Description:** Provides simulations of physical processes involving extreme thermomechanical environments; for example, extreme pressure and stress, strain and strain rate, and high and low temperature, that can cause damage to materials and devices over long time scales.

**Technology Challenge:** Require enhanced analytical methods to better understand the fundamental nano-/micro-scale processes that cause degradation of materials in extreme environments.

**Technology State of the Art:** Predicting failure of materials in extreme environment applications can be approximated using models of varying fidelity to predict defect generation and motion, phase transformations, and crack propagation under quasi-static and dynamic thermomechanical conditions.

**Parameter, Value:**

Current coupling factor: 6

**TRL**

3

**Technology Performance Goal:** Robust high-fidelity multiphysics methods with a rigorous representation of the thermomechanical environment are required to predict material damage due to dislocation nucleation and glide, grain boundary migration, nanocrack coalescence, and percolation under extreme temperatures and pressures.

**Parameter, Value:**

Coupling factor: 9

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing, 11.3.5 Exascale Simulation, 11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods, 11.3.8 Verification and Validation.

#### CAPABILITY

**Needed Capability:** Require high-fidelity methods for accurately performing coupled multiphysics simulations pertaining to extreme thermomechanical environments.

**Capability Description:** Provide models and analytical tools to predict the behavior of materials in-situ under thermomechanical extremes of high pressure and stress, strain and strain rate, and high and low temperature.

**Capability State of the Art:** Modeling the effects of thermomechanical extremes on material behavior includes interactions at the atomic, molecular, and microstructural level.

**Parameter, Value:**

Current coupling factor: 6

**Capability Performance Goal:** Improved modeling methods of the effects of thermomechanical extreme environments on material behavior. Coupled high-fidelity analyses of material processes at subatomic, atomic, molecular, and microstructural levels are needed.

**Parameter, Value:**

Coupling factor: 9

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	7 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	10 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	10 years

11.3 Simulation  
11.3.7 Multiscale, Multiphysics, and  
Multifidelity Simulation

### 11.3.7.6 Electro-Magnetic Extreme Analysis Toolset

#### TECHNOLOGY

**Technology Description:** Provides simulations of physical processes involving extreme electro-magnetic environments that can cause damage to materials and devices over long time scales.

**Technology Challenge:** Requires greater scope and accuracy in the application of methods for simulating magnetic, electro-magnetic coupling, and propagation effects on materials and devices.

**Technology State of the Art:** Fast multi-pole method, rank reduction methods, iterative methods, boundary element methods (BEM), finite element method (FEM), hybrid FEM-BEM, and asymptotic methods.

**Parameter, Value:**

Coupling factor: 6

**TRL**

3

**Technology Performance Goal:** An enhanced capability is needed to analyze materials and devices operating at extreme electric and magnetic fields. Need to consider much larger problem sizes and resolutions than are currently available.

**Parameter, Value:**

Coupling factor: 9

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing, 11.3.5 Exascale Simulation, 11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods, 11.3.8 Verification and Validation.

#### CAPABILITY

**Needed Capability:** Require high-fidelity methods for accurately performing coupled multiphysics simulations pertaining to extreme electromagnetic environments.

**Capability Description:** Analysis of new materials to predict the ability of materials and structures operating in extreme electric and magnetic fields that include insulators that withstand extreme electric fields, permanent magnet materials that produce high magnetic fields for generators and motors, and conductors and superconductors for coils that carry high current at low voltage for generators, motors, and transformers.

**Capability State of the Art:** Modeling the multiscale nature of breakdown, from slow charging of isolated, randomly-placed atomic defects to the sudden discharge of electrons along a macroscopic percolation path, is a recent development in standard simulation methods.

**Parameter, Value:**

Coupling factor: 6

**Capability Performance Goal:** Simulation enhancements are required to extend the range and size of problems solved by the methods of thermodynamics. Improved ab initio and molecular dynamics methods are needed for predicting material performance in extreme electro-magnetic fields.

**Parameter, Value:**

Coupling factor: 9

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	10 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	10 years



11.3 Simulation  
11.3.8 Verification and Validation

### 11.3.8.1 Model Verification Frameworks

#### TECHNOLOGY

**Technology Description:** Provide capabilities for quantifying the level of agreement between the predicted numerical solutions for a suboptimal discretization/fidelity setting and the solution corresponding to an optimal one.

**Technology Challenge:** Extensive development of code-specific libraries and resources would be required for the elimination of manual model verification.

**Technology State of the Art:** Manufactured solutions, grid/iterative convergence, and truncation/discretization error analysis are used to perform computational model verification.

**Parameter, Value:**

Reduction in time spent verifying code: 80%

TRL

4

**Technology Performance Goal:** Automated verification domain boundary estimators based on user-prescribed level of accuracy or error tolerance

**Parameter, Value:**

Reduction in time spent verifying code: 99%

TRL

5

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

#### CAPABILITY

**Needed Capability:** Verification technologies for simulation models.

**Capability Description:** Methods and tools to assure that simulation models match specifications and assumptions employed in their development.

**Capability State of the Art:** Limited verification using analytic solutions, cross-code comparison, discretization convergence studies, and Richardson extrapolation.

**Parameter, Value:**

Percentage of total engineering effort spent on verifying a new code: 70%

**Capability Performance Goal:** Substantial reduction in the amount of manual verification typically performed.

**Parameter, Value:**

Percentage of total engineering effort spent on verifying a new code: 35%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Safe, Efficient Growth in Global Operations: Improved Efficiency and Hazard Reduction within NextGen Operational Domains	Enhancing	--	--	2025	5 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	5 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	5 years
Real-Time System-Wide Safety Assurance: Introduction of Advanced Safety Assurance Tools	Enhancing	--	--	2025	5 years

11.3 Simulation  
11.3.8 Verification and Validation

### 11.3.8.2 Model Validation Frameworks

#### TECHNOLOGY

**Technology Description:** Provide rigorous tools to validate physics-based simulation models across a broad range of operating conditions.

**Technology Challenge:** Broad-domain general validation methods are still in development.

**Technology State of the Art:** Inspection, hypothesis testing, and intersection of confidence intervals/validation domains to validate models.

**Parameter, Value:**

Beyond nominal operation envelope validation in the presence of uncertainties.

**TRL**

4

**Technology Performance Goal:** Tools and methods using limited experimental data to produce validation domains that account for all forms of uncertainties.

**Parameter, Value:**

Full application domain validation.

**TRL**

4

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods.

#### CAPABILITY

**Needed Capability:** Validation of simulation models.

**Capability Description:** Quantification of the level of agreement between a model's predictions and observations of the physical phenomenon. Determination of the range of applicability of the model based on its assumptions, accuracy, and limitations.

**Capability State of the Art:** Current usage limited primarily to steady-state analyses. Development and implementation into unsteady and dynamic simulations is severely lacking. Inconsistent usage across disciplines.

**Parameter, Value:**

Limited single-point or multi-point validation methods. Limited validation capability in the presence of uncertainties.

**Capability Performance Goal:** Tools and methods using limited experimental data to produce validation domains that account for all forms of uncertainties.

**Parameter, Value:**

Full nominal operation envelope validation in the presence of uncertainties.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Safe, Efficient Growth in Global Operations: Improved Efficiency and Hazard Reduction within NextGen Operational Domains	Enhancing	--	--	2025	5 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	5 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	5 years
Real-Time System-Wide Safety Assurance: Introduction of Advanced Safety Assurance Tools	Enhancing	--	--	2025	5 years

11.4 Information Processing  
11.4.1 Science, Engineering, and  
Mission Data Lifecycle

### 11.4.1.1 Reference Information System Architecture Frameworks

#### TECHNOLOGY

**Technology Description:** Provide reference information system architectures for the end-to-end science, engineering, and mission data lifecycle.

**Technology Challenge:** Architectures need to be viable to support the planned increase in data and computing requirements that are unique to NASA's end-to-end science and engineering lifecycle.

**Technology State of the Art:** Reference software architecture describing multiple views for different NASA models/use cases.

**Technology Performance Goal:** Explicit data intensive reference architectures (technology, information models, processes) for the information and technical architecture.

**Parameter, Value:**

Percentage of reference architectures completed: 25%

**TRL**

5

**Parameter, Value:**

Percentage of reference architectures completed: 75%

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

#### CAPABILITY

**Needed Capability:** Reference space information system architecture.

**Capability Description:** Design software and information system architectures that identify common design patterns in science and exploration missions showing the end-to-end data lifecycle from data collection to data analysis.

**Capability State of the Art:** Reference architectures generally look specifically at subsystems, rather than across the entire lifecycle.

**Capability Performance Goal:** Define an integrated space information architecture that describes end-to-end software and data architectures from point of collection to use, analysis, and decision support.

**Parameter, Value:**

Percentage of reference architectures completed: 25%

**Parameter, Value:**

Percentage of reference architectures completed: 75%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.4 Information Processing  
11.4.1 Science, Engineering, and  
Mission Data Lifecycle

### 11.4.1.2 Distributed Information Architecture Frameworks

#### TECHNOLOGY

**Technology Description:** Provide reference information architectures to define data across the end-to-end engineering, science, and mission data lifecycle.

**Technology Challenge:** Information architectures need to support the definition of the variety of data across missions, science, and operations that are unique to NASA.

**Technology State of the Art:** Distributed services and architecture enabling multi-center configurations for operations and analysis.

**Technology Performance Goal:** Increase efficiency of operations by sharing data through common information architectures.

**Parameter, Value:**

Percentage of NASA data shared across systems/  
centers: < 5%

TRL

5

**Parameter, Value:**

Percentage of NASA data shared across systems/  
centers: 15%

TRL

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.4.1.1 Reference Information System Architecture Framework

#### CAPABILITY

**Needed Capability:** Reference space and engineering information architectures.

**Capability Description:** Design software and information architectures that span multiple systems and organizations that must integrate and/or orchestrate the operations and data.

**Capability State of the Art:** Systems are not well integrated, with limited data sharing.

**Capability Performance Goal:** Define an integrated space information architecture that describes end-to-end data architectures from point of collection to use, analysis, and decision support.

**Parameter, Value:**

Percentage of NASA data shared across systems/centers: < 5%

**Parameter, Value:**

Percentage of NASA data shared across systems/centers: 15%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.4 Information Processing  
11.4.1 Science, Engineering, and  
Mission Data Lifecycle

### 11.4.1.3 Information Modeling Frameworks

#### TECHNOLOGY

**Technology Description:** Provide tools for the development of complex information models to explicitly describe the information architecture across missions, science, and operations.

**Technology Challenge:** Models describing NASA data in missions, science, and operations need to be explicitly defined in order to ensure data can be searched, accessed, and used.

**Technology State of the Art:** Explicit domain information architectures for science and engineering.

**Parameter, Value:**

Percentage of information models defined for NASA data: 10%

**TRL**

4

**Technology Performance Goal:** Develop complex information models that capture the semantics in science and mission data.

**Parameter, Value:**

Percentage of information models defined for NASA data: 25%

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.4.1.2 Distributed Information Architecture Framework

#### CAPABILITY

**Needed Capability:** Common information models for science and engineering data.

**Capability Description:** Common information models and standard data structures are used to describe the data that flows from point of collection through analysis and use for different data domains. These are unique to NASA.

**Capability State of the Art:** Many applications have embedded information architectures in software/applications. Some domain information architectures exist (such as Planetary Science ontology).

**Parameter, Value:**

Percentage of information models defined for NASA data: 10%

**Capability Performance Goal:** Define common information models that describe the data objects that are used within NASA science, engineering, mission operations, etc. systems.

**Parameter, Value:**

Percentage of information models defined for NASA data: 25%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.4 Information Processing  
11.4.1 Science, Engineering, and  
Mission Data Lifecycle

### 11.4.1.4 Onboard Data Capture and Triage Methodologies

#### TECHNOLOGY

**Technology Description:** Apply novel machine learning capabilities onboard to support data reduction, model-based compression, and triage of massive data sets.

**Technology Challenge:** Application of machine learning technologies for onboard data reduction and triage for massive/Big Data instruments and observational data, providing high compression rate at a fidelity similar to lossless compression.

**Technology State of the Art:** Research efforts investigating onboard planning and triage. Compressive sensing algorithms enable the capture of signals at a rate significantly below the Nyquist rate. The algorithms employ non-adaptive linear projections that preserve the structure of the signal, which is then reconstructed from these projections using an optimization process.

**Parameter, Value:**

Percentage of data reduction: 20%

TRL

3

**Technology Performance Goal:** Deployment of much more capable flight software onboard using advanced machine learning capabilities that can leverage more computational processor and memory management. Demonstration of in-space compressive sensing.

**Parameter, Value:**

Percentage of data reduction: 50%

TRL

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing

#### CAPABILITY

**Needed Capability:** Onboard data capture, triage, and reduction.

**Capability Description:** Utilize onboard processing and analysis combined with autonomous decision making to optimize mission return while minimizing data downlink. Design common methods for data reduction directly at the point of collection in order to address challenges in capture, management, and analysis of massive science and engineering data.

**Capability State of the Art:** Minimal methods onboard for intelligent data reduction. NASA's Earth Observing 1 (EO-1) experiments have performed onboard cloud detection and data targeting based on onboard planning and scheduling. Sensor web demonstrations for fire detection involving the Moderate Resolution Imaging Spectroradiometer (MODIS), EO-1, unmanned aerial vehicles (UAV), and ground sensors (not entirely autonomous). Lossless compression is performed onboard for all sensors.

**Parameter, Value:**

Percentage of data reduction: 5%

**Capability Performance Goal:** Data triage and reduction methods achieve significant reduction in collected data, autonomously.

**Parameter, Value:**

Percentage of data reduction: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.4 Information Processing  
11.4.1 Science, Engineering, and  
Mission Data Lifecycle

### 11.4.1.5 Real-time Data Triage and Data Reduction Methodologies

#### TECHNOLOGY

**Technology Description:** Apply novel machine learning capabilities in ground data processing systems to support data reduction and triage of massive data sets.

**Technology Challenge:** Massive observational data from multiple observing instruments will overwhelm ground systems and data archives, requiring real-time data triage and reduction. Limited data reduction methods occurring across the data lifecycle.

**Technology State of the Art:** Data is generally not reduced across the data lifecycle. In science, data processing occurs at the end of the pipeline, rather than earlier, which increases the size of the data.

**Parameter, Value:**

Percentage data reduction: 20%

**TRL**

3

**Technology Performance Goal:** Real-time data triage and reduction occurs across the data lifecycle.

**Parameter, Value:**

Percentage data reduction: 20%

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.4.6.1 Scalable On-Demand Storage and Computation

#### CAPABILITY

**Needed Capability:** Real-time data triage and reduction.

**Capability Description:** Provide triage methods on massive data sets across the mission lifecycle (from data collection to data streaming to data archives) to reduce the size of data and support data mining and discovery.

**Capability State of the Art:** All data is generally processed. Limited techniques for data reduction.

**Parameter, Value:**

Percentage data reduction: 0%

**Capability Performance Goal:** Real-time data triage and reduction methods achieve reduction in data streams throughout ground data systems.

**Parameter, Value:**

Percentage data reduction: 20%

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.4 Information Processing  
11.4.1 Science, Engineering, and  
Mission Data Lifecycle

### 11.4.1.6 Scalable Data Processing Frameworks

#### TECHNOLOGY

**Technology Description:** Provide scalable software processing frameworks for processing scientific, engineering, and mission data sets.

**Technology Challenge:** Support a significant increase in data and computational data processing demands to support mission and science needs for Big Data.

**Technology State of the Art:** Data processing occurring as part of data production pipelines as well as on-demand computational workflows.

**Parameter, Value:**

Cores available on demand: 1,000

**TRL**

6

**Technology Performance Goal:** Allow systems to scale to high-performance computing (HPC) and other environments to support compute-intensive data processing.

**Parameter, Value:**

Cores available on demand: 10,000

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing, 11.3.5 Exascale Simulation

#### CAPABILITY

**Needed Capability:** Scalable data processing.

**Capability Description:** Provide scalable processing methods of science and engineering data.

**Capability State of the Art:** Data is processed through scripts or one-of-a kind systems often using locally developed capabilities.

**Parameter, Value:**

Cores available on demand: 1,000

**Capability Performance Goal:** Data processing uses well-orchestrated software (such as workflow systems) and computing infrastructures to scale computational to internal and external services using a massive number of computing cores.

**Parameter, Value:**

Cores available on demand: 10,000

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.4 Information Processing  
11.4.1 Science, Engineering, and  
Mission Data Lifecycle

### 11.4.1.7 Massive Engineering and Science Data Analysis Methodologies

#### TECHNOLOGY

**Technology Description:** Provide scalable infrastructures for analysis of massive data.

**Technology Challenge:** Ability to perform distributed data analytics (including data fusion, extraction, etc.) through systematic data science frameworks within a distributed architecture.

**Technology State of the Art:** Data analysis is performed in distributed environments where data is brought to the computation, rather than computation to the data.

**Technology Performance Goal:** Data analysis is performed in distributed environments making appropriate decisions regarding whether to bring computation to the data or move the data to the computation.

**Parameter, Value:**

Percentage of data analysis needs met by server-side computations: 5%

TRL

4

**Parameter, Value:**

Percentage of data analysis needs met by server-side computations: 50%

TRL

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing, 11.3.5 Exascale Simulation, 11.4.6.1 Scalable On-Demand Storage and Computation.

#### CAPABILITY

**Needed Capability:** Scalable data analytics.

**Capability Description:** Provide scalable analysis services to support engineering and scientific data analysis.

**Capability State of the Art:** Data analysis is performed by end users. Limited data fusion occurring across instruments through ad hoc methods.

**Capability Performance Goal:** Scalable analytics capabilities are available on demand for engineering and science applications.

**Parameter, Value:**

Percentage of data analysis needs met by server-side computations: 5%

**Parameter, Value:**

Percentage of data analysis needs met by server-side computations: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.4 Information Processing  
11.4.1 Science, Engineering, and  
Mission Data Lifecycle

### 11.4.1.8 Remote Data Access Framework

#### TECHNOLOGY

**Technology Description:** Provides access to and sharing of distributed data sources in a secure environment.

**Technology Challenge:** Takes advantage of high-speed networks, advanced cache algorithms, and advanced software interfaces to distributed resources across heterogeneous systems and environments.

**Technology State of the Art:** Application programming interfaces (APIs) that provide access to data and services across systems using common protocols, including cloud storage systems.

**Technology Performance Goal:** Server-side APIs available for 50% of engineering and science data. Tera-petabytes of engineering and science data can be accessed and shared across multiple sources in a secure, persistent NASA data store.

**Parameter, Value:**

Percentage of engineering and science data for which server-side APIs are available: 10%  
Speed of data access: 5 GB x 1 Mbps.

**TRL**

6

**Parameter, Value:**

Percentage of engineering and science data for which server-side APIs are available: 50%  
Speed of data access: 10 TB x 10 Mbps.

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing, 11.4.8 Cyber Security

#### CAPABILITY

**Needed Capability:** Fast and transparent access between distributed and remote data storage and simulations.

**Capability Description:** Provides services to access, distribute, and synchronize terabytes of data, whether local or remote, including the ability to download the data and/or a portion of the data through common APIs.

**Capability State of the Art:** Data access is performed through web-based clients and APIs. Remote data access is limited, in an unsecure environment and often ad hoc.

**Capability Performance Goal:** Common data services available online for access to and reduction of data in a fast and secure fashion.

**Parameter, Value:**

Percentage of engineering and science data for which server-side APIs are available: 10%  
Speed of data access: 5 GB x 1 Mbps.

**Parameter, Value:**

Percentage of engineering and science data for which server-side APIs are available: 50%  
Speed of data access: 10 TB x 10 Mbps.

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Enhancing	2027	2027	2021	5 years

Exploring Other Worlds: DRM 6 Crewed to NEA

11.4 Information Processing  
11.4.1 Science, Engineering, and  
Mission Data Lifecycle

### 11.4.1.9 Massive Data Movement Services

#### TECHNOLOGY

**Technology Description:** Develop new technologies for the movement of massive, multi-petabyte data over the network.

**Technology Challenge:** Increase movement of data to support higher data rates, from observing systems through to analysis.

**Technology State of the Art:** High-speed data movement mechanisms in place for moving massive amounts of data.

**Parameter, Value:**

Online data movement: 500 GB a day per dataset.

**TRL**

4

**Technology Performance Goal:** Movement towards higher performance data movement technologies.

**Parameter, Value:**

Online data movement rate: 50 TB a day per dataset.

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing, 11.4.8 Cyber Security

#### CAPABILITY

**Needed Capability:** Large-scale data movement.

**Capability Description:** Provide software and networking capabilities to support movement of massive data over the network, including mechanisms from ground/space and across ground networks using advanced techniques like parallel data transfer.

**Capability State of the Art:** Data is moved between several institutions and centers to computing services. Movement of massive data is limited to current network capacities and use of traditional data movement technologies.

**Parameter, Value:**

Online data movement rate: 500 GB a day per dataset.

**Capability Performance Goal:** Movement of petabyte scale data sets across institutions.

**Parameter, Value:**

Online data movement rate: 50 TB a day per dataset.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.4 Information Processing  
11.4.1 Science, Engineering, and  
Mission Data Lifecycle

### 11.4.1.10 Large-Scale Data Dissemination Environments

#### TECHNOLOGY

**Technology Description:** Enable scaling data infrastructures, including software, computation, and networks, that are required to support large-scale data dissemination.

**Technology Challenge:** Develop new data dissemination technologies to increase the distribution and use of data for engineering and science analysis.

**Technology State of the Art:** Multiple mechanisms in place for performing computation and reduction of data at the storage location. Ability for users to reduce data for distribution. Ability to distribute NASA observational data to a massive user base for both research and public use.

**Parameter, Value:**

Data dissemination rate across NASA: 10 TB per day.

TRL

5

**Technology Performance Goal:** Distribution of massive data across highly distributed environments (such as, NASA centers).

**Parameter, Value:**

Data dissemination rate across NASA centers: 10 PB per day.

TRL

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing, 11.4.1.9 Intelligent Search Methodologies for Massive Data, 11.4.1.10 Massive Data Movement Services, 11.4.6.1 Scalable On-Demand Storage and Computation, 11.4.8 Cyber Security.

#### CAPABILITY

**Needed Capability:** Data dissemination.

**Capability Description:** Provide scalable distribution services for engineering and science data and/or a set of the data for use in analysis, operations, and decision support.

**Capability State of the Art:** Users download data for use (such as science analysis). Data dissemination bound by network capacities and sizes of data sets.

**Parameter, Value:**

Data dissemination rate across NASA: 10 TB per day.

**Capability Performance Goal:** Enable dissemination of massive data sets for science, engineering, and mission operations. Leverage data movement services, server-side processing, data access, etc.

**Parameter, Value:**

Data dissemination rate across NASA: 10 PB per day.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.4 Information Processing  
11.4.1 Science, Engineering, and  
Mission Data Lifecycle

### 11.4.1.11 Toolset for Massive Model Data

#### TECHNOLOGY

**Technology Description:** Makes data and information transparent, scalable, and usable when infusing multiple large and diverse datasets into complex models.

**Technology Challenge:** Increase the number of types of data sources that can be examined (discrete, continuous, text, time series, image, graph, etc.), thus making NASA models more accurate.

**Technology State of the Art:** Today's data analytics technology tools include databases and open source tools for large-scale data processing on commodity clusters, such as clouds.

**Parameter, Value:**

Percentage of automated steps to select and integrate large and various datasets: 30%

TRL

3

**Technology Performance Goal:** For a given model, develop all the tools needed to mine, discover, and fuse all the available datasets appropriate for the model.

**Parameter, Value:**

Percentage of automated steps to select and integrate large and various datasets: 100%

TRL

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing

#### CAPABILITY

**Needed Capability:** Big Data analytics for complex NASA modeling.

**Capability Description:** Analyzes, performs data mining, and develops computer-aided discovery tools to provide the ability to handle very large amounts of disparate data that are intrinsic to NASA missions.

**Capability State of the Art:** Algorithms use a large number of carefully-selected datasets to derive merged products. Example of 3B42 algorithm that produces tropical rainfall measurement mission-adjusted merged-infrared (IR) precipitation and root-mean-square (RMS) precipitation error estimates.

**Parameter, Value:**

Percentage of automated steps to select and integrate large and various datasets: 20%

**Capability Performance Goal:** Complex NASA models utilize many datasets of various data types in a seamless and automated fashion.

**Parameter, Value:**

Percentage of automated steps to select and integrate large and various datasets: 100%

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enhancing	--	2024*	2020	5 years
Living with a Star: Geospace Dynamics Constellation (GDC)	Enhancing	--	2030	2019	5 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.4 Information Processing  
11.4.2 Intelligent Data Understanding

### 11.4.2.1 Intelligent Data Collection and Prioritization Toolset

#### TECHNOLOGY

**Technology Description:** Provides a means to reduce the size of the data, such as removing clouds and corrupted data, prioritizing data based on content, and/or collecting complementary data for value-added information.

**Technology Challenge:** High-performance space computer with fast, reliable, autonomous data processing techniques.

**Technology State of the Art:** NASA's SpaceCube 2.0 onboard processor for onboard science data processing and analysis.

**Technology Performance Goal:** Full onboard data reduction for instruments acquiring large amounts of data, such as hyperspectral and radar sensors.

**Parameter, Value:**

Percentage of decisions made autonomously: 30%

TRL

6

**Parameter, Value:**

Percentage of decisions made autonomously: 100%

TRL

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing

#### CAPABILITY

**Needed Capability:** Onboard intelligence.

**Capability Description:** Utilize onboard processing and analysis combined with autonomous decision making to optimize the missions return while minimizing data downlink.

**Capability State of the Art:** NASA's Earth Observing 1 (EO-1) experiments have performed onboard cloud detection and data targeting based on onboard planning and scheduling. Sensor web demonstrations for fire detection involving Moderate Resolution Imaging Spectroradiometer (MODIS), EO-1, unmanned aerial vehicle (UAV), and ground sensors (not entirely autonomous). Lossless compression is performed onboard for all sensors.

**Capability Performance Goal:** All routine and near-routine onboard operations are performed autonomously.

**Parameter, Value:**

Percentage of decisions made autonomously: 30%

**Parameter, Value:**

Percentage of decisions made autonomously: 100%

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.4 Information Processing  
11.4.2 Intelligent Data Understanding

## 11.4.2.2 Event Detection and Intelligent Action Toolset

## TECHNOLOGY

**Technology Description:** Provides computational mechanisms to identify high information content data, either pre-specified, novel, or anomalous, including multi-spacecraft collaborative event detection, and to make an autonomous or assisted onboard decision as a result of data analysis.

**Technology Challenge:** Reliability, speed, and appropriate computing systems (such as cognitive computing) on the ground and onboard.

**Technology State of the Art:** Smart sensing technologies through autonomous sensor webs to enable autonomous event detection and re-configuration of sensors associated with knowledge technologies, intelligent agents, and other technologies to transform data into information into knowledge into wisdom in prearranged ways.

**Parameter, Value:**

Percentage of decisions made autonomously: 20%

**TRL**

3

**Technology Performance Goal:** Autonomous smart sensing capability, such as full autonomy of future assets using onboard decision making based on a combination of human knowledge and experience.

**Parameter, Value:**

Percentage of decisions made autonomously: 100%

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing, 4.1.4.3 Event Recognition

## CAPABILITY

**Needed Capability:** Onboard intelligence.

**Capability Description:** Utilize onboard processing and analysis combined with autonomous decision making to optimize the missions return while minimizing data downlink.

**Capability State of the Art:** NASA's Earth Observing 1 (EO-1) experiments have performed onboard cloud detection and data targeting based on onboard planning and scheduling. Sensor web demonstrations for fire detection involving Moderate Resolution Imaging Spectroradiometer (MODIS), EO-1, unmanned aerial vehicles (UAV), and ground sensors (not entirely autonomous). Lossless compression is performed onboard for all sensors. The Mars exploration rovers can automatically identify dust devils in a series of images and can identify rocks with certain properties and autonomously acquire additional data on those rocks.

**Parameter, Value:**

Percentage of decisions made autonomously: 30%

**Capability Performance Goal:** All routine and near-routine onboard operations are performed autonomously.

**Parameter, Value:**

Percentage of decisions made autonomously: 100%

## Technology Needed for the Following NASA Mission Class and Design Reference Mission

Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Enhancing	--	2023*	2020	6 years
Enhancing	--	2020	2017	3 years
Enhancing	--	2022*	2019	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.4 Information Processing  
11.4.2 Intelligent Data Understanding

11.4.2.3 Data on Demand Toolset

TECHNOLOGY

**Technology Description:** Enable users and models to task sensors and leverage sensor webs to develop “on-demand” products.

**Technology Challenge:** Intelligent non-predicted in advance, analysis of data in response to a trigger, such as a science event onboard or a model output on the ground.

**Technology State of the Art:** Use of resource oriented architecture (ROA) and workflows to gather data from various and existing assets.

**Technology Performance Goal:** Data acquired and prioritized based on models comparing data collected with predicted observations, identifying unexpected trends as well as individual events.

**Parameter, Value:**

Percentage of required unplanned data acquired on demand after launch: 20%

TRL

4

**Parameter, Value:**

Percentage of required unplanned data acquired on demand after launch: 100%

TRL

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing, 11.4.1 Science, Engineering and Mission Data Lifecycle

CAPABILITY

**Needed Capability:** Seamless data acquisition.

**Capability Description:** Develop architectures to seamlessly move components from ground to flight and from flight to flight.

**Capability State of the Art:** Usually regular acquisition schedule, except for tech demo/testbed, such as Earth Observing 1 where data targeted and acquired is based on a ground-based campaign manager.

**Capability Performance Goal:** Target and acquire datasets as needed by onboard product generation, as well as by ground models and applications.

**Parameter, Value:**

Percentage of required unplanned data acquired on demand after launch: 20%

**Parameter, Value:**

Percentage of required unplanned data acquired on demand after launch: 100%

Technology Needed for the Following NASA Mission Class and Design Reference Mission

Enabling or  
Enhancing

Mission  
Class Date

Launch  
Date

Technology  
Need Date

Minimum  
Time to  
Mature  
Technology

Strategic Missions: Exoplanet Direct Imaging Mission

Enhancing

--

2030\*

2025

10 years

Living with a Star: Geospace Dynamics Constellation (GDC)

Enhancing

--

2030

2019

5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.4 Information Processing  
11.4.2 Intelligent Data Understanding

### 11.4.2.4 Intelligent Data Search and Mining Toolset

#### TECHNOLOGY

**Technology Description:** Develops search services and engines for massive, distributed data holdings; enables the application of different searching rules/schemes that learn from past searches; and develop “agents” to find and create the most relevant products. It includes rich queries, including fact-based, free-text searches, web-service based indexing as well as anomaly/novelty detection, where the system suggests items of interest to the user without the user necessarily prescribing the information being sought.

**Technology Challenge:** Data is defined by different models and formats and exposed through different systems for access (including different security rules), discovery, and use. Challenges include: implementing community-based standards and application program interfaces (APIs); cost of implementation; handling large amounts of heterogeneous data, characterized by volume (data at rest), velocity (new data arriving), variety (data in many forms), value (multiple uses), and veracity (trustworthiness and provenance); and appropriate computing resources, on the ground (cognitive computing) and onboard (high performance spaceflight computing).

**Technology State of the Art:** Multiple search approaches are in place for search and discovery across distributed engineering and science repositories, both at the metadata and data levels. With Open Geo-Social APIs, available data products are discovered and the methods used to create them are shared with other users through social media. Anomaly detection is also applied to find operationally significant events in Aeronautics.

**Parameter, Value:**

Percentage of relevant data for each query: 60%

**TRL**

4

**Technology Performance Goal:** Ability to easily, transparently, seamlessly obtain data and products in different locations without a central catalog. Common services are in place for search and discovery of massive, distributed, heterogeneous data sets. Data are fused with other data, models, and simulations to derive knowledge that will best help the mission. Potential extension to onboard data mining and applications to exploration.

**Parameter, Value:**

Percentage of relevant data for each query: 90%

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing, 11.4.1 Science, Engineering and Mission Data Lifecycle

#### CAPABILITY

**Needed Capability:** Data search and discovery, data mining to derive useful knowledge.

**Capability Description:** Provide services to support data discovery using different search techniques based on annotations of the data, arithmetic attributes, textual search, semantic search, etc.

**Capability State of the Art:** Search is discipline-specific. On the ground, data exploration unifies theory, experiment, and simulation: (1) data captured by instruments or simulated; (2) processed by software; (3) information/knowledge stored in computer; and (4) scientist analyzes database/files using data management and statistics. User-intensive catalog, web searches; lack of interoperability.

**Parameter, Value:**

Percentage of relevant data for each query: 40%

**Capability Performance Goal:** Common services are in place for search and discovery of massive, distributed, heterogeneous data sets. Data returned by query are most relevant to users' needs.

**Parameter, Value:**

Percentage of relevant data for each query: 90%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	7 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Strategic Missions: Exoplanet Direct Imaging Mission	Enhancing	--	2030	2025	10 years
Safe, Efficient Growth in Global Operations: System-Wide Safety, Predictability, and Reliability Through Full NextGen Functionality	Enhancing	--	--	2035	10 years

11.4 Information Processing  
11.4.2 Intelligent Data Understanding

11.4.2.5 Data Fusion Toolset

TECHNOLOGY

**Technology Description:** Combines data from multiple sources, including remote sensing, in-situ, and models, in order to make inferences that might otherwise not be possible with single data sources, or in order to improve the uncertainty characteristics of these inferences, over what might be achieved with single data sources.

**Technology Challenge:** Reliability, accuracy, robustness, sustainability, and applicability of the tools.

**Technology State of the Art:** Science: Development of data fusion algorithms to propagate measurement and data product uncertainty estimates into resulting data fused products.

Exploration: Development of algorithms for real-time fusion of light detection and ranging and visible data to perform autonomous planetary landing and navigation.

**Parameter, Value:**

Final product uncertainty improvement compared to using only one source of data: 60%

TRL

3

**Technology Performance Goal:** Reusable software libraries for data fusion tools.

**Parameter, Value:**

Final product uncertainty improvement compared to using only one source of data: 80%

TRL

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.4.1 Science, Engineering and Mission Data Lifecycle

CAPABILITY

**Needed Capability:** Data and information integration.

**Capability Description:** Utilize redundant and complementary data and information to create higher-impact data products.

**Capability State of the Art:** Science: Fusion of climate data to provide a better estimate of the total amount of carbon dioxide in the troposphere and above.

Exploration: autonomous car challenges.

**Parameter, Value:**

Final product uncertainty improvement compared to using only one source of data: 40%

**Capability Performance Goal:** Integrating multi-source data improves significantly the uncertainty of the final data products.

**Parameter, Value:**

Final product uncertainty improvement compared to using only one source of data: 80%

Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enhancing	--	2024*	2020	6 years
Earth Systematic Missions: Global Atmosphere Composition Mission (GACM)	Enhancing	--	2024*	2019	5 years
Solar Terrestrial Probes: Interstellar Mapping and Acceleration Probe (IMAP)	Enhancing	--	2022	2019	5 years
Solar Terrestrial Probes: Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)	Enhancing	--	2025	2021	7 years
Strategic Missions: Far Infrared Surveyor Mission	Enhancing	--	2035	2035	7 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.4 Information Processing  
11.4.2 Intelligent Data Understanding

### 11.4.2.6 Information Representation Standards for Persistent Data

#### TECHNOLOGY

**Technology Description:** Provide an extensible, evolvable human and machine readable information representation that is key to rapid and persistent understanding of science and engineering phenomena.

**Technology Challenge:** Standards definition is a challenge.

**Technology State of the Art:** NASA's Earth Exchange: human exchange of information and knowledge.

**Parameter, Value:**

Percentage of interoperability between all datasets used in a given application: 50%

**TRL**

7

**Technology Performance Goal:** An extensible, evolvable human and machine readable information system.

**Parameter, Value:**

Percentage of interoperability between all datasets used in a given application: 100%

**TRL**

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.4.1 Science, Engineering and Mission Data Lifecycle

#### CAPABILITY

**Needed Capability:** Standards for intelligent data understanding.

**Capability Description:** Develop standards for interoperability that enable the exchange and use of high-level information.

**Capability State of the Art:** Extensible modeling language (XML)-based simulation state information.

**Parameter, Value:**

Percentage of interoperability between all datasets used in a given application: 50%

**Capability Performance Goal:** All datasets used in a given application are interoperable.

**Parameter, Value:**

Percentage of interoperability between all datasets used in a given application: 100%

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	7 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	7 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	7 years
Strategic Missions: Exoplanet Direct Imaging Mission	Enhancing	--	2030*	2025	10 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

## 11.4 Information Processing

### 11.4.3 Semantic Technologies

#### 11.4.3.1 Semantic Enabler for Data (Text, Binary, and Databases)

##### TECHNOLOGY

**Technology Description:** Ingests data of all types and produces a data model and a precision ontology; improves the quality of any existing metadata, including provenance and quality of the source document; and disambiguates words in the context of the document, database, or file and visualizes the results.

**Technology Challenge:** Technologies needed to apply natural language programming to extract formal knowledge models. Handling documents with internal structure, such as chapters, sections, tables, graphics, embedded metadata, data models for non-SQL databases, and files.

**Technology State of the Art:** Commercial tools provide current limited functionality with adequate performance, but require extraordinary effort to prepare input data. Existing data modeling tools are limited to structured query language.

**Parameter, Value:**

Time to ingest new datasets: 2 weeks

Time to search collection: 30 minutes

Presentation of relevant data at top of results: 1 parameter.

**TRL**

6

**Technology Performance Goal:** Time to ingest unknown data sets with no handling or pre-ingest grooming.

**Parameter, Value:**

Time to ingest new documents: 2 minutes

Time to search collection: 30 seconds

Presentation of relevant data at top of results: 10 parameters.

**TRL**

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.4.1 Science, Engineering and Mission Data Lifecycle

##### CAPABILITY

**Needed Capability:** Knowledge capture from raw datasets.

**Capability Description:** Grooms existing datasets of all types to enable analysis, synthesis, assessment, and extraction of insight, experience, and information.

**Capability State of the Art:** Ingest tools lack automation and flexibility. No semantic ability to self-groom or trap context. Many dataset types and formats cannot be ingested, including tables, hand-written notes, etc. Advanced tools are emerging for recycling information extraction.

**Parameter, Value:**

Time to ingest new datasets with minimum quality: weeks with full time attendant

Time to search collection: minutes

Presentation of relevant data at top of results: 1 parameter.

**Capability Performance Goal:** Automatically create a data model and a precision ontology from unknown dataset with no human interaction.

**Parameter, Value:**

Time to ingest new documents: 2 minutes

Time to search collection: 30 seconds

Presentation of relevant data at top of results: 10 parameters.

##### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Earth Systematic Missions: Geostationary Coastal and Air Pollution Events (GEO-CAPE)	Enhancing	--	2024*	2019	5 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years
Safe, Efficient Growth in Global Operations: Improved Efficiency and Hazard Reduction within NextGen Operational Domains	Enhancing	--	--	2025	5 years
Real-Time System-Wide Safety Assurance: Introduction of Advanced Safety Assurance Tools	Enhancing	--	--	2025	5 years
Enable Assured Machine Autonomy for Aviation: Ability to Fully Certify and Trust Autonomous Systems for NAS Operations	Enhancing	--	--	2035	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

#### 11.4 Information Processing

##### 11.4.3 Semantic Technologies

#### 11.4.3.2 Ultra Large-Scale Visualization and Incremental Toolset

##### TECHNOLOGY

**Technology Description:** Enables and automates analysis of ultra-large-scale datasets and visualizes the results in the context of the knowledge domain.

**Technology Challenge:** Development of unstructured grids and automated workflow process; reduction of execution time through software efficiencies.

**Technology State of the Art:** NASA and other agencies are supporting the Ultra-scale Visualization Climate Data Analysis Tools project.

**Parameter, Value:**

Size of dataset: 100 TB

Time to perform analysis: weeks

TRL

6

**Technology Performance Goal:** Up to five datasets for simultaneous analysis in less than six hours.

**Parameter, Value:**

Size of dataset: 10 PB

Time to perform analysis: 1 hour

TRL

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing, 11.3.5 Exascale Simulation

##### CAPABILITY

**Needed Capability:** Analysis of ultra-large datasets.

**Capability Description:** Makes tractable exponential increases in the computational and storage capabilities of high-performance computing platforms. Climate model simulations are evolving toward higher numerical fidelity, complexity, volume, and dimensionality. The practical problems created by data volume extend into other domains, including, the data collected about other planets, exploration mission environmental data, space ship maintenance data, etc.

**Capability State of the Art:** Provides a means of quickly analyzing ultra-large-scale datasets with high accuracy.

**Parameter, Value:**

Size of dataset: 100 GB

Time to perform analysis: weeks

**Capability Performance Goal:** Increased size and number of datasets that can be simultaneously analyzed rapidly for decision making.

**Parameter, Value:**

Size of dataset: 10 PB

Time to perform analysis: 1 hour

##### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Gravity Recovery and Climate Experiment (GRACE)-II	Enhancing	--	2024*	2019	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



## 11.4 Information Processing

### 11.4.3 Semantic Technologies

#### 11.4.3.3 Semantic Bridge Framework

##### TECHNOLOGY

**Technology Description:** Enables the alignment of two or more data sources based on their respective ontological descriptions to achieve semantic interoperability and facilitates calculations to be properly made using data from each dataset.

**Technology Challenge:** Agreement among participants, natural language processing integrated into ontological models.

**Technology State of the Art:** Experiments in air space management have been conducted linking data from dissimilar datasets through a custom-built semantic bridge. Weak semantic alignment is currently achieved on a limited basis through discussion within a community of interest and replication of data using an enterprise vocabulary.

**Parameter, Value:**

Time required to integrate a new data product: weeks

TRL

5

**Technology Performance Goal:** The number of data elements that can be correctly aligned with those from another related datasets without human intervention in a given time interval.

**Parameter, Value:**

Time required to integrate a new data product: seconds

TRL

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.4.3.1 Semantic Enabler for Data

##### CAPABILITY

**Needed Capability:** Alignment of dissimilar but related data sources.

**Capability Description:** Enables automated, pointwise computation using unfamiliar datasets based on the context and meaning of the data.

**Capability State of the Art:** Provides a means of rapidly examining and comparing large, unfamiliar datasets but requires considerable manual effort.

**Parameter, Value:**

Time required to integrate a new data product: weeks.

**Capability Performance Goal:** Automatically integrate data sets for use without human intervention, applying proper meaning of the data.

**Parameter, Value:**

Time required to integrate a new data product: seconds.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Safe, Efficient Growth in Global Operations: Improved Efficiency and Hazard Reduction within NextGen Operational Domains	Enhancing	--	--	2025	5 years
Safe, Efficient Growth in Global Operations: System-wide Safety, Predictability, and Reliability Through Full NextGen Functionality	Enhancing	--	--	2035	5 years
Enable Assured Machine Autonomy for Aviation: Ability to Fully Certify and Trust Autonomous Systems for NAS Operations	Enabling	--	--	2035	5 years

11.4 Information Processing  
11.4.3 Semantic Technologies

11.4.3.4 Analysis of Competing Hypotheses (ACH) Framework

**TECHNOLOGY**

**Technology Description:** Generates multiple hypotheses starting from a seed postulate to produce a range of candidate hypotheses.

**Technology Challenge:** Complex projects involve a growth of discrete judgements at an exponential rate. Goals and data are ambiguous.

**Technology State of the Art:** Currently, single parameter measurements can be used to generate multiple hypotheses that can then be tested as the additional data is collected. Aircraft tracking algorithms for radar systems do this in a very simple way.

**Parameter, Value:**

Number of distinctions (dimensions): 1

Number of variations: 2

Time to resolve: seconds

**TRL**

2

**Technology Performance Goal:** Within a given study topic, a wide aperture of possible candidates are identified, stated formally, and test criteria for evaluation are defined.

**Parameter, Value:**

Number of distinctions (dimensions): 5

Number of variations: 4

Time to resolve: 20 minutes

**TRL**

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

**CAPABILITY**

**Needed Capability:** Automated generation and management of multiple hypotheses.

**Capability Description:** Accelerates the assessment of datasets by generating alternative explanations sufficiently well-formulated that they can be tested.

**Capability State of the Art:** Provides means of defining multiple hypotheses from a given postulate and managing their evaluation.

**Parameter, Value:**

Number of distinctions (dimensions): 1;

Number of variations: 2;

Time to resolve: seconds

**Capability Performance Goal:** Transition from manual labor to purely machine time with adequate quality in formulation.

**Parameter, Value:**

Number of distinctions (dimensions): 5;

Number of variations: 4;

Time to resolve: 20 minutes

**Technology Needed for the Following NASA Mission Class and Design Reference Mission**

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.4 Information Processing  
11.4.4 Collaborative Science and Engineering

### 11.4.4.1 Immersive Data Explorer

#### TECHNOLOGY

**Technology Description:** Provides tools to support exploration of complex science and engineering data sets using immersive virtual reality technology.

**Technology Challenge:** Develop immersive virtual reality (VR) data exploration technologies that can support science and engineering data.

**Technology State of the Art:** Immersive VR tools are integrated with the data, allowing users to explore virtual worlds in support of engineering and science activities at NASA.

**Parameter, Value:**

Availability of immersive VR tools for NASA science and engineering data: 10%

**TRL**

3

**Technology Performance Goal:** Immersive VR data exploration capabilities used to simulate telepresence for science and engineering.

**Parameter, Value:**

Availability of immersive VR tools for NASA science and engineering data: 100%

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.4.1 Science, Engineering and Mission Data Lifecycle, 11.4.6.1 Scalable On-Demand Storage and Computation.

#### CAPABILITY

**Needed Capability:** Immersive virtual reality data exploration.

**Capability Description:** Provide immersive VR data exploration capabilities to support exploration of data in engineering and science, simulating physical presence.

**Capability State of the Art:** Limited VR and visualization tools in place; research in immersive technologies underway.

**Parameter, Value:**

Availability of immersive VR tools for NASA science and engineering data: 10%

**Capability Performance Goal:** Immersive VR tools provide simulation environments to support science and engineering.

**Parameter, Value:**

Availability of immersive VR tools for NASA science and engineering data: 100%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.4 Information Processing  
11.4.4 Collaborative Science and Engineering

## 11.4.4.2 Distributed Collaborative Engineering Frameworks

### TECHNOLOGY

**Technology Description:** Provide integrated tools to support engineering collaboration across distributed teams, including teams or tens or hundreds of people.

**Technology Challenge:** Develop tools and new collaboration approaches for multi-center, multi-institution collaboration.

**Technology State of the Art:** Tools in place to support data sharing and collaboration by engineering teams as early as possible in a mission. Movement toward concurrent design for widely distributed teams.

**Parameter, Value:**

Use of collaborative engineering tools across centers: 25%

TRL

5

**Technology Performance Goal:** Highly distributed teams can co-design a mission together.

**Parameter, Value:**

Use of collaborative engineering tools across centers: 100%

TRL

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.4.1 Science, Engineering and Mission Data Lifecycle, 11.4.6.1 Scalable On-Demand Storage and Computation.

### CAPABILITY

**Needed Capability:** Collaborative engineering to support design across distributed teams.

**Capability Description:** Provide software and hardware frameworks to support distributed collaboration for engineering functions including design, modeling, and proposal development. Exmples include: computer-aided design (CAD), outer mold line and grid generation; computational fluid dynamics (CFD) and multi-physics (such as fluid-structure); modeling and simulation; flight database generation; results analysis and visualization; availability of experimental testing capabilities (such as wind tunnel) and results integration; workflow sharing; verification and validation; and uncertainty quantification, results publication, and program planning.

**Capability State of the Art:** Open mulitdisciplinary analysis and optimization developed by NASA and is now being used by various NASA and non-NASA organizations.

**Parameter, Value:**

Use of collaborative engineering tools across centers: 25%

**Capability Performance Goal:** Enable mission design across highly distributed teams. Ensure capabilities can scale.

**Parameter, Value:**

Use of collaborative engineering tools across centers: 100%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

## 11.4 Information Processing

### 11.4.4 Collaborative Science and Engineering

## 11.4.4.3 Distributed Collaborative Science Data Analysis Frameworks

### TECHNOLOGY

**Technology Description:** Enable data, computation, and services to be brought together to support distributed data analysis in collaborative environments for science.

**Technology Challenge:** Develop tools and new collaboration approaches for multi-center, multi-institution collaboration in science. Scale computational infrastructure for data-intensive science research.

**Technology State of the Art:** Science analysis tools are in place to enable collaboration between multiple institutions.

**Parameter, Value:**

Size of data accessed: 10 PB  
Number of computation cores: 1,000

**TRL**

4

**Technology Performance Goal:** Scientists have access to distributed data, computation, storage, and algorithms that can scale and support analysis with distributed science teams and collaborators.

**Parameter, Value:**

Size of data accessed: 500 PB  
Number of computation cores: 10,000

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing, 11.1.2 Ground Computing, 11.4.1 Science, Engineering and Mission Data Lifecycle, 11.4.6.1 Scalable On-Demand Storage and Computation.

### CAPABILITY

**Needed Capability:** Collaborative science across distributed teams and data.

**Capability Description:** Provide software tools that allow scientists/engineers to partner, share, and build on each other's work. Include remote access to observational and computed data, computational systems, and science results. Enable sharing of science workflows, modeling and simulation (M&S) and data analysis applications, computed results, and publications.

**Capability State of the Art:** The NASA Earth Exchange (NEX) and OpenNEX have many of these capabilities. They currently offer a limited amount of Earth observational data, workflow management is in development, and ease of access and use can be improved.

**Parameter, Value:**

Size of data accessed: 5 PB  
Number of computation cores: 1,000

**Capability Performance Goal:** Scalable, distributed data analysis and tools in place to support collaborative science research. Spans multiple centers and institutions.

**Parameter, Value:**

Size of data accessed: 500 PB  
Number of computation cores: 10,000

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.4 Information Processing  
11.4.5 Advanced Mission Systems

### 11.4.5.1 Mission Planner/Monitor

#### TECHNOLOGY

**Technology Description:** Selects goals for missions from database or manual pre-formatted input, schedules mission segments with detailed activities, and monitors performance and conditions, adjusting plan as necessary.

**Technology Challenge:** Challenges include (1) developing a suite of sensors that can provide automatic input into mission planning; (2) managing a swarm of devices; (3) responding to changing conditions or opportunities in real time; and (4) onboard planning and re-planning.

**Technology State of the Art:** Ground planning tools for piloted aircraft and uncrewed aircraft system missions within a limited range of options and manual operation.

**Parameter, Value:**

Mission planning time: 4 weeks  
Mission replanning time: 4 hours  
Ground crew: continuous coverage

**TRL**

8

**Technology Performance Goal:** Integrated ground and onboard planning/scheduling, which can respond to changing goals, environments, and opportunities.

**Parameter, Value:**

Mission planning time: 1 hour  
Mission replanning time: 5 minutes  
Ground crew: 1 shift per day

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing

#### CAPABILITY

**Needed Capability:** Integrated or complementary ground/inflight automated mission planning and scheduling with ability to autonomously alert and re-plan when thresholds are breached or opportunities emerge.

**Capability Description:** Provides elements of automated mission planning and re-planning.

**Capability State of the Art:** Performs mission planning manually with some help from simulators and operator aids in most places in NASA.

**Parameter, Value:**

Mission planning time: 14 weeks  
Mission replanning time: 4-10 hours, single agent  
Time to replan: 1 hour  
Number of mission objectives completed: 1  
Cost optimization: none  
Level of knowledge of environment: high.

**Capability Performance Goal:** Permit autonomous operations in low-latency or distant environments.

**Parameter, Value:**

Mission planning time: 1 hour, up to 1,500 agents  
Time to replan: 10 seconds  
Number of mission objectives completed: 5  
Cost optimization: minimum compared to manual steering  
Level of knowledge of environment: minimal.

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (suborbital program)	Enhancing	--	On-going	--	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Enable Assured Machine Autonomy for Aviation: Ability to Fully Certify and Trust Autonomous Systems for NAS Operations	Enhancing	--	--	2035	5 years
Safe, Efficient Growth in Global Operations: Improved Efficiency and Hazard Reduction within NextGen Operational Domains	Enhancing	--	--	2025	5 years



11.4 Information Processing  
11.4.5 Advanced Mission Systems

### 11.4.5.2 Adaptive Systems Framework

#### TECHNOLOGY

**Technology Description:** Manages a set of interacting or interdependent entities, real or abstract, forming an integrated whole that together are able to respond to environmental changes or changes in the interacting parts.

**Technology Challenge:** Challenges include guidance algorithms matured into flight-ready systems; improved reconfigurable and adaptive guidance systems for unmanned aerial vehicles (UAVs) and spacecraft; design methodologies, tools, and modeling; and simulation capabilities.

**Technology State of the Art:** Financial forecasting, fraud detection, and other financial applications are heavily dependent upon adaptive systems. Industrial control for manufacturing and chemical production is performed by operators on a limited number of sensor inputs.

**Parameter, Value:**

Mission failure rate without human intervention: high

TRL

5

**Technology Performance Goal:** Increase in the range and complexity of missions which can be met without human intervention.

**Parameter, Value:**

Mission failure rate without human intervention: < 50%

TRL

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.3.1 Distributed Simulation, 11.3.3 Simulation-Based Systems Engineering

#### CAPABILITY

**Needed Capability:** Adaptive systems.

**Capability Description:** Enables robust performance in the presence of changing goals, environments, and objectives.

**Capability State of the Art:** Intelligent, adaptive systems are coming online, principally for the health monitoring of both commercial and military engine systems. This capability will anticipate and prevent failures, using control logic to reconfigure engine operation.

**Parameter, Value:**

Mission failure rate without human intervention: high

**Capability Performance Goal:** Onboard fault detection, correction, and/or compensation, improved efficiency of maintenance through condition-based maintenance, weather-detection, and compensation.

**Parameter, Value:**

Mission failure rate without human intervention: < 0.1% per year

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Safe, Efficient Growth in Global Operations: Improved Efficiency and Hazard Reduction within NextGen Operational Domains	Enhancing	--	--	2025	5 years

11.4 Information Processing  
11.4.5 Advanced Mission Systems

### 11.4.5.3 Multi-Agent Master Framework

#### TECHNOLOGY

**Technology Description:** Manages over 2,500 remote agents of various sizes and designs, including initiation, assignment, coordination, monitoring, and termination of assignment.

**Technology Challenge:** Inter-device communications and software frameworks.

**Technology State of the Art:** Most implementations occur in industrial control applications and system diagnostics, transportation logistics, and network management. Considerable current work lies in modeling systems, usually focused on human behavior.

**Parameter, Value:**

Time to optimize performance: 10 hours

Number of agents: 1

**TRL**

2

**Technology Performance Goal:** Number of agents that can be managed simultaneously.

**Parameter, Value:**

Time to optimize performance: 10 seconds in airspace to hours for design reference mission (DRM)-6

Number of agents: 2,500

**TRL**

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing

#### CAPABILITY

**Needed Capability:** Multi-agent systems.

**Capability Description:** Enables robust coordination of large numbers of remote assets, critical to enable such missions without prohibitive operations costs. Such systems consist of loosely-coupled networks of software agents interacting to solve problems beyond the capacity of individual elements to solve.

**Capability State of the Art:** The Orbital Communications Adapter Mirroring System on the International Space Station (ISS) uses an intelligent multi-agent system to deliver files via various sets of hardware.

**Parameter, Value:**

Time to optimize performance: hours

Number of systems: 1

**Capability Performance Goal:** Coordination of different robots in a common space. Large quantities are needed for swarm behavior.

**Parameter, Value:**

Time to optimize performance: seconds for airspace to hours for DRM-6

Number of systems: 25

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Safe, Efficient Growth in Global Operations: System-Wide Safety, Predictability, and Reliability Through Full NextGen Functionality	Enhancing	--	--	2035	5 years
Safe, Efficient Growth in Global Operations: Improved Efficiency and Hazard Reduction within NextGen Operational Domains	Enhancing	--	--	2025	5 years
Enable Assured Machine Autonomy for Aviation: Ability to Fully Certify and Trust Autonomous System for NAS Operations	Enhancing	--	--	2035	5 years

11.4 Information Processing  
11.4.5 Advanced Mission Systems

### 11.4.5.4 High Fidelity Spacecraft Simulator

#### TECHNOLOGY

**Technology Description:** Monitors system conditions and simulates the remainder of the mission plan to determine probability of success and any points of inflection where decisions can increase or reduce risks.

**Technology Challenge:** The main challenges are to increase the speed of the software simulations of the flight processor.

**Technology State of the Art:** Current implementations on high-end server can achieve 6x real time.

**Parameter, Value:**

Single day simulation runs in one day real wall clock time: 5

**TRL**

4

**Technology Performance Goal:** Number of single day simulations that can be run per wall clock day.

**Parameter, Value:**

Single day simulation runs in one day real wall clock time: 24

**TRL**

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing, 11.3.5 Exascale Simulation, 11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods, 11.3.3 Simulation-Based Systems Engineering.

#### CAPABILITY

**Needed Capability:** High-fidelity software spacecraft simulation.

**Capability Description:** Enables robust testing of instruments, operational procedures, reducing risk, and speeding response to changing requirements or conditions.

**Capability State of the Art:** Full operational simulators include the Global Precipitation Measurement Operational simulator and the James Webb Space Telescope integrated simulation and test. Their ground systems send command/telemetry packets to a spacecraft communications and data handling flight computer, which transfers status data over a spacecraft bus to determine the spacecraft environment. Spacecraft environmental models simulate the spacecraft (star trackers, gyros, power units, etc.).

**Parameter, Value:**

Single day simulation runs in one day real wall clock time: 5

**Capability Performance Goal:** Increasing speed to enable parametric studies and Monte Carlo simulations.

**Parameter, Value:**

Single day simulation runs in one day real wall clock time: 100

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.4 Information Processing  
11.4.6 Cyber Infrastructure

## 11.4.6.1 On-Demand, Multi-Mission Data Storage and Computation

## TECHNOLOGY

**Technology Description:** Provides scalable storage and computing available on demand across projects, including both internal and external (hybrid) clouds at center and NASA levels.

**Technology Challenge:** Developing massively scalable infrastructures at the center or Agency level.

**Technology State of the Art:** Commercial and open source solutions exist that provide massive scalability.

**Parameter, Value:**

Scalable, shared storage capacity: < 1 PB

**TRL**

6

**Technology Performance Goal:** Exabyte scale storage infrastructure available across NASA both internally and from external providers.

**Parameter, Value:**

Scalable, shared storage capacity: 500 PB

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing, 11.1.2 Ground Computing, 11.4.1 Science, Engineering and Mission Data Lifecycle.

## CAPABILITY

**Needed Capability:** On-demand, multi-mission data storage and computation.

**Capability Description:** Provide scalable storage and computational services that can support multi-mission operations and science projects/systems.

**Capability State of the Art:** Most projects fund their own storage and computing capabilities. NASA supercomputing capabilities are also in place.

**Parameter, Value:**

Scalable, shared storage capacity: < 1 PB

**Capability Performance Goal:** Scalable storage and computing available on demand across projects including both internal and external (hybrid) clouds at center and NASA levels.

**Parameter, Value:**

Scalable, shared storage capacity: 500 PB

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.4 Information Processing  
11.4.6 Cyber Infrastructure

## 11.4.6.2 Scalable Data Management Frameworks

### TECHNOLOGY

**Technology Description:** Extensible, scalable data management frameworks that can take advantage of massive storage and computing resources.

**Technology Challenge:** Increasing the amount of data managed by a factor of 1,000 (from PB to Exabyte) is a challenge.

**Technology State of the Art:** Availability of data management frameworks, particularly through open source, are increasingly being used and applied to reduce cost and increase efficiency and capability.

**Parameter, Value:**

Bytes of data managed per system: 1 PB

TRL

5

**Technology Performance Goal:** Reusable data management software services are available across mission and science functions.

**Parameter, Value:**

Bytes of data managed per system: 1 Exabyte

TRL

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing, 11.1.2 Ground Computing, 11.4.1 Science, Engineering and Mission Data Lifecycle.

### CAPABILITY

**Needed Capability:** Data management for large-scale, distributed data environments.

**Capability Description:** Provide component-based software frameworks for data management/systems in order to increase reusability, reduce cost, increase efficiency, and provide more capable systems in mission operations and science.

**Capability State of the Art:** Projects generally build their own data management capabilities. Limited software reuse across projects and/or contributions and use of open source technologies.

**Parameter, Value:**

Bytes of data managed per system: 1 PB

**Capability Performance Goal:** Scalable data frameworks in place that can support data management capabilities across missions, science and engineering. Extensive use of open source.

**Parameter, Value:**

Bytes of data managed per system: 1 Exabyte

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.4 Information Processing  
11.4.6 Cyber Infrastructure

## 11.4.6.3 Scalable Data Archives Systems

## TECHNOLOGY

**Technology Description:** Support scalable archives that can capture, manage, and preserve massive data sets, both engineering and science.

**Technology Challenge:** Capture, movement, and preservation of massive data, including provenance.

**Technology State of the Art:** Archives are in place to capture massive data. A shift is needed to move towards integrated analytics across multiple archives.

**Parameter, Value:**

Long-term archiving capacity: 15 PB

**TRL**

5

**Technology Performance Goal:** Archives available to support capture of science, engineering, and other artifacts. Support for integrated data access and analysis across archives.

**Parameter, Value:**

Long-term archiving capacity: 1 Exabyte

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing, 11.1.2 Ground Computing, 11.4.1 Science, Engineering and Mission Data Lifecycle.

## CAPABILITY

**Needed Capability:** Massive science and engineering data archives.

**Capability Description:** Provide technologies to support the capture, management, and distribution of massive data archives.

**Capability State of the Art:** NASA science archives are in place to capture, manage, and preserve petabytes of data. Support towards usability of the data for analytics.

**Parameter, Value:**

Long-term archiving capacity: 15 PB

**Capability Performance Goal:** Ensure that massive data sets are preserved to ensure that they are usable and their results can be reproduced.

**Parameter, Value:**

Long-term archiving capacity: 1 Exabyte

## Technology Needed for the Following NASA Mission Class and Design Reference Mission

Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Enhancing	2027	2027	2021	5 years
Enhancing	2027	2027	2021	5 years
Enhancing	--	2023	2020	5 years
Enhancing	--	2022*	2019	5 years
Enhancing	--	2023*	2020	5 years
Enhancing	--	2026	2023	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.4 Information Processing  
11.4.6 Cyber Infrastructure

### 11.4.6.4 High Performance Networking

#### TECHNOLOGY

**Technology Description:** Provide terabit data networks to handle movement of massive datasets, particularly those for scientific research.

**Technology Challenge:** To support and fully exploit forecast exascale ( $10^{18}$ ) science data requirements, NASA must continue to research and deploy ever faster network routers, switches, and links, together with high performance systems capable of interfacing to these high-performance Tbps networks, requiring major advances in network and system hardware/software/protocols.

**Technology State of the Art:** Local area network (LAN): NASA's Science and Engineering Network has a 40-gigabit per second (Gbps) backbone. Wide area network (WAN): other agencies operate up to 100 Gbps production wide area networks.

**Parameter, Value:**

LAN: 40 Gbps

WAN: 100 Gbps

Network interface cards (NICs): 40 Gbps

**TRL**

4

**Technology Performance Goal:** 100x increase in network performance for both the LAN and WAN environments, together with comparable advances for high performance systems network interfaces.

**Parameter, Value:**

LAN: 4 Tbps

WAN: 10 Tbps

NICs: 400 Gbps

**TRL**

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Ratification of network and PCI Express standards and development of related network products, higher speed processors, memory, NICs, and other system components.

#### CAPABILITY

**Needed Capability:** Terabit per second high performance networking.

**Capability Description:** Support operations on and analysis of huge datasets, such as the exabyte scale total data holdings forecast for an international climate research program, which will require the exchange of petabyte-scale datasets within and between NASA centers, and among NASA and its national and international science partners.

**Capability State of the Art:** LAN: The NASA Science and Engineering Network has a 40 Gbps backbone. WAN: There are multiple 10 Gbps WAN connections, including the NASA Integrated Services Network, and 10 Gbps connections to Internet2.

**Parameter, Value:**

LAN: 40 Gbps

WAN: 100 Gbps

NICs: 40 Gbps

Supported dataset size: 10 Terabyte (TB)

**Capability Performance Goal:** 100x increase in network performance for both the local area network and wide area network environments, together with comparable advances for high performance systems network interfaces.

**Parameter, Value:**

LAN: 4 Tbps (100x)

WAN: 1 Tbps (100x)

NICs: 400 Gbps (40x)

Supported dataset size: 1 PB (100x)

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enhancing	--	2024*	2020	5 years
Earth Systematic Missions: Global Atmosphere Composition Mission (GACM)	Enhancing	--	2024*	2019	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.4 Information Processing  
11.4.7 Human-System Integration

### 11.4.7.1 Mobile Mission Operation Toolset

#### TECHNOLOGY

**Technology Description:** Allows space mission crews to effectively and efficiently view and interact with mission operation functions in extreme, constrained, or distributed environments using mobile devices.

**Technology Challenge:** Requires easy-to-learn, easy-to-use (such as displays only the relevant information on a small form factor device) software that is responsive on a mobile device.

**Technology State of the Art:** Two NASA applications Playbook and Augmented Reality Electronic Procedure are examples of operational toolsets to enhance operational efficiency. Both applications support rich bidirectional communication using text, video, or pictures between crew members and mission operators.

**Technology Performance Goal:** Provide comprehensive mission operations functionality on mobile devices in extreme environments like space.

**Parameter, Value:**

Percentage of mission operation tasks that can be conducted on a mobile device: 10%

**TRL**

5

**Parameter, Value:**

Percentage of mission operation tasks that can be conducted on a mobile device: 100%

**TRL**

9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing

#### CAPABILITY

**Needed Capability:** Mobile mission operations.

**Capability Description:** Mobile mission operations allow space mission crews to effectively and efficiently view and interact with mission operation functions in extreme, constrained, or distributed environments using mobile devices, allowing autonomy. That is, without continuous connection to and control by mission control.

**Capability State of the Art:** Onboard Short Term Plan Viewer (OSTPV) is a web-based application to support the International Space Station's (ISS) real-time operations. OSTPV is currently deployed on laptops on the ISS.

**Capability Performance Goal:** Crew should be able to handle all mission functions autonomously and from any location, without reliance on mission control.

**Parameter, Value:**

Percentage of mission operation tasks that can be conducted on a mobile device: 10%

**Parameter, Value:**

Percentage of mission operation tasks that can be conducted on a mobile device: 100%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – crewed in DRO	Enhancing	2022	2022	2015-2021	3 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

11.4 Information Processing  
11.4.7 Human-System Integration

## 11.4.7.2 Crew Autonomy Mission Operation System

### TECHNOLOGY

**Technology Description:** Allows space mission crews to effectively and efficiently conduct mission operation functions without continuous connection to and control by mission control.

**Technology Challenge:** Developing an intelligent system that works effectively with crew, such as efficiently distributing the task workload between crew and automation.

**Technology State of the Art:** NASA's web-based mobile mission planning tool, Playbook, allows the crew to self-schedule a mission plan without ground support; requires little or no training.

**Parameter, Value:**

Percentage of mission operation tasks that crew can conduct autonomously: 5%

**TRL**

6

**Technology Performance Goal:** Facilitate crew autonomy.

**Parameter, Value:**

Percentage of mission operation tasks that crew can conduct autonomously: 100%

**TRL**

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.2.3 Human-System Performance Modeling

### CAPABILITY

**Needed Capability:** Crew autonomy mission operations.

**Capability Description:** Autonomous mission operations allow space mission crews to effectively and efficiently view and interact with mission operation functions in extreme, constrained, or distributed environments using mobile devices, allowing autonomy. That is, without continuous connection to and control by mission control.

**Capability State of the Art:** Onboard Short Term Plan Viewer (OSTPV) is a web-based application to support the International Space Station's (ISS) real-time operations. OSTPV is currently deployed on laptops on the ISS.

**Parameter, Value:**

Percentage of mission operation tasks that crew can conduct autonomously: 5%

**Capability Performance Goal:** Crew should be able to handle all mission functions autonomously and from any location, without reliance on mission control.

**Parameter, Value:**

Percentage of mission operation tasks that crew can conduct autonomously: 100%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years



11.4 Information Processing  
11.4.7 Human-System Integration

### 11.4.7.3 Rich Light-Weight Web-Based Mission Interface

#### TECHNOLOGY

**Technology Description:** Allows for easier code deployment and maintainability as well as allows mission operations to be performed on any commodity browser.

**Technology Challenge:** Comprehensive mission interface, fully integrated in web interface; responsive, simplified development.

**Technology State of the Art:** Technologies used for online maps allow for responsive, rich interactions such as panning, zooming, and 3 dimensional visualizations on commodity browsers.

**Parameter, Value:**

Percentage of mission operation tasks that can be done on the Web: 10%

Percentage of mission operations tasks that use visualizations that are on the Web: 10%.

**TRL**

3

**Technology Performance Goal:** Comprehensive mission interface, fully integrated in Web interface; responsive, simplified development.

**Parameter, Value:**

Percentage of mission operation tasks that can be done on the Web: 100%

Percentage of mission operations tasks that use visualizations that are on the Web: 100%.

**TRL**

8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.2.3 Human-System Performance Modeling

#### CAPABILITY

**Needed Capability:** Web-based mission operations.

**Capability Description:** Provide a comprehensive, responsive, web-based framework providing mission information and rich lightweight interactions and visualizations, facilitating ease of deployment and pushing out updates. Transition away from current Java-based tools that are more costly to develop/update and that might not be supported by the Mars 2020 mission.

**Capability State of the Art:** A NASA-developed activity scheduling system provides a web-based visualization of current mission status by playing back plans from a mission. It also provides spatial visualization of orbital and mission planning data and runs on commodity web browsers.

**Parameter, Value:**

Percentage of mission operation tasks that can be done on the Web: 10%

Percentage of mission operations tasks that use visualizations that are on the Web: 10%.

**Capability Performance Goal:** Flight controllers and engineers need the ability to conduct mission operations with comprehensive integrated tool.

**Parameter, Value:**

Percentage of mission operation tasks that can be done on the Web: 100%

Percentage of mission operations tasks that use visualizations that are on the Web: 100%.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Mars 2020	Enabling	--	2020	2017	2 years
Discovery: Discovery 13	Enhancing	--	2020	2017	2 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	2 years
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	2 years
New Frontiers: New Frontiers 5 (NF5/~2022 AO Release)	Enhancing	--	2029	2021	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	2 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.4 Information Processing  
11.4.7 Human-System Integration

11.4.7.4 Enhanced Certifiable Unmanned Aircraft System Ground Station

### TECHNOLOGY

**Technology Description:** Maximizes human automation teaming, operator situational awareness, and supervisory control for nominal and contingent operations.

**Technology Challenge:** Move to a certifiable supervisory control approach for operations, reducing manpower, for nominal and contingent operations in the National Airspace System (NAS). New design of information display and control needed to support supervisory instead of control operation role.

**Technology State of the Art:** Cockpit-like displays and controls that require multiple operators per unmanned aerial vehicle (UAV).

**Technology Performance Goal:** Integrated information/control unmanned aircraft system (UAS) ground control station that maximizes human-automation teaming, supervisory control, to provide operator situation awareness to provide safe nominal and contingent operations in NAS.

**Parameter, Value:**

Manpower to safely operate UAVs in NAS: 4 persons per UAV.

**TRL**

9

**Parameter, Value:**

Manpower to safely operate UAVs in National Airspace: 4 UAVs per person.

**TRL**

9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.2.3 Human-System Performance Modeling, 4.4.8.2 Supervisory Control

### CAPABILITY

**Needed Capability:** Multiple UAS flight control workstation.

**Capability Description:** Enables coordination between UAVs and pilots (of other aircraft) in the same airspace.

**Capability State of the Art:** Current air traffic management system.

**Capability Performance Goal:** NAS-certifiable UAV ground control station.

**Parameter, Value:**

Manpower to safely operate UAVs in NAS: 4 persons per UAV.

**Parameter, Value:**

Manpower to safely operate UAVs in NAS: 4 UAVs per person.

### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Enable Assured Machine Autonomy for Aviation: Ability to Fully Certify and Trust Autonomous Systems for NAS Operations	Enabling	--	--	2035	5 years

11.4 Information Processing  
11.4.7 Human-System Integration

### 11.4.7.5 Smart Object Integration

#### TECHNOLOGY

**Technology Description:** Allows for humans to effectively interact with and control smart objects and robotic equipment.

**Technology Challenge:** Efficiently leverage and control large numbers of smart objects through intuitive, easy-to-use interfaces. Provide useful feedback to crew on system/object status without increasing crew overhead.

**Technology State of the Art:** Everyday objects that are connected and aware of one another. Users can control or get information from large numbers of these devices at once using assistive interfaces.

**Parameter, Value:**

Percentage of objects addressable through a network:  
1%

Percentage of objects that are aware of one another:  
1%

Percentage of objects that are controllable by humans through an interface: 1%.

**TRL**

3

**Technology Performance Goal:** Facilitate crew autonomy; communicate health status of systems or objects to crew members; and provide feedback on crew tasks when conducting procedures, payload experiments, or maintenance operations.

**Parameter, Value:**

Percentage of objects addressable through a network:  
100%

Percentage of objects that are aware of one another:  
100%

Percentage of objects that are controllable by humans through an interface: 100%.

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.2.3 Human-System Performance Modeling

#### CAPABILITY

**Needed Capability:** Interactive intelligent connected objects.

**Capability Description:** Enables humans (such as space mission crew) to interact with smart objects and systems that also interact with each other to help accomplish complex tasks safely.

**Capability State of the Art:** Early development of ground-based technologies.

**Parameter, Value:**

Percentage of objects addressable through a network: 0%

Percentage of objects that are aware of one another: 0%

Percentage of objects that are controllable by humans through an interface: 0%.

**Capability Performance Goal:** Systems and objects used by space mission crew members are wirelessly networked, aware of the procedure and status, and provide feedback to correctly complete procedures.

**Parameter, Value:**

Percentage of objects addressable through a network: 100%

Percentage of objects that are aware of one another: 100%

Percentage of objects that are controllable by humans through an interface: 100%.

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Enhancing	2027	2027	2021	4 years
Enhancing	2033	--	2027	4 years
Enhancing	2033	--	2027	4 years

Exploring Other Worlds: DRM 7 Crewed to Lunar Surface

Planetary Exploration: DRM 8a Crewed Mars Orbital

Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)



11.4 Information Processing  
11.4.7 Human-System Integration

### 11.4.7.6 Assistive Tool for Heterogeneous Data Integration

#### TECHNOLOGY

**Technology Description:** Allows integration of heterogeneous data sources to enable querying and linking data.

**Technology Challenge:** Develop software that interfaces with existing systems (often lacking common communication methods, relying on distinct formats, and different schemas) and facilitates a human mapping the data to allow for rapid information retrieval.

**Technology State of the Art:** Data integration information technology enables current linking and validation of key data sets.

**Parameter, Value:**

Response time: days

Percentage of relevant data sources integrated: 2%

**TRL**

9

**Technology Performance Goal:** Integrate all engineering data sets such that a mission can readily understand technical risk and make design and mission-critical operational decisions.

**Parameter, Value:**

Response time: minutes

Percentage of relevant data sources integrated: 100%

**TRL**

9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.1 Flight Computing, 11.1.2 Ground Computing, 11.4.1 Science, Engineering and Mission Data Lifecycle.

#### CAPABILITY

**Needed Capability:** Graph of related engineering data.

**Capability Description:** Assists humans in integrating data and information from disparate (often archaic) sources and formats (such as hazard > operations control > flight rule).

**Capability State of the Art:** Paper-based, human-intensive processes for using data and information from multiple sources and formats to respond rapidly to mission safety questions.

**Parameter, Value:**

Response time: days

Percentage of relevant data sources integrated: 0%

**Capability Performance Goal:** Need automated integration of all relevant data sources to enable response in minutes rather than days.

**Parameter, Value:**

Response time: minutes

Percentage of relevant data sources integrated: 100%

#### Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	4 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	4 years

## 11.4 Information Processing

### 11.4.7 Human-System Integration

#### 11.4.7.7 Hyperwall

##### TECHNOLOGY

**Technology Description:** Enables analysis and visualization of high-resolution, high-density, petascale NASA data.

**Technology Challenge:** NASA's challenge is to develop a visualization application framework that dramatically simplifies deployment of new data exploration applications. High-resolution displays, high-bandwidth storage and networks, and fast graphics clusters will be developed by industry.

**Technology State of the Art:** Retina displays (up to 300 pixels per inch) exist on laptops and smaller devices; expensive graphics cards capable of rendering 8.3M pixels are available (about half the need).

**Technology Performance Goal:** Increase pixel resolution by about 3x (linear), 10x total, to limit of human perception; increase data I/O bandwidth by 10x, to supply the data for higher resolution; develop a software environment that enables 10x faster deployment of new applications.

**Parameter, Value:**

Total pixels: 0.25 billion

Pixel resolution: 100 per inch

Input/output (I/O) rate: 100 GB/s;

Typical new app development time: 3 weeks.

**TRL**

5

**Parameter, Value:**

Total pixels: 2.5 billion

Pixel resolution: 300 per inch

I/O rate: 1,000 GB/s

Typical new app development time: 2 days.

**TRL**

9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 11.1.2 Ground Computing, 11.4.1 Science, Engineering and Mission Data Lifecycle

##### CAPABILITY

**Needed Capability:** High-bandwidth visualization environment.

**Capability Description:** Enables users to view, explore, and interact with exascale observational and computed data sets through a high-resolution visual interface, powerful data analysis and rendering engine, one or more interaction devices (such as a control workstation), visualization application software suitable for NASA data, and high-bandwidth connectivity to massive NASA data sources.

**Capability State of the Art:** Hyperwall-2 at the NASA Advanced Supercomputing Facility has a 245 megapixel display wall, a powerful compute and rendering cluster, a variety of analysis and visualization software, and a 100 GB/s I/O connection to the Pleiades supercomputer and storage system.

**Capability Performance Goal:** Increase pixel resolution to limit of human perception (by ~3x in both dimensions, 10x total), equal increase in I/O bandwidth.

**Parameter, Value:**

Total pixels: 0.25 billion

Pixel resolution: 100 per inch

I/O rate: 100 GB/s

Typical new app development time: 3 weeks.

**Parameter, Value:**

Total pixels: 2.5 billion (10x)

Pixel resolution: 300 per inch (3x)

I/O rate: 1,000 GB/s (10x)

Typical new app development time: 2 days (10x).

##### Technology Needed for the Following NASA Mission Class and Design Reference Mission

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enhancing	--	2035*	2030	5 years
Earth Systematic Missions: Three-dimensional Tropospheric Winds from Space-based Lidar (3D Winds)	Enhancing	--	2030*	2025	5 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	5 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.4 Information Processing  
11.4.8 Cyber Security

## 11.4.8.1 Cyber Security and Information Assurance Framework

## TECHNOLOGY

**Technology Description:** Provides the process and tools to ensure that best security practices are applied throughout the mission data life cycle.

**Technology Challenge:** Crosscutting cyber security architecture to the data (and object) level.

**Technology State of the Art:** Security across the data lifecycle is currently ad hoc.

**Parameter, Value:**

Percent of data lifecycle with integrated security: 10%

**TRL**

4

**Technology Performance Goal:** Security integrated with data management services and data across the lifecycle.

**Parameter, Value:**

Percent of data lifecycle with integrated security: 100%

**TRL**

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Cyber security across mission data lifecycle.

**Capability Description:** Ensure that systems are secured across the entire mission and science data lifecycle, allowing access to authorized users. This requires integration between data and security architectures that are crosscutting.

**Capability State of the Art:** Security is often localized to particular applications. As systems move to more decentralization, this will become a greater need.

**Parameter, Value:**

Percent of data lifecycle with integrated security: 10%

**Capability Performance Goal:** Common security architecture and mechanisms in place across the data lifecycle to ensure that systems and data are not compromised.

**Parameter, Value:**

Percent of data lifecycle with integrated security: 100%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enhancing	--	2035*	2030	5 years
Earth Systematic Missions: Three-dimensional Tropospheric Winds from Space-based Lidar (3D Winds)	Enhancing	--	2030*	2025	5 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	5 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	5 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.4 Information Processing  
11.4.8 Cyber Security

## 11.4.8.2 Cyber Security Situational Assessment Environment

## TECHNOLOGY

**Technology Description:** Uses the confluence of multiple security relevant datasets, such as intrusion detection, flows, log, vulnerability scans, known vulnerabilities, domain name server inquiries, and asset characteristics to identify when there is an attack or probe that warrants action by a security analyst or automated program to counter this threat.

**Technology Challenge:** Developing sufficiently intelligent rules and bringing in additional information so that the large number of false positives can be eliminated, but all or a majority of the actual actionable events are detected.

**Technology State of the Art:** While commercial security information and event management systems are available, they tend to generate large numbers of false positives and do not provide the analyst with only actionable security event identification.

**Parameter, Value:**

Percent of identified security events that are actionable:  
< 1%

TRL

3

**Technology Performance Goal:** The identification of only those security events that require human or automated intervention to mitigate, while not burdening the analyst with events that do not reach the level of severity requiring human or automated mitigation.

**Parameter, Value:**

Percent of identified security events that are actionable:  
99%

TRL

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Cyber security situational awareness.

**Capability Description:** Ensure that monitored data from flows, intrusion detection systems, log systems, vulnerability scans, and other information technology-relevant sources will allow NASA security personnel to quickly identify security events that require human or automated action.

**Capability State of the Art:** While a large volume of data is available, there is currently no system to easily identify actionable events. Security systems that exist, such as intrusion detection systems or security information and event management systems, generate a large volume of false positives, which limits their effectiveness.

**Parameter, Value:**

Percent of identified security events that are actionable: < 1%

**Capability Performance Goal:** Identify all and only those security events for which human or automated action is required to mitigate them, with a false positive rate approaching zero.

**Parameter, Value:**

Percent of identified security events that are actionable: 99%

## Technology Needed for the Following NASA Mission Class and Design Reference Mission

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	2 years
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enhancing	--	2035*	2030	2 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2035	2 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	2 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.4 Information Processing  
11.4.8 Cyber Security

## 11.4.8.3 User/Asset Geographic Tracking System

## TECHNOLOGY

**Technology Description:** Couples the identification of all relevant users, mobile devices, and security assets with their geographical location.

**Technology Challenge:** Challenges include gaining access to mobile asset location information and refining the geolocation of computer assets, which are not currently very accurate, based only on the location associated with their IP addresses.

**Technology State of the Art:** Currently, the technology exists for users or cell-phone providers to locate lost cell phones.

**Technology Performance Goal:** The technology must not only keep track of a large number of users, mobile devices, and computer assets, but must also identify their current and past locations.

**Parameter, Value:**

Percent of entities that are location-tracked: 0%

TRL

3

**Parameter, Value:**

Percent of entities that are location-tracked: 100%

TRL

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Cyber security tracking of users and information technology assets.

**Capability Description:** NASA needs the ability to combine sensory data in near-real time to depict the location of an individual, the status of the user's mobile device, computer assets, etc. (in use, not in use).

**Capability State of the Art:** Currently, the NASA security operations center has no way to track entities, such as users, mobile devices, or computer assets.

**Capability Performance Goal:** Identify location of individual using an IT device, the location of the user's mobile device, and the location of NASA computer assets.

**Parameter, Value:**

Percent of entities that are location-tracked: 0%

**Parameter, Value:**

Percent of entities that are location-tracked: 100%

## Technology Needed for the Following NASA Mission Class and Design Reference Mission

Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Enhancing	2027	2027	2021	2 years
Enhancing	2027	2027	2021	2 years
Enhancing	--	2035*	2030	2 years
Enhancing	--	--	2035	2 years
Enhancing	--	--	2025	2 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

11.4 Information Processing  
11.4.8 Cyber Security

## 11.4.8.4 Anomaly Detection System

## TECHNOLOGY

**Technology Description:** Characterizes normal human and system behavior and then identifies any behavior that deviates from the norm by some delta that could be set by the users.

**Technology Challenge:** Data used in the anomaly detection is extensive, diverse, and distributed.

**Technology State of the Art:** Data mining systems perform anomaly detection that identifies events or observations that deviate from some expected pattern, but this does not provide the distributed capability required here.

**Parameter, Value:**

Time to detect anomalous behavior: days.

TRL

3

**Technology Performance Goal:** The real-time detection of anomalies across a distributed set of systems within no longer than 10 minutes from the start of a detection cycle.

**Parameter, Value:**

Time to detect anomalous behavior: 10 minutes.

TRL

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:**

11.4.8.2 Cyber Security Situational Assessment Environment

## CAPABILITY

**Needed Capability:** Cyber security anomalous behavior analysis.

**Capability Description:** NASA needs the ability to analyze anomalous behaviors, based on large and diverse data set across information technology systems.

**Capability State of the Art:** Currently, there is no system for detecting anomalous behavior among the diverse set of security-relevant data that NASA has, across the large number of NASA information technology (IT) systems. Such behavior may be detected through manual means, or may be missed entirely.

**Parameter, Value:**

Time to detect anomalous behavior: days.

**Capability Performance Goal:** Identify anomalous behavior that may involve multiple data types across geographically-distributed NASA IT systems within a period of time measured in minutes, so that NASA security operations center (SOC) personnel could take action.

**Parameter, Value:**

Time to detect anomalous behavior: 10 minutes.

**Technology Needed for the Following NASA Mission Class and Design Reference Mission**

	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	2 years
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enhancing	--	2035*	2030	2 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2025	2 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	2 years

\*Launch date is estimated and not in Agency Mission Planning Model (AMPM)



11.4 Information Processing  
11.4.8 Cyber Security

## 11.4.8.5 Secure Cloud Bursting Infrastructure

## TECHNOLOGY

**Technology Description:** Enables workflows to transfer seamlessly between a physical data center and a cloud.

**Technology Challenge:** Supporting all of the security controls of a moderate or high system, as defined in NIST SP 800-53, including support for identification, authentication, confidentiality, and integrity as the workflow moves between cloud and non-cloud processors, so that latency is not impacted by requiring human interaction.

**Technology State of the Art:** This type of technology was used with Grid computing technology as jobs migrated seamlessly, but with proper identification, authentication, confidentiality, and integrity from one Grid processor to another. This has not been applied to the cloud.

**Technology Performance Goal:** To move data with low latency and high throughput between NASA facilities and commercial clouds for workflows that involve both cloud and non-cloud processing. This would support both cloudbursting and hybrid systems supporting workflows that normally involve of cloud and non-cloud systems.

**Parameter, Value:**

Time to establish a secure connection to the cloud: 1 minute.

TRL

3

**Parameter, Value:**

Time to establish a secure connection to the cloud: 1 second.

TRL

7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Cyber security confidentiality and integrity in cloudbursting.

**Capability Description:** Confidentiality and integrity of workflows involving both cloudbursting and hybrid systems involving clouds and non-cloud processing of NASA data, while avoiding the need for human interaction to log on to individual systems as the workflow moves between cloud and non-cloud processing system.

**Capability State of the Art:** Currently, a user would have to log on, presumably with two-factor authentication, at each site, thus the workflow could not move seamlessly or automatically between cloud and non-cloud processing systems.

**Capability Performance Goal:** High throughput due to the ability of the processing to flow seamlessly and automatically between the cloud and non-cloud processors.

**Parameter, Value:**

Time to establish a secure connection to the cloud: 1 minute.

**Parameter, Value:**

Time to establish a secure connection to the cloud: 1 second.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	2 years
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Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enhancing	--	2035*	2030	2 years
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Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Enhancing	--	--	2025	2 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	2 years

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