NASA
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Advanced Modeling, Simulation and Analysis Capability Roadmap
Executive Summary
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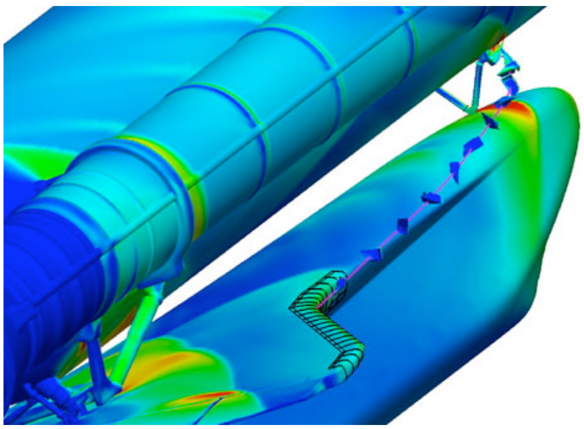

These highly detailed flowfield simulations were developed to understand the RCC panel failure mechanism after the Columbia accident. They could have been performed prior to the accident and perhaps have averted the disaster.

NASA cannot afford to continue to underutilize modeling and simulation. The AMSA roadmap presented here addresses these deficiencies and enables effective and safe exploration of space and conduct of science experiments.

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1 Advanced Modeling, Simulation and Analysis (AMSA) - Vision of the future

FUTURE Integrated System Scenario

This section describes a possible future scenario to illustrate the power and importance of an integrated, end-to-end modeling system provided by Advanced Modeling, Simulation and Analysis (AMSA). It is based on work done in relation to (or: to develop) the Earth Science community's Sensor Web observing concept. The key to the sequence below is as follows:

- Items with blue labels would normally be accomplished with an extension of application capability,
- Items with green labels require integration of models within a technical domain,
- Items with red labels require integration of models across technical domains.

a) The scenario begins with a group of scientists executing a suite of Earth Science models to understand a particular aspect of the Earth System behavior. These scientists assimilate past observations into the model solution to determine which additional observational data would most improve the model results. [Integration within science]

b) The detailed description of the measurements needed, including coverage, temporal and spatial resolution and accuracy are provided as a model for a new spaceborne observation system to engineers. [science<-->engineering integration]

c) The engineers, beginning with the observation model, develop a mission model, which is executed to determine all viable mission concepts that will satisfy the science measurement model at the lowest cost. [science<-->engineering integration]

d) Upon selection of the desired mission model, a system description model is developed and high fidelity analysis is performed to design the measurement system. [Integration within Engineering]

e) During mission development, operations models are formulated from the system model and analyzed to provide feedback to the system model and to the science observation model, allowing further system optimization. [engineering <--> operations integration]

f) The system is built, launched and operated, transitioning the operations model from the development period into the operations system for trouble-shooting as needed. [engineering <--> operations integration]

g) The spaceborne observing system begins reliably collecting, processing and delivering the default routine global observations that the modeling and data assimilation system (MDAS) needs to produce operational forecasts. [operations <--> science integration]

h) The Modeling & Data Assimilation System (MDAS) generates the weather forecast, and performs the assimilation by which observations are incorporated into the model. [application augmentation]

i) An unanticipated event/or departure (from model forecast) begins, signaling that a future event is anticipated at a certain time and location that requires additional observations. MDAS requests new observations through a command and control system. [operations<--> science integration]

j) The command and control system executes a model to determine how to optimally manage and schedule observing assets, and then elicits particular behaviors at the platform and sensor level. [application augmentation]

k) The observing system executes new measurement strategies in response to needs identified by the modeling system. [application augmentation]

l) The Observing System itself detects an incipient phenomenon and asks for confirmation from other sources, invoking the command and control system model. [operations<--> science integration]

m) Ground-based observing systems, part of the Sensor web, collect in-situ data, calibrate it, geo-locate it, quality-check it, reformat it at the sensor or platform, and uplink it, real-time, to a collection point for use in processing data. [application augmentation]

n) An Observation Conversion System converts surrogate measurements into geophysical parameters for direct comparison between observations and model predictions. [application augmentation]

o) The MDAS model provides the Sensor Web with predictions of what individual sensors should expect to see at a given time and place throughout their next observation. [application augmentation]

p) MDAS compares model predictions and actual observations and reconfigures itself by adapting its grid resolution in order to better capture what has been observed. [Integration within Engineering]

q) An External Control System (ECS) continuously executes a model of the entire system, to inform the humans in the loop, implement security, and provide overall monitoring and control for the combined observing and modeling systems. [Integration within Operations]

r) The data from the observation system are used to improve the science models and new science studies are conducted to determine which additional observational data would improve the model results... which is where we came in.

This future scenario is model-driven, from the concept definition throughout the life-cycle. A scenario such as this cannot be realized without AMSA.

2 Introduction-Current Status of MS&A

The complexity and sophistication of space systems has reached the stage where Modeling, Simulation and Analysis (MS&A) are an integral necessity throughout the lifecycle of NASA products. These needs apply to the following application areas:

1. Engineering of the vehicles, spacecraft, habitats and instruments;
2. Science (phenomenology) modeling;
3. Specification and validation to support acquisition;
4. Operation of space and ground systems;
5. Distribution, storage, reduction and understanding of science data; (necessary for science discovery and the interrogation of nature to learn about and understand physical universe).

The current use of MS&A is not sufficient for planned NASA missions. The AMSA roadmap presented here addresses these deficiencies and enables effective and safe exploration of space and conduct of science experiments.

AMSA is needed for Exploration system development and analysis; space system operations, and for science modeling and analysis. This plan addresses the needs of all three of these major application areas.

2.1 Science Assessment

Science models are an integral part of the overall NASA capability to field missions, and are executed for Earth System Science, Space Weather, and a variety of astrophysics problems (globular cluster formation, stellar atmospheres, interiors, galaxy interactions, etc). These science models, coupled with visualization techniques, provide unprecedented understanding of highly complex physics and chemistry problems.

Earth system science has models that now strain the capabilities of the world's largest computers and require still higher grid resolution to obtain proper solutions. The current state of the art in this community has pioneered several future-looking M&S advancements: real-time observational data have been assimilated into their models; they have begun to use models as a science experiment, *simulating* data assimilation from observations, to determine which future space measurements would have the greatest impact on improving predictions; and they have led model integration by developing a framework for coupling computational capabilities from multiple disciplines through the Earth Science Modeling Framework (ESMF). This is the first-ever suggestion that it may be possible to 'close the loop' from science modeling to specification of measurements of a future mission, to use of future observed results in science simulations.

The Sun-Earth environment modeling community has been pushing the boundaries of computing capabilities as well, with solution grids of several million, embedded mesh refinement, and multiple interacting codes. The basis of code interactions is the Space Weather Modeling Framework (SWMF), similar in concept to ESMF. Total solutions require hours of clock time using 256 processors of the Columbia system at NASA Ames.

Finally, in astrophysics simulation current modeling is limited in dynamic range (optimal: $>10^9$, current: $\sim 10^5$) due to limited computing power. Microphysical processes (star formation, feedback, etc.) must be heuristically modeled, and require parameter exploration and model tuning. Simulation codes are scalable to thousand of processors whereas analysis codes generally lag behind in sophistication and lack standardization. A new mission concept has been proposed in this community: "The Universe Computer." This would operate like a space mission, but with the primary goal of providing theoretical models for comparison with/analysis of observations. The "Satellite" is actually supercomputers and the observations are the simulation results. The largest obstacle to such a concept is cultural/political. It is necessary to show that such a "mission" will greatly enhance science returns of current and planned satellites; that there are a unique/small set of parameter and input physics choices, and that simulation & analysis models reasonably represent the real Universe.

2.2 Operations Assessment

The space environment is hazardous, and complex, and space system survival requires a thorough understanding of the interaction between the space environment and the system being developed. These interactions are inherently complex and uncertain, yet space systems require high performance and high reliability. Modeling and simulation can and should play a central and critical role in decomposing complexity, and producing a clear understanding of eventual system effectiveness.

As increasingly ambitious space missions are envisioned, the operational complexity also increases. Two examples illustrate this complexity. The safe operation of the Crew Exploration Vehicle (CEV) will require coordination of many space, ground and communications assets. Similarly, the Earth Science community has proposed a Sensor Web observational concept, in which multiple space assets collaborate with each other and with airborne and surface assets to acquire data at appropriate scales, resolution and temporal coverage to adequately characterize some identified environmental behavior. To design such a system and to evaluate alternative approaches requires that the behavior of the fielded system be appraised. Obviously, MS&A is the only tool available to perform such an evaluation prior to deployment. Similar situations could be described for advanced robotic exploration systems.

In the latter stages of the development cycle, Operations MS&A can and should be utilized to focus physical tests and define appropriate measurement parameters and accuracies and so that the tests will be more effective in providing useful supporting information.

Historically, the role for MS&A for operations has been largely confined to post-launch mission operation support. In the future, thorough operational simulations done during concept formulation and development can support trade-offs in the design, resulting in a much more effective operational system.

2.3 Engineering Assessment

Some of the space systems that are being planned will not be amenable to testing on the ground. These systems depend on a space environment that cannot be replicated on the ground other than through MS&A. Examples include thermal protection of atmospheric entry vehicles, and large, lightweight telescopes that cannot withstand deployment in a 1g environment. Simulation codes serve as the primary tools to integrate limited observational data into a structure to validate and verify entire systems.

The mission development approach calls for key architectural decisions in an early stage of development, when little is known about the mission. This limited information is provided by shallow models that are, at best, executed in an integrated environment such as Team X at JPL or IMDC at GSFC. This approach leads to point solutions and fragile designs. Future design environments that will allow higher fidelity models early in a mission lifecyle, coupled with sensitivity solutions and uncertainty models, are needed to resolve these limitations.

Later in the development cycle, the current approach to detail development of space systems is typically a sequential 'bucket brigade' of models, simulations and analyses. One notable exception to this rule, IMOS, integrates the analyses of optics, thermal, and mechanical dynamics and statics into a single code to predict the image quality of a telescope system. IMOS has been a critical element in defining the architecture of the Space Interferometer Mission (SIM) and will continue to perform mission-critical simulations in the testing and qualification of the flight system. IMOS serves as a good example of the power of integrating high fidelity solutions in engineering.

Future space systems will have cost, performance and reliability requirements that will not be achievable with this 'bucket brigade' approach. A broadly integrated engineering environment will provide significant efficiencies in the development phase, following the example given by IMOS.

2.4 Integrated AMSA

The discussion to this point has focused on the three primary domains of NASA business: Science, Engineering and Operations, and has given some insight to the possible improvements and gains that MS&A could provide within each of those activities. However, the view of this roadmap team is that to truly achieve *Advanced* MS&A (AMSA) additional steps are needed. First, integration within domains, already demonstrated by IMOS in engineering, should be expanded. Secondly, and more importantly, the next step is to integrate *across* these domains to an enterprise-wide system. What this will produce, in effect, is an end-to-end system that supports NASA from models of launch vehicles and crew systems to models of physical phenomena to models of the instruments that will make measurements of the physical phenomena to the engineering of the systems that will make the measurements, to operations, to data collection, storage, distribution, assimilation and mining. These types of integration have analogs in the business world, and can be described in the following terms:

Horizontal Integration normally refers to the degree to which an organization has control over business activities at the same level of the value chain. For AMSA, "horizontal integration" refers to the integration of models across disciplines within a domain. Examples include, coupled ocean, atmosphere and solid-earth models in the Science domain, or integrated structural, thermal, optical modeling (e.g., IMOS) in the Engineering domain.

Vertical Integration refers to the degree to which an organization has control over the stages in the production of a product. In the AMSA world, ”vertical integration” refers to the integration, or coupling, of models relating to phenomenology, observables, sensors, instruments, spacecraft, orbits or trajectories, operations, data and science models. This type of integration has not yet been started, but this is where the biggest impact to NASA would arise.

Temporal Integration refers to a project development cycle wherein simple models used early in the system development process stages are integrated with more complex and sophisticated models used later in the development process. This type of integration is just beginning in pockets of NASA business and is also critical to achievement of the full impact of AMSA.

2.5 Summary: AMSA embodies both Vertical and Horizontal Integration

The approach recommended here is an integrated AMSA system in which NASA's global mission is enabled in the broadest sense, allowing bold technical solutions with cost effectiveness, by integrating

- engineering modeling and simulation, driven by the science model results, used to define a mission.
- science modeling, exercised to define the best measurements to answer motivating questions.
- operations simulation, driven by both the science observations and the engineering approach, used to aid in defining the mission system and to troubleshoot problems during flight operations.
- science analysis and data assimilation, performed on the observational data, to improve the science models and to identify the next steps of observations.

This cycle repeats.

2.6 AMSA Benefits

Numerous benefits will accrue from a bold adoption of AMSA. A summary is presented here:

Proposal Development

Missions in the future will be under pressure long before the actual mission development steps begin: The nature of the measurements, precisions, coverage, and lifetime will all have to be simulated to convince policy makers and funding managers that the proposed mission not only is feasible but also that it will provide critical answers to the most important science questions, or meet the most ambitious exploration goals, in a timely and cost-effective manner. AMSA can provide those answers.

Cost management

Missions that have overrun costs in the past have, most often done so because the early development stage analyses had been over-simplified, and key points have been missed that could have been observed with more detailed analyses. Moreover, a significant fraction of costs arises in physical test and verification. Parametric cost analyses teach us that, as an agency, we continue to operate on the same cost curve that we have for decades. To depart from that cost curve, substantial changes must occur, one of which is substitution of analyses in place of much of the physical testing, and the use of analyses to define the proper test conditions when testing cannot be avoided.

Risk management

Much of the technical risk of a project arises from the lack of visibility into which problems to anticipate. AMSA can provide much of that visibility, in a manner analogous to the former adoption of 3-D CAD tools: Assembly and interferences of systems was not predictable prior to the use of 3-D CAD. As a result, Integration and Test was frequently the site of ugly surprises, when parts designed by different designers would not fit. This problem has been mitigated to a large degree by 3-D geometric CAD.

Technical solutions

Without AMSA, the boldness of proposed solutions will be limited by systems that can be assembled and tested on Earth. More ambitions approaches will be avoided due to cost and schedule impacts. With AMSA, high fidelity systems can be developed and validated through simulation. NASA cannot afford to overlook the opportunities opened by AMSA.

3 Moving from Today to the Vision: A paradigm shift

This roadmap advocates a new paradigm for the end-to-end conduct of NASA business: This paradigm is one in which *models*, not paper, become the basis for forming, analyzing and communicating information throughout the system. In it, validation and verification is also largely model-based, except for those cases where physical testing is the only (or final) means of validating and verifying performance. Even for these cases, the data from the physical test is integrated into a modeling framework that makes it accessible to *other*, collaborating modeling simulations and analyses.

This transformation has already begun in limited pockets: In both Earth Sciences (OSSE) as well as Space Sciences (LISA and SDO missions) models representing the best prediction of the underlying physics are used to understand phenomena to form detector designs, spacecraft configuration and observation strategy. During the mission and in post mission analysis, techniques such as data assimilation and synthesis are used to develop more accurate predictive capabilities using these same models.

In the engineering field a similar strategy allows broad exploration of the design space and elimination of competing designs and tests. Another emerging trend is the use of extremely high fidelity models during mission formulation to guide system design and operations. As a specific example Boeing has reduced the number of wind tunnel tests by and order of magnitude by relying heavily on simulation to explore the design space and to analyze the performance of competing designs. Physical testing is used only for final verification.

The AMSA vision articulates a cradle-to-grave modeling concept, integrating across various professional communities with NASA, including science, engineering and operations. AMSA provides that architecture to realize this end-to-end, wall-to-wall integration. AMSA itself is not a new idea, but rather a substantial escalation of activities already begun in all of the communities mentioned. Proof of concept is already behind us. The challenge is to expand and extend the existing capabilities and, most importantly, convert those capabilities into common practice. This last point will receive much attention later in the report, and well may be the biggest challenge for NASA.

3.1 Current capabilities and limitations

3.1.1 Science modeling today

Although analytical modeling has always been an indispensable component of science, it took the establishment of the NSF Supercomputing Centers in 1982 to move large-scale computational science from a niche activity centered in government laboratories to a vibrant, broadly utilized component of earth and space science in the university community.

Nevertheless, NASA's science efforts are still overwhelmingly "observation-based," certainly in the sense that far more resources are devoted to observational capabilities than to modeling, simulation and analysis capabilities. This, despite the fact that a significant proportion of NASA-generated observational data have never been analyzed.

In most of the science application domains, individual discipline models are quite mature, limited more by computational capability/capacity or algorithmic efficiency than by modeling sophistication. Development and deployment of coupled, multi-disciplinary models, e.g., air-ocean-land-ice-solid earth, is just beginning. Here there still is a significant modeling challenge, primarily in defining well-posed coupled science models. Moreover, collaborative software development and integration is a big challenge. An open policy issue is software ownership and sharing amongst individuals and institutions competing for NASA funding.

In the past several years NASA science program management has begun to utilize MS&A to evaluate future measurement goals and the impact of particular technology developments, especially instruments, on science objectives.

3.1.1.1 Capabilities

Some of the highlights of NASA's science MS&A achievements are summarized below in terms of state-of-the-art codes:

- ART for dark matter simulation,
- N-body multimass simulation of 20 million particles in the formation of galaxy clusters
- GEODYNAMO to simulate magnetic fields in deep interiors of stars and planets
- fcGCM for Earth global climate and weather prediction model
- ECCO for Earth eddy-resolving ocean and sea ice interaction
- QuakeSim for simulating earthquakes and incorporating observational data
- ESMF for coupling Earth systems models
- SWMF for modeling space weather
- GCDM for search and access to Earth science data collections
- VICAR for analysis of multi-dimensional imaging data

3.1.1.2 Limitations

The power of computers has increased to the point that extremely demanding, high fidelity solutions are now available. However, there still is latent demand for even more capability such that the size of problems can be further increased. One such example is in Earth global ocean models, where the current model grid sizing of 1 degree of latitude/ longitude is commonly used. To accurately capture eddy currents in the ocean, a much finer resolution of 0.16 degrees is required. Similar deficiencies exist in other disciplines.

Despite the progress of coupling demonstrated by ESMF and SWMF, it is still extremely difficult to couple models.

Validation is another serious deficiency at this time. In many cases sensitivity studies have been only partially performed to assess solution dependency on grid distribution and density.

Of the few coupled science models that exist, almost none have undergone appropriate validation.

Data assimilation is a fundamental need for many science models, driven by the need to improve model predictions. Techniques for performing data assimilation have been pioneered in some disciplines. Much more remains to be done.

Finally, there is a growing issue with data management. Historically, data management was thought to apply only observational data. The growing realization is that both model and observational data require similar attention. At the moment, data span multiple sites, with varying architectures and accessibility. There is no support for complex queries spanning multiple observational databases. As a result, existing data are of very limited value.

3.1.2 Operations modeling today

NASA currently makes extensive use of modeling and simulation to support the operations phases of missions, both as a training/planning tool and to help resolve anomalies that appear during mission operations. As the complexity and cost of future missions continues to increase, the use of these capabilities to offset considerable growth in the required infrastructure, and in fact to help define the infrastructure itself, will continue to gain momentum. At the same time, however, the increasing complexity of both the systems and the environments in which they are deployed will make development of the operations models much more challenging. Nonetheless, the most daunting challenge may be associated with integrating operations models with the science and engineering models early enough to ensure an effective system/architectural design for future missions.

3.1.2.1 Capabilities

NASA has a long history of the use of modeling to support operations planning for both science and manned programs, often utilizing approaches and tools developed in the defense arena that have seen increased emphasis over the last decade. The manned programs in particular have utilized sophisticated methods and models for many years to support training of astronaut and mission operations personnel. The aeronautics community as well is quite well versed in the use of modeling and simulation capabilities for operations modeling of individual flights as well as complex scenarios such as the nations air traffic control system.

However, in most, if not all, instances, the operations modeling is completed well after the system design is converged - and quite often deployed. The impetus behind development of these capabilities is usually cost; it is clearly cheaper to exercise the models to investigate operational performance than to use the [usually very expensive] assets themselves. But there is normally little explicit attempt, or ability for that matter, to actually influence the fundamental system design using the results of operational simulations.

A change in this philosophy is suggested in the emphasis of development of Concepts of Operations (ConOps) in support of the new exploration activities. Though no sophisticated operations modeling and simulation of the ConOps scenarios has been attempted, the clear indication is that operations requirements will be clear system design drivers during the critical stages of early design

In addition to the relationship to the system engineering models, there is emerging emphasis on also integrating science and operations models in order to help develop the complex measurement schemes necessary for next generation science investigations. For example, development of integrated earth science models might lead to suggesting a more effective use of multiple, heterogeneous assets, both space and ground, to achieve hyperspectral measurements or more cost-effective operations.

3.1.2.2 Limitations

The complexity of future NASA operations, particularly those supporting the integrated human/robotic operations typical of future exploration activities, suggest that current operations modeling capabilities will fall far short of that required.

Key limitations include the following:

1) Future missions, supporting both human and robotic exploration, are quite likely to be deployed in more unstructured and inconsistent environments - and almost certainly in more hazardous ones. The uncertainty associated with the characterizations of these environments means that the operational aspects of the mission or system will be increasingly difficult to both model and validate in the future.

2) The challenges associated with modeling increasingly complex and highly coupled human/machine operations in remote, hazardous environments are significant and not well characterized. Modeling the interactions of multiple robotic and human assets working in tandem, potentially under simultaneous local, remote, and/or autonomous control, is beyond current operations modeling capability.

3) The full benefits associated with the use of operational modeling and simulation will not be realized until the capability can be effectively integrated with other modeling assets; in particular, the operations models must at some point significantly influence the design of the system itself through their interface with the engineering models. This approach, whereby science, operations, and engineering models would be components of a fully integrated system model, derived in that order, has not yet been realized.

3.1.3 Engineering modeling today

NASA’s engineering functions span from high-level system analyses to detailed component design. The systems analyses are typically used to inform decision-makers of the effectiveness, cost and risk for alternative architectures, advanced concepts, and technologies. Current NASA system analyses use some combination of expert opinion and MS&A. Generally, the MS&A aspects of system analyses are performed with a broad set of low-fidelity models, and there is relatively little automation of multidisciplinary models. Current trends are to decrease reliance on expert opinion, to increase the automation of multi-disciplinary integration, to increase model fidelity in selected disciplines, to develop more rigorous models of cost, risk and operations, to expand the use of optimization, to provide some measure of confidence in the results, and to provide better connectivity to decision support tools,

NASA has traditionally developed advanced algorithms and tools for use by the U. S. aerospace industry in preliminary and detailed design of aerospace systems. Support for this type of activity has waned considerably in the past several years, and the emphasis has shifted from physics-based discipline models, to integrated multi-disciplinary models and to models suitable for analyzing noise, emissions, safety, security, capacity, transportation systems and operations.

For system design "experimental-based engineering" is the rule, i.e., simulations may be used to guide the design, and experiments are used to validate the design (not to validate the simulation). "Validation" of designs is based largely on review committees and not on mission/engineering scenario models. Mission risk mitigation is based on utilizing as many testable hardware components in the system design as possible.

3.1.3.1 Current capabilities

Some of the highlights of NASA's engineering MS&A capabilities are:

- Finite Element structural modeling
- Computational fluid dynamics
- Aerospace high-performance computing pathfinder (NAS)
- Deep space trajectory navigation
- Radiation space environmental and contamination effects modeling
- Optical systems modeling, wave-front sensing and control
- Collaborative engineering systems modeling for mission planning
- Radar target simulators
- Rover kinematics models
- Instrument design, including optical and thermal design

AMSA capabilities have significantly advanced over those in existence 20 years ago, enabled by both improvements in computational hardware and software environments. Advances have been made in development of physics-based discipline models and large-scale environments supporting end-to-end system modeling. Past efforts in this area have largely failed due to insufficient computational capabilities and a lack of software infrastructure. An encouraging example of AMSA work is on the JWST mission, which utilizes large segmented primary mirrors with wavefront control to achieve mission goals. Due to system complexity, subsystem interactions and the difficulty of system-level ground testing, integrated modeling tools are proving to be essential for validating the wavefront control system and for evaluating the sequence of events during the commissioning process. Similarly, the TPF program has done extensive modeling to demonstrate feasibility of several concepts for exo-solar planet detection. Modeling has enabled all new optical concepts for the TPF mission effectively demonstrating the viability of visible wavelength coronagraphs in addition to the original IR interferometer concepts.

3.1.3.2 Limitations

New missions are straining modeling resources to support system engineering decision processes and accurately predict performance. Although normally adequate for the high-risk NASA environment, these limitations sometimes contribute to dramatic failures and also limit the development of innovations that would improve our engineering capabilities. Indeed, innovations are typically invented, adopted and further advanced by industry rather than by NASA itself. Moreover, NASA's engineering modeling capabilities remain discipline specific, are too highly dependent on heroism and credibility of key individuals, and have largely fallen from the state-of-the-art relative to many peer organizations. Data flow between commercial design and analysis packages has been amply demonstrated but the process is far from seamless and many times requires human intervention and development of specialized data translators. Because there is little or no commercial market for many of the discipline tools that NASA needs for its missions, advances in these capabilities must necessarily be sponsored by NASA.

Modeling of systems has increased in complexity but not as fast as the increased complexity of the systems themselves (and our confidence in the complex models lags even further behind). MS&A developments to deal with additional complexity, end-to-end model architectures and increased fidelity discipline models are generally concurrent with mission development, allowing minimal time for verification and validation. This lack of V&V translates into a large financial risk since a large portion of mission costs are committed early and later changes are very costly.

Not only is there a critical lag in model availability, but also there is significant uncertainty as to the validity of system models. Engineering system models are usually validated by comparison with specific discipline model results and with subsystem tests. The methods of data management and model correlation are not well established and frequently rely upon ad hoc procedures. Little automation exists between testing and model updating. This means there is little opportunity to fully exercise these models and take advantage of the cost savings and reduced mission risks afforded by exploration of the trade space and optimization enabled by more capable environments.

As an example, the Mars atmosphere is so poorly modeled that large design margins must be carried for EDL. These shortcomings can be cast into the larger arena of uncertainty management. Tracking and propagation of uncertainty models should become a standardized process with established tools supported by well understood mathematical frameworks. However, consistent methodologies and approaches and the ability to handle large-scale systems has not been firmly established and varies significantly.

3.1.4 Integration status today

As described in the previous three sections, horizontal integration of MS&A within each domain of science, operations and engineering provides key capabilities in scientific discovery, training and mission planning, and engineering development processes, respectively. This section will focus on the integration across these three domains into a single NASA–wide MS&A capability: A Genuine AMSA.

Given the resource demand of the MS&A capabilities, even today, in each of the three domains, the necessary extensions of those capabilities and the multiplicative increase in resource demands resulting from cross-integration, this is a long-term development area. Over the next 30 years this increasing level of integration will be paced by our ability to conduct the necessary research, provide the tools and resources needed to operate in such a different environment, educate a workforce for the new environment, and validate the solutions provided so that acceptable confidence in the results can be achieved. Moreover, this approach heavily depends on advancements being made in the computing and software business world outside NASA and must therefore adapt as new, perhaps unforeseen, capabilities become available. The underlying message is that this proposed system cannot be so hard-wired and inflexible that it obviates our ability to leverage and incorporate future available technologies.

Integration will not happen naturally. It requires focused objectives, investment, and a different practice environment, where the modeling teams are more tightly integrated into every phase of the mission design process. Such a major development effort will need to proceed in phases and in concert with capabilities being developed in other elements of this roadmap. These phases are briefly described below.

Phase 1 focuses on the establishment of an awareness of, and architecture for, cross-domain integration. The community of developers needs to understand that their codes are intended to fit into a broader structure and to therefore adhere to interface standards and expect to do verification, validation and accreditation (VV&A) such that the resulting codes are reliable and transportable. At the same time, provisions must be made for developers' accessibility to computing resources, archival systems and the like.

Phase 2 is widely applied integration at the discipline and scale level, which are essentially confidence-building steps leading to phase 3.

Phase 3 is the final phase, allowing multi scale, multi-fidelity, multi domain integration. To be successful in this final phase will require focused attention to architectural issues in earlier phases such that the architecture enables this phase, and does not impede it.

3.1.4.1 Capabilities

Current integration is limited to discipline-specific applications, best typified in the science domain by the Earth System Modeling Framework and the Space Weather Modeling Framework. For engineering, multidisciplinary models that use high fidelity analysis capability are very limited and are typified by the application Integrated Modeling of Optical Systems.

3.1.4.2 Limitations

The current MS&A environment is one of separate tools and algorithms that are not designed to inter-operate on a larger scale. Even though the distinction between science modeling and engineering modeling is breaking down (examples are models connecting planetary weather to parachute design, solar models to radiation prediction for operations), generalized systems to allow necessary coupling do not exist. Except for specific (heroic) solutions depending heavily on human intervention, coupled solutions have not been done.

Within the science area, other than ESMF and SWMF, frameworks for producing coupled solutions do not exist. Within engineering, frameworks are needed to support multidisicplinary analyses as well as for translating early design cycle low fidelity exploration solutions to later, higher fidelity solutions. These frameworks do not exist, although there is limited research being done to develop such frameworks.

3.1.5 Environments and Infrastructure today

Current MS&A environments have evolved within local MS&A communities, with some of the impetus coming from the science domain, some from engineering and some from operations. However, much has also arisen from the operators of the large scale computing systems themselves, as a response to the varied user community. These are outlined below.

3.1.5.1 Capabilities

Each of the MS&A components will be greatly enhanced by developing an effective method of bridging components of a system model into a larger modeling system, physically distributed, with equivalent virtual presence for all participants. Today, remote collaboration is enabled by high bandwidth connections that allow geographically dispersed work groups to operate in a tight-knit virtual environment. The foundation of this high speed connectivity is being installed and demonstrated now as the national *LambdaRail* optical network, and many NASA Centers are subscribing to it.

Tools and environments for developing these integrated systems are exemplified by the ESMF and SWMF. These systems provide tools for turning model codes into components of a larger system with prescribed interfaces and standard drivers.

They also provide data structures and common utilities that components use to organize codes; to improve performance portability; and to provide routine services such as data communications, regridding, time management and message logging. One of their essential goals is to provide standards for model and data description. This is a prerequisite for an advanced modeling and collaboration environment that includes knowledge management. These tools are still in their infancy and continued development is required to bring them up to the level of production use.

Parallelization tools and environments are foundation capabilities needed to take advantage of new computing architectures. Although the parallelization of large application codes is necessary for productivity, it is time-consuming and error-prone. To address this problem, NASA researchers have been integrating three prototype software development tools to enable rapid transformation of serial codes into efficient, correctly functioning multi-level parallel codes. Some of these are outlined below.

- CAPO Parallelization Assistant includes sophisticated static program analysis, an informative and intelligent user interface, and portable parallel code generation.
- P2D2 Automatic Debugger compares executions of serial and parallel programs, with information from CAPO, to determine where the executions start to diverge.
- Paraver Performance Analyzer (in collaboration with the European Center for Parallelism) supports OpenMP, nested OpenMP, MPI, MPI+OpenMPI, and MLP parallelism

This roadmap does not deal with the actual computing hardware needed to accomplish the capabilities listed. However, the largest operational computational capability available at any given time will be required.

Issues that are being addressed to assure that such a large supercomputer is a highly versatile and productive computational environment for Engineering and Science is available include high capability networking, storage, visualization, and code porting and scaling services. These all require continuing development to remain at the state of the art.

A specific example of the latter is visualization. Current capability is represented in the hyperwall, which has more than 64 million pixels distributed over 55 square feet of viewing surface, with 100 Gigabytes of visual output. As model complexity grows and as display and data management technology advances, this capability will need to advance commensurately.

3.1.5.2 Limitations

Systems to control access to product model libraries and data repositories are not in widespread use throughout NASA and need to be developed and implemented. MS&A

programs and outputs will join other data as information to be kept and utilized throughout end-to-end efforts, and which must be archived for long-term access. Corruption of programs or outputs can cause catastrophic failures, and even mere access can expose vulnerabilities in operational missions.

It is inevitable that data, resources and researchers will be geopolitically distributed. Many of the tools necessary to be successful in this distributed and collaborative environment do not exist. Work is needed to incorporate the work being done by multiple agencies and couple this with the NASA-specific needs.

One major obstacle to sharing data and collaborating in a global modeling environment is the issue of Intellectual Property. IP issues can arise within each MS&A subsystem both in the capability of the models as well as in the ownership and handling of the data. While no specific proposals for IP are made here, policies and procedures must be established to permit data and model exchange, interoperation and integration.

The functions of validation, verification, and accreditation (VV&A) have been used for many years to evaluate and approve the effectiveness and deployment of systems. However, for MS&A there is little discipline or process definition for validating and verifying models and model outputs, resulting in insufficient credibility of system models. Engineering system models are usually (partially) validated by comparison with specific discipline model results and with subsystem tests. The methods of data management and model correlation are not well established and frequently rely upon *ad hoc* procedures. Very little automation exists for testing and model updating. This means there is little opportunity to fully exercise these models and take advantage of the cost savings and reduced mission risks afforded by exploration of the trade space and optimization enabled by more capable environments.

Finally, there are a number of technology limitations that prevent comprehensive use of modeling and simulation methodologies, tools, and techniques for VV&A activities. Three key areas that stymie success involve the quantification and management of uncertainty, the use of formal math methods to assess modeling and simulation software, and the derivation, assessment, and recalibration of physical/behavioral models.

3.2 Investment Plan

The problem with the current levels of MS&A at NASA is not that any one capability is deficient, but rather that each capability (with minor exceptions, noted below) is independent of all others, and the necessary interactions do not exist to allow NASA to obtain the full benefit of an integrated capability. For example, in engineering, the state of the practice of MS&A during mission development is a series of data transfers, in which successive modeling activities must manually import data, develop appropriate mathematical models independently, conduct analyses, and then send the results to yet another related, but disconnected analysis activity. This has arisen because domain experts, seeking better solutions to their specific problems, developed discipline-centric analysis tools but lacked any incentive to integrate into an overall process. The result is a series of unconnected locally optimized simulation codes with little analysis of uncertainty.

A full AMSA capability will be accomplished when there can be a smooth transition of ideas and concepts from one domain of expertise to another and the smooth transition of products from one environment (mission phase to another) to the other. In short, we need to carry the concepts of standards and procedures from the system level through to the overall mission or group of missions level. The processes that have already proved useful in scientific discovery are applicable to the coupling of various components needed for engineering and operations. Provenance of the data, actual capture of decisions, issues of accuracy of the models, and archival capture of design data are all key topics that must be addressed.

Left to itself, NASA's current MS&A capabilities will not undergo the necessary transformation to affordably and effectively support future missions. Inertia will carry the Agency forward on its current trajectory. The basic technical approach will remain unchanged, costs will continue to escalate, science modeling will remain constrained by discipline boundaries, whole classes of missions will be unachievable, and for those attempted, the risk of failure will continue to be unacceptably high.

3.3 MS&A Future: Three possible layers of investment and benefit

Given the discussion above, three alternative paths are open to NASA with respect to MS&A, characterized below as levels of investment.

3.3.1 Investment Level 1. Expanded application base

Level 1 represents minimal but expanded investment over today, in which specific MS&A capabilities are developed on a highly focused and near-term schedule basis, to expand the analysis applications base. This is the least desirable approach presented in this plan because it will further perpetuate the multiple, incompatible, non-interoperable "stovepipes" in which MS&A has been developed. While specific projects may be able to benefit from this localized process, an integrated capability will not be attained. In addition, several projects may create similar (but still incompatible) MS&A tools, duplicating efforts. The actual cost of this duplication will be difficult to detect or measure, since it will simply appear as a cost of project business.

The objective of this level of investment is to identify and fund development of new, mission-driven, individual discipline capabilities in each technical domain (Science, Engineering, Operations) and subject these and legacy capabilities to Agency-level integration requirements.

3.3.1.1 What is needed, and when: Science

Additional science applications are needed in three discipline areas: Earth science, Moon-Mars system and Giant planet exploration.

Earth: The following science codes require substantial development: carbon cycle model, solid earth model, composition model, and radiance-based assimilation

There are two scientific AMSA capabilities essential for the Moon-Mars system, deriving from the plan for human exploration:

- predictive model for solar energetic particle (SEP) radiation: essential for the radiation protection of astronauts during EVA or moonwalk.
- predictive whole atmosphere model for Mars: essential for predicting meteorological conditions for astronaut activity (dust storms, etc) and for precision landing, aerobraking and aerocapture of space transportation vehicles.

Giant planet exploration: Radiation environment models of the giant planets (in particular Jupiter).

Details are shown in Appendix F.

3.3.1.2 What is needed and when: Operations

The cost effectiveness of missions is largely determined early in the design cycle, when key system decisions are made. Often, the costs are deferred downstream to a later phase of the mission and are not even considered during mission development. To overcome that tendency, a number of specific operations models are recommended, most of which are intended to be used during development and are expected to improve decision making, giving the potential for significantly lower life cycle costs. These models are shown in Appendix F.

3.3.1.3 What is needed and when: Engineering

The next generation of space-based platforms require models for better understanding formation flying, sparse apertures, extremely precise control of surface figure and wavefront errors, metrology systems, new cameras and instruments for space observations and remote sensing, interplanetary trajectories and Lagrange point orbits, and quiet structures and low level disturbances, aerodynamic decelerator models, the impact of nanotechnology, new thruster technology and structural microdynamics. Several upcoming programs combine these technical challenges.

With advances proposed in this section, modeling can have a large impact in lowering mission risk and cost.

The roadmap for these investments is shown in Appendix F.

3.3.2 Level 2 plan: integration within domains

3.3.2.1 Science

One of the difficult, persistent, issues in science involves the integration of multiple disciplines and their models into a unified model that more accurately reflects the complexity and behavior of the phenomena being studied. Legacy science codes may be quite accurate within their intended domain of application, but they impose simplistic boundary conditions to mimic those aspects not modeled. It is often the interaction at these boundaries where new, complex, phenomena occur. However, merely making it possible to exchange data between models is not sufficient to create a valid compound model, and hence systematic use of VV&A for all compound models is a key component of this activity.

<u>Earth Systems Models</u>

There is need to couple together current component models, such as those for the atmosphere, ocean, land, and sea ice, to model global phenomena such as the impact of the release of chlorofluorocarbons, or the results of an accidental oil spill. Including models of social behavior, such as those of population density and the panic behavior of groups, can help predict the effect of earthquakes and tsunamis. Often subscale phenomena, such as aerosol models relative to an atmospheric model, can have feedback on the larger model, such as altering radiation absorption.

Missions such as L-Band MEO InSar Constellation (2014), High Resolution CO2 (2014), and MEO (2016) will provide important real-time data, which, when assimilated into advanced models, can aid in the prediction, monitoring, and response to major events.

Predictive SEP model

This model must be able to give a 24-hour local forecast of major SEP events at the 90% confidence level. The model will use a 4-D view of Sun and the inner heliosphere to be provided by a succession of missions: SOHO, Stereo (2005), SDO (2010), Earth L1 monitor (not in the plan), Heliospheric Sentinels (2014) and eventually a Mars L1 monitor (not in the plan). It must recognize pre-eruption solar configurations and predict the location and timing of solar eruptions with high reliability. Following the eruption it must provide a reliable simulation of the structure, evolution and transport of the interplanetary event, the acceleration and transport of solar energetic particles in the heliosphere and in the magnetospheres of Earth and Mars. Stereo and SDO mission data sets need to be used to provide reliable observational signatures of imminent solar eruptions. This must be done not later than by 2015 to allow adequate time for model validation.

Design-Trade Sensitivity Modeling.

Science modeling will also have a significant role in design of instruments and development of mission plans to enable future ambitious science measurements. High resolution and fidelity science phenomena models will be needed for various DRMs (such as InSAR (2014), SAFIR (2020+), & Constellation X (2014)) to provide a reference for exploring instrument and mission concept design trade studies. A capability to develop such Observing System Simulation Experiments (OSSEs) that can be integrated with instrument design to provide greater confidence on the ability to obtain specific science results is needed.

Bio-Planetary Protection Modeling.

Preventing bio-planetary contamination, and detecting exobiology, requires computational biology models of terrestrial "bio-agents" and their binding to spacecraft surfaces, and models of the impact of forward and backward contamination on life-detection techniques and analysis.

The roadmap showing this development effort is shown in Appendix G.

3.3.2.2 Operations

The motivation for operations integration derives from the need to pull operations considerations into the early phases of mission development to assure that decisions being made at that time do not increase operations complexity. To do this, new types of operations models are necessary that provide both high fidelity in capturing the operations functions but also provide results in parameters characteristically used in early concept explorations.

A second important motivation is to allow execution of high fidelity operations models in a simulation environment prior to launch for mission rehearsal, and early identification of potential anomalies and their resolution. Moreover, these same models would be used post-launch for anomaly resolution.

Specific integrated models are discussed below:

Distributed, coupled simulators

Mission teams are likely to be even more widely distributed in the future, and missions are likely to increase in complexity requiring much more interaction across geopolitical boundaries and straining the limits of physical relocation. System simulators will be needed that are connected by broad-band (gigabit) data links, with high performance information management systems to allow simultaneous operation with virtual presence across large distances.

The software tools that run on such simulators must provide modeling of the interactions of multiple robotic and human assets working in tandem, potentially under simultaneous local, remote, and/or autonomous control, and must be available for execution during the earliest phases of mission development.

Anomaly Resolution

As mission development proceeds, operations models of the mission must develop in tandem, such that the operations models at launch represent the system as built. These operations models should be sophisticated enough to assimilate engineering data during operation to assess performance trends and to provide predictions of potential failure modes before failure occurs. These models will require integration of environmental characterizations, detailed system models, and physics of failure models into a single operational code.

These investments are shown in Appendix G.

3.3.2.3 Engineering

Many of the future missions proposed in the DRM will require integration of extremely complex technologies, which will challenge management and system engineering. Advancement in discipline-specific engineering codes is not enough to adequately address future mission cost and risk issues. An additional level of integration, cross-discipline, is required:

- Large-Scale Systems Models (LSSM) which enable system evaluations and therefore leverage the increased knowledge gained early in the design cycle. These are intended to be evolutionary cradle-to-grave tools with an environment supporting data management and multiple optimization tools, allowing full exploration of the trade space. These are characterized as multi-level models, with an open but controlled architecture allowing distributed resources and computing.
- Anomalous Behavior Models (ABM) for proactive consideration of low probability but high risk events. These models typically reserved for post-mortem should become more part of the early design cycle process thereby minimizing failure modes and effects. It is proposed that artificial intelligence tools play a larger role in evaluating system culpability by developing AI-based Agents-of-Doom software tools.
- Increased support and rigor in development of Uncertainty Models (UM). These are tools to characterize inherent variability due to lack of knowledge and errors and are strongly coupled to design space size and optimization processes. In the early phases, these are important for characterizing chances of mission success.

- Selective use of virtual testing models (VTM) due to environmental and economic constraints. This is the use of modeling for the untestable product and/or unobservable parameter and for updating flight LSSM.
- Support for increased space-based Robotics Manufacture and Servicing Models (RMSM). This is a virtual environment for dynamically replicating assembly, servicing and repair processes in space.

Managing this complexity will require full integration of performance, science and cost models within an environment which facilitates data management, optimization, and distributed computational and user interaction – this is the domain covered by LSSM.

To establish the validity of these models, separate tools are needed to establish uncertainty bounds on discipline and system models. There are many available frameworks that can be borrowed from different communities that should be better established in NASA's modeling tools. For example, the control community has developed formalisms known under the generic term of robust control (μ analysis, H^{∞} control) which deal with modeling uncertainty. The statistics community has evolved new tools based upon Bayesian techniques utilizing efficient Monte Carlo Markov Chain methods, which can help evaluate results of complex systems. The DoE's ASCI program has made significant progress recently on uncertainty quantification for AMSA.These tools could be used now on complex systems such as JWST and certainly would reduce risk on future missions. However, there are many challenges still remaining.

These investments are shown in Appendix G.

3.3.2.4 Infrastructure

Investments required to allow widespread integration within all domains address three basic deficiencies: VV&A of MS&A software, product data repositories, and high fidelity virtual environments, all of which are non-existent or inconsistently applied today.

Verification tests functionality and determines that a MS&A implementation accurately represents the developer's conceptual description and specification. It seeks to ask "Was the modeling and simulation built right?" Validation evaluates fidelity and determines the degree to which MS&A and its associated data is an accurate representation of the real world for its intended use. It seeks to ask "Was the right modeling and simulation built?" Accreditation determines credibility and is an official stamp of approval that a modeling and simulation application and its associated data are acceptable for use for a specific purpose. It seeks to answer the question "Is this the right modeling and simulation to use?" Developing capabilities in these areas will overcome today's questionable quality and traceability of results.

One primary challenge in integrating within domains is to maintain a complete and accurate data set for the life of the project. This will require definitions for meta-data standards and tracking of model versions. This work is expected to lead the way into broader definitions that will be applied across the whole range of model data, physical test data, model applications and test system applications, to allow maintenance of data regardless of source.

Technologies that can merge and/or integrate model results, generated across distributed locations, will need further enhancement. The concept of a "virtual presence," the ability to support views and interactions with model (or in-situ instrument) data as if the observer was actually present, would provide mechanisms to gain new insights from the data in addition to providing another "observational" capability. Visual programming, where appropriate, to simplify the development of complex systems may also have an important role.

These investments are shown in Appendix G.

3.3.2.5 Level 3 plan: agency-wide integration

Level 3 investment is required to attain a seamless and integrated agency-wide capability. It builds upon the localized integration efforts in the three domains and provides the bridges across those integrations to allow agency-wide interoperability as illustrated below. For this investment, attention focuses on the bridgework development and the necessary infrastructure support. Participation from the three technical domains is required, but primarily in a supporting role.

3.3.2.6 What is needed and when: Integration

<u>Optimization tools</u>

To support the integrated system, an optimization engine for trade studies and configuration decisions is required. With the coupling of models in each domain, the large growth in the number of parameters will require more attention to development of advanced optimization approaches. The development of large-scale optimization tools should enable their usage across domains.

<u>Modeling Bridgeworks</u>

In order to advance scientific investigation, MS&A is increasingly dependent on interoperating models from different domains. NASA has funded and participated in several interagency efforts to develop modeling frameworks. These multiyear efforts are designed to promote earth and space scientific advance by providing a software "infrastructure" which allows application interoperability, application reuse, reconfigurability and facile movement from research to production for complex multidisciplinary modeling, simulation and analysis applications. The infrastructure capability demonstrated in the existing frameworks is essential for a robust and viable contribution of modeling and simulation to NASA.

For the next stage of integration, across domains, we must learn from the experiences of the framework development. Current frameworks are directionally correct but of questionable sustainability as currently configured, funded and supported. For bridgeworks, studies should determine whether commercial software infrastructure tools or open source could be leveraged in partially satisfying the needed capability. This would allow NASA, in conjunction with other related communities who share modeling/simulation components, to focus and limit the infrastructure development and support to those items, which will not be delivered from the marketplace.

<u>Interfaces/ standards / protocols</u>

Interfaces and standards are certainly in use today, even outside the rigor of ESMF. These focus primarily on application-to-application interface standards, and generally do not focus on tightly integrated application systems. The definition of new standards that accounts both for data interchange and performance standards is essential to the new modeling environment.

NASA needs to ensure that models will interface with data systems and decision support systems. The development and evolution of a common standard interface that can be used by the modeling and analysis services should be a high priority activity.

One promising approach is standardizing on a service-oriented architecture based on self-describing web-services to support the discoverability and dynamic reusability of tools and services. NASA needs to track and be involved in the standards defining process so that its requirements and needs are well represented. This would allow NASA to leverage the frameworks and the supporting tools being developed elsewhere and adapt them to meet its own modeling and simulation.

The next step is to facilitate the sharing of information and capabilities across geographically dispersed facilities. Remote collaborative data access is the third component to enable the easy reconfiguration of models or simulations to enable timely modification of assumptions.

Data Architectures

NASA's modeling and simulation needs currently strain data management technical capability. While the geographic distribution of data sources, the variety of data types and differing uses of data, are not unique, the sheer volume of data sets NASA need significantly apart from other entities.

High speed data networks, distributed data management tools and security access models are commercially available. NASA's scientific research demands an Agency-wide cohesive data and metadata architecture(s) to use those capabilities effectively. Adaptation to NASA's specific and unique mission needs, including NASA's collaborations with external entities, require ongoing investment.

Real-time simulation

One of the unique requirements resulting from integration across domains is an increased need for real-time simulation and modeling capability. For example, science observations need to be modeled and coupled to science instrument models and spacecraft operation models to determine the performance trade-offs during mission development as well as during operations. Current applications of real-time systems are dedicated solutions and will not support the range of models and the model fidelity required for this simulation. New tools and simulation systems are required.

These investments are shown in Appendix H.

3.3.2.7 What is needed and when: Enabling environments and infrastructure

Product model Repositories

In the absence of end-to-end data management architectures, product data sets are distributed in archives not easily discoverable. There is a need to develop such architectures for products that NASA will deliver in the future, accounting for all horizontal, vertical and temporal integration. This architecture should extend into the data delivery from the flight mission.

VV&A

VV&A products that would be delivered under the level 2 funding plan must become the foundation for deliveries under this level 3 plan. A variety of mixed-fidelity models and simulations will be shared amongst teams. Just as technology is measured for its level of maturity, models, simulations and their associated data sets require some measure of their maturity in order to facilitate this sharing and reuse.

To facilitate reuse and this integration, techniques to improve code identification, accessibility, interoperability, and recalibration amongst new and legacy models and simulations need to be derived. Recalibration involves the tuning of models and simulations over time with observed phenomena and physical tests as we use physical tests to calibrate our models.

NASA will need to develop careful policies in data security and access, and, as current Internet attacks illustrate, will need to constantly maintain vigilance. It will need to make extensive use of COTS and federally developed software and best practices, and should be an active participant in relevant standards development efforts. Fortunately the commercial and federal efforts in this area are significant, and hence NASA will not need to bear the much of the burden of development cost. However, it will bear a significant burden of implementation and continuous updates of its security procedures.

<u>Simulation tools and environments</u>

The growing gap between sustained and peak performance for scientific modeling and simulation applications is a well-known problem in high performance computing. Future supercomputers will have ever-increasing peak theoretical performance with extremely high levels of concurrency, but unless NASA applications are able to effectively exploit these technological advances, key performance metrics such as time-to-solution and reduction in design cycle time will not see a commensurate improvement.

To improve sustained performance, appropriate programming tools and techniques for these emerging architectures will have to be developed. Advances will also be required in systems software for these immensely parallel machines, particularly in the area of lightweight operating system kernels for robustness (fault detection and graceful recovery). Optimized numerical libraries that meet NASA's diverse requirements must be developed and provided to scientists and engineers to serve as building blocks for MS&A application codes. Research and development work will also have to be conducted in user-friendly runtime environments and expressive language systems. The essential keys to success are being able to efficiently scale to many processing units, and control data placement, movement, and reuse. As in other areas, NASA needs to collaborate with academia, industry, and other agencies to guide, acquire, evaluate, and adapt technologies for its own needs and purposes.

Development of effective Virtual Environments must be advanced to support MS&A. Fundamentally, easier and more direct mechanisms to convert model simulation results into meaningful visualizations are needed. Currently, scientists must learn and integrate a number of tools (or rely on expert help) to gain insight into results from their models. Many engineering tools integrate sophisticated visualization capabilities into the modeling software, but such tools are generally limited to small and moderate sized models that run on personal computers. Advances are needed for visualization of large-scale data sets that must also account for real-time and interactive capabilities. Techniques are also needed that allow exploration and understanding of highly complex multi-dimensional/multivariate data.

Modeling applications and tools

With the increasing complexity of NASA's MS&A applications, frameworks and infrastructure are needed that support the efficient execution of applications. Such frameworks should include capabilities to (a) manage the overall execution process, e.g. setting up and executing parameter space studies via GUIs and portals; (b) discover the appropriate data sources and execution resources both hardware and software, e.g., computers, tools, and services for optimal execution of the sub-tasks; (c) manage the actual execution in a secure and fault tolerant manner, including launching of tasks across distributed systems and facilitating the inter-task data transfers; and (d) monitor, control, and steer the overall execution.

A significant and sustained investment is needed in adapting legacy algorithms and developing new algorithms and applications that exploit the architectural features of the simulation platforms. This may require developing new methods that are more appropriate for the target platforms. In addition, it might entail revisiting and modifying previously discarded strategies because they may now map better on emerging architectures. Furthermore, enhanced physical models are also needed to simulate entire systems and mission life cycles, and thereby go beyond our current capabilities of simulating only components and subsystems

Assimilation is the process of combining observational data with prior knowledge and modeling to produce an optimal estimate of the state of a system. The resultant "analyses" are the best way to initialize predictive models of high-dimensional dynamical systems (e.g., numerical weather prediction forecasts). The important roles of assimilation in prediction, model development, instrument design and monitoring, and control, span all three domains of science, engineering, and operations. Software environments are needed that will allow access, management, quality control, and deployment of the highly variable types of data streams involved in assimilation. The environments must support large-scale weather and climate prediction studies, with immense archival data repositories and enormous numerical models, as well as fine-scale control capabilities, with live data streams and real-time analysis and feedback. Environments will also be needed to investigate and deploy newly developed and emerging methods, such as non-sequential four-dimensional variational data assimilation.

Model based contracting

The goal of MBC is to go beyond digital text to facilitate procurement transactions between customer and supplier. The objective is to specify performance of a future product through model behavior. Getting to that stage of sophistication will require a number of discrete steps, beginning with contracts requiring delivery of models as process artifacts of the contract, then VV&A done using models and finally to the end goal. One major obstacle to be overcome is to define acceptable legal policies on sharing of models without compromising competitive position of the contractors.

These investments are shown in Appendix H.

3.4 Relationship to NASA Vision

There are a number of NASA goals that require this new approach:

Goal #	Statement	Comment
1	Implement a sustained and affordable human and robotic program to explore the solar system and beyond	The emphasis on sustained and affordable imply that the role of MS&A will have to be increased to minimize expenses associated with large operations teams and to allow highest efficiency space systems
2	Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations	The technical and cost challenges with such demanding missions requires a new, less costly engineering approach, tightly coupled to science measurements
3	Develop innovative technologies, knowledge, and infrastructure both to explore and to support decisions about the destinations for human exploration	The objective of improving the fidelity of individual simulations early in a product life-cycle and the integration across all involved communities are essential to provide highly credible data, early in the life cycle, to support decisions.
4	Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests	By including the entire community in the development of these new MS&A approaches, the international and commercial sectors will become more highly integrated into the NASA program
5	Study the Earth system from space and develop new space-based and related capabilities for this purpose	The technical and cost challenges with such demanding missions requires a new, less costly engineering approach, tightly coupled to science measurements

3.4.1 Specific AMSA Applicability

Goal: Return the Space Shuttle to flight as soon as practical,

> ASMA will continue to have a major impact throughout the vehicles' lives, similar to the impact of flowfield simulations following the Columbia shuttle disaster.

Goal: Complete assembly of the International Space Station, including the U.S. components that support space exploration goals

> The space environment effects on human health and the development of countermeasures will require simulation first and then later testing in the station.

Generally, aging systems and increased complexity increase the demand on model capabilities.

Goal: Undertake lunar exploration activities to enable sustained human and robotic exploration of Mars and more distant destinations in the solar system;

AMSA will play critical roles in mission design, including landers,

Goal: Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration.

AMSA will play critical role in mission design, from science modeling to engineering and finally, operations modeling.

Goal: Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore Jupiter's moons, asteroids and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources.

AMSA will be key component of mission design

Goal: Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars;

AMSA is required for the design and testing of largest telescopes as well as V&V of the systems to be flown.

Goal: Develop and demonstrate power generation, propulsion, life support, and other key capabilities required to support more distant, more capable, and/or longer duration human and robotic exploration of Mars and other destinations.

AMSA will support modeling of nuclear power,

Goal: Develop a new crew exploration vehicle to provide crew transportation for missions beyond low-Earth orbit.

AMSA will provide rapid design and tests will rely on advanced modeling as well as parametric studies

Goal: Conduct human expeditions to Mars after acquiring adequate knowledge about the planet using robotic missions and after successfully demonstrating sustained human exploration missions to the Moon.

AMSA is critical to entry, descent and landing, atmospheric modeling, radiation environment modeling,

3.4.2 Impact if AMSA recommendations are not implemented

If level 2 capabilities not met:

NASA's research activities have traditionally focused on observations and the technology to make the observations. However, technology and large data sets are only part of the system research approach: a system is not fully understood until a quantitative model can be built, executed and validated. Experimental data from NASA's observations would be un-interpretable without detailed models against which they can be compared. MS&A is thus no less important than observations. Lack of MS&A capability hampers NASA's ability to set priorities for future observational requirements, and ultimately leads to greater inherent uncertainty in scientific advice to inform national policy on scientific issues.

In system development and operation, the impact of MS&A is to allow a wider range of systems to be evaluated and to understand them to a much greater depth. Failing to invest in Level 2 objectives leads to limited application of Large Scale Systems Modeling. The efficiencies of temporal integration, maintaining a coherent data system throughout the lifecycle, and ultimately, cost and time-to-solution benefits will not be realized as well as generalized multi-disciplinary analyses and optimization will not be enabled.

The impact will be *less well-informed design decisions* due to inability to conduct the necessary early systems assessments and optimizations, perform systems trades, and assess technical risks. *There will be less ability to assess failure modes, consequences, and recovery paths*. In short, business will proceed very much as usual, with the predictable results of schedule delays, cost overruns and potential system malfunctions.

If level 3 capabilities are not achieved:

MS&A at NASA will remain a stove-piped capability. NASA programs will not be able to perform end-to-end system optimization to maximize mission ROI and to minimize risk to human explorers. NASA will not be able to improve the efficiency of its own and its teammates', design processes. As a result, mission quantity and quality will suffer, large uncertainties will remain in evaluation of mission risk, and sub-optimal allocation of NASA resources will continue. In short, NASA will be relegated to second-world MS&A status (and to third-world if Level 2 is not done). The long-term impact is that NASA will stop attracting "the best and the brightest" in MS&A and in mission development.

4 Challenges and overcoming them

4.1 Technical

Major Technical Challenges
2006-2010
Level 1 - Identification of and funding for new application development
Level 2 - Definition and implementation of appropriate framework architectures
Level 3 - Definition of bridgeworks architecture compatible with multiple frameworks
2010 - 2020
Level 1 - Identification of and funding for new application development
Level 2 - Populating of multiple frameworks with all applicable applications -Acceptance of framework approach and development of processes in which to embed the frameworks
Level 3 - Implementation and population of bridgeworks,

2020 and beyond
Level 1 - Identification of and funding for new application development
Level 2 - Broadening the frameworks approach to include the whole NASA community
Level 3 - Development of end-to-end system processes using bridgeworks.

4.2 Cultural / political / legal challenges

4.2.1 IP/ITAR & Data Rights

In the 1999 Department of Defense Authorization bill, Congress transferred responsibility for satellite technology to the State Department from the Commerce Department. Research activity that once was subject to the fundamental research exclusion under National Security Directive 189 was formally regulated and made subject to the State Department's International Traffic in Arms Regulation (ITAR). As NASA starts implementing the Exploration Vision and as NASA increases partnering with international partners in the development of satellite instruments, spacecraft platform, and launch technologies, many of the model algorithm and analysis results will be shared broadly with the scientific community. In addition, as the modeling, simulation, and the data management environment becomes more and more distributed and openly shared, there is an immediate need to reaffirm and use the fundamental research exclusion whenever the information produced is published and shared within the scientific community.

4.2.2 Partnerships and COTS (academia, industry, other agencies)

Many aspects of Federal R&D, particularly aspects of simulation and computational science are sufficiently small or specialized to lack commercial viability. Consequently, aspects of modeling and simulation unique to Federal research must be developed within the research sector itself. In such an environment, partnerships are important so as to avoid duplication and to assure maximum leveraging between different R&D activities. These partnerships must continue to pursue extensible, open source solutions to common problems encountered in the specialized simulation research community. Further, cooperation on specifying the hardware and software needs for future simulation environments may be essential to influence industry direction and encourage the development of architectures suitable for simulation science.

In the past, NASA's modeling, simulation, and analysis capability has been benefited significantly from the Government-industry partnerships. For example, NASA and its industry partner's specialization in the shared memory architecture have produced computing systems significantly easy to use for high-end scientific modeling and simulation. Other agencies and academia institutions have also developed specific partnerships with the industry. As the modeling, simulation, and analysis systems mature and the problem size and scope begin to include the complex interactions between many sub-systems, there is a greater need to establish collaborative modeling framework, distributed computing environments, and data standards. Simulation frameworks, metadata standards, and future generations of compiler technologies, including advanced scripting languages, and libraries are just a few of the areas that should be pursued cooperatively with other agencies, especially DOD, DOE, and NSF.

Whenever possible, NASA should also partner with the industry to adapt and adopt the tools, which support the infrastructure and integration of applications and data. For example, visualization technologies, data management systems and "science- oriented" application architecture tools are emerging industry areas of direct relevance to NASA's needs. NASA should pursue partnerships that result in the effective use of COTS products in the modeling, simulation, and analysis environment as much as possible to efficiently leverage industry trends and academic training.

4.3 Human Resource Challenges

The talent pool for computational science remains thin, with competition existing between academia, industry and government. A recent report from the Council on Competitiveness, based on an industry survey, noted that lack of experienced computational scientists was a major limitation to broader use of computational science within industry. There are many reasons for this talent dearth, but most are related to inadequate or inappropriate education and funding uncertainties related to computational science.

4.3.1 Education

Computational science, broadly defined as the use of modeling and simulation to analyze complex problems, requires diverse skills, ranging from computer architecture and software through numerical and non-numerical algorithms and mathematics, data management, visualization and domain expertise. A new dimension recommended here, the development and deployment of multi-disciplinary models (e.g., air-ocean-land-ice-solid earth), is in its infancy. Moreover, collaborative software development and integration remain major challenges.

Despite the clear need for skills in diverse areas, computational science education remains largely ad hoc, with skills acquired informally from collaborators or mentors. Relatively few computational scientists receive formal training via university computational science programs. There are many reasons for this, but most are consequences of the current structure of Federal agencies and universities, which often limit the interdisciplinary education and information exchange needed by computational scientists.

Experience has shown that students benefit when research experiences are coupled with execution. This suggests new programs should foster experiential and collaborative learning environments at the graduate and undergraduate level and should tie these environments to ongoing research and development efforts. These learning experiences should place students in real-world situations, including internships and field experiences. This also suggests that greater funding is needed for curriculum development in computational science, targeting best practices, models and structures.

4.3.2 Workforce

Industry surveys show that there is an inadequate computational science workforce to meet current needs. Informally, many universities have reported a declining interest in high-performance computing, due to uncertain funding and job prospects. Although high-performance computing is but one component of computational science, it is central to its operational practice. If NASA is to ensure the availability of a new generation of computational sciences, fluent in the techniques and methods of computational science, it must work collaboratively with industry and academia to create, foster and ensure visible and attractive career paths for computational scientists. Curriculum development, scholarships and fellowships and public science outreach are all critical.

4.3.3 Internal Education

Given the rapid pace of technical change (e.g., with COTS systems becoming the predominant hardware platforms for computational science) and the increasing need for development of multidisciplinary applications, the free flow of information and staff across NASA centers and projects is the best way to ensure ongoing internal education. Concomitantly, software standards and interchange must be encouraged, as the development of complex applications often requires a decade or more to realize the full benefits of cross-disciplinary education.

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Appendices

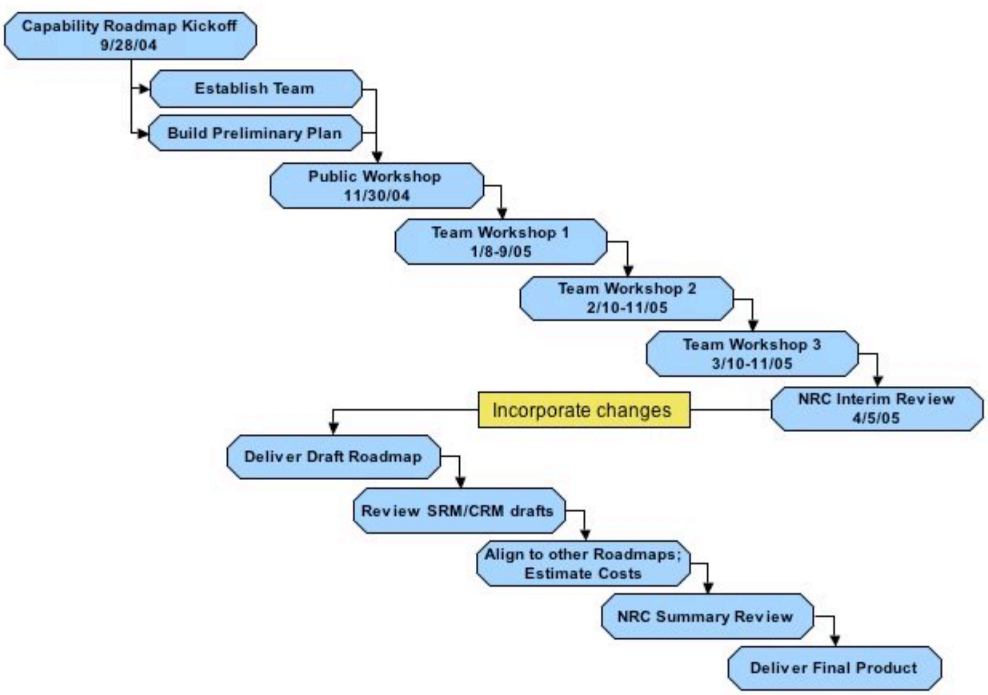
Appendix A. Team Charter and process

The material in this report was generated as part of a NASA roadmapping exercise led by the Advanced Planning and Integration Office. This team was one of 16 capability roadmap teams identified to address needed capabilities that would satisfy NASA strategic plans. Strategic plans were identified by 13 Strategic roadmap teams.

The charter of the AMSA team is:

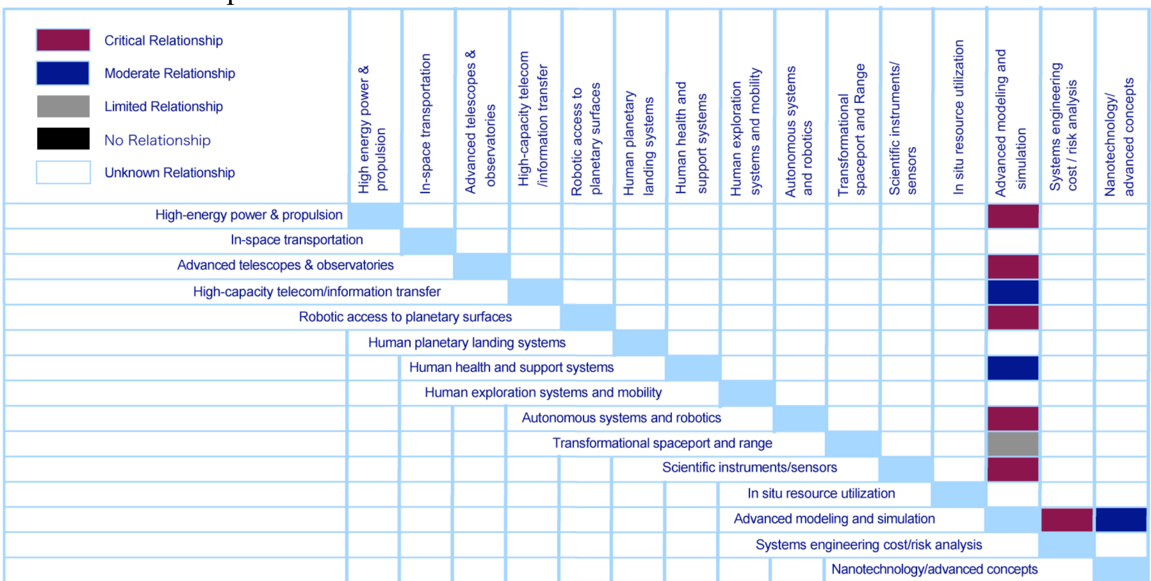
To identify what is needed to enhance NASA's capabilities to produce leading-edge exploration and science missions by improving engineering system development and science understanding through broad application of advanced modeling, simulation and analysis techniques.

The overall process that this team followed is illustrated in the flowdown diagram shown below:



Relationships between the AMSA team and the other roadmapping efforts are show below:

CRM Relationship



Details of the CRM crosswalk are shown below:

Advanced Modeling, Simulation, Analysis capability	Capability Flow and Criticaltiy	Related Roadmap	Nature of Relationship
Scientific modeling and simulation engineering modeling and simulation All instrument/sensor types	→	**Scientific Instruments & Sensors**	*Enables Systems architecture studies *Provides applications for science discovery and analysis *Enables instrument design tradespaces *Allows end-to-end instrument design and performance assessment
Engineering modeling and simulation	→	**Systems engineering and cost/risk analysis**	*Provides advanced modeling techniques for all aspects of project *Provides frameworks for tying multiple models together
Operations modeling and simulation	→		Requirements determination, and expansion of the trade
Engineering modeling and simulation	→	**Advanced telescopes and observatories**	Provides understanding of system trades and risks across implementation approach Enables system level assessment of size and stability (mechanical & thermal) properties from both passive and active approaches
Engineering modeling and simulation	→		Provides advanced mission system and subsystem level modeling, simulation and analysis tools to analyze and do design trades on future telescope and observatory architectures and systems.
Engineering modeling and simulation Operations modeling and simulation System Integration	↔		Provides anomalous behavior models to minimize failure modes and consequences in the design phase. Provides virtual system testing for untestable systems. Provides simulations of robotics assembly and servicing.
M&S Environments and Infrastructure	→		Provides infrastructure tools that enable efficiently managed data for future advanced telescopes and observatories
Engineering modeling and simulation	→	**Nanotechnology and advanced concepts**	Provides multi-scale modeling for materials, devices and systems
Engineering modeling and simulation	→	**Robotic access to planetary surfaces**	Provides EDL modeling for entry systems. Provides aero-structural modeling of aerodynamic decelerators.
Engineering modeling and simulation	→		Provides EDL Control sys modeling for entry systems
Scientific Modeling and Simulation	→		Provides planetary atmospheres modeling for design entry controls systems, and planetary "weather forecasts" for EDL operations.
Engineering modeling and simulation	→		Provides radiative aeroheating modeling for TPS design.
Engineering modeling and simulation	→	**Space Communications**	Improved modeling and manufacturing process increases power efficiency for RF communications
Engineering modeling and simulation	→	**Autonomous Systems, Robotics, and Computing Systems**	High fidelity terrain modeling and analysis; Model-based detection for ISHM; Logistics: Modeling of failure mechanisms; ISHM: V&V methods for models;
M&S Environments and Infrastructure	→		Collaborative information analysis and sharing
Operations	→		Activity plan development and analysis; Autonomous Science Analysis, Predictive Modeling, and Optimization
Engineering modeling and simulation	→	**High Energy Power and Propulsion**	Autonomous Control (Nuc Power) Design/Model; Heat Rejection System design analysis and trades; Shield design analysis and trades.
Engineering modeling and simulation	→	**Human Health & Support Systems**	Space Human Factors Models & simulations; Design tools & requirements; Radiation shielding design tools; Maintain, improve risk assessment models/ Analyze proposed mission architectures; Risk analysis model for med events; Med simulation model (testbed); Biomedical models of human systems in microgravity; Validated Exercise Model; Verify individualized predictive models for fatigue (ISS); Predictive models for lunar-cognitive & fatigue related decrements; Predictive models for team cohesion/productivity; Digital anthropometry models; Models of human-automation performance

SRM relationship

AMSA Identified Need (AMSA) · SRM Identified Need (SRM)

Broad Topics Captured / SRM Teams	Lunar: Human & Robotic	Mars: Human & Robotic	Solar System Exploration	Search for Earth-Like Planets	Exploration Transport System	International Space Station	Space Shuttle	Universe Exploration	Earth Science & Apps. From Space	Sun-Solar System Connection	Aeronautical Technologies	Education	Nuclear Systems
Large Deployable Lightweight Apertures				SRM			No Data Available	SRM	SRM			No Data Available	
System/Instrument Design and Performance		SRM	SRM	SRM				SRM	SRM	SRM			SRM
On-Board Processing		SRM							SRM				
Mission Planning, Impact, and Operations	SRM	AMSA	SRM	AMSA	SRM	SRM		AMSA	SRM	SRM			
Space Environment Effects	AMSA	SRM	SRM		SRM	SRM		AMSA	SRM	SRM			
Spacecraft Design and Broad Applicability		SRM			SRM	SRM				SRM	SRM		SRM
In Situ Exploration and/or Sample Return	AMSA	SRM	SRM										
Science Needs		SRM	SRM	SRM		SRM		SRM	SRM	SRM			
Engineering Analysis and Design Needs			SRM		SRM	SRM			AMSA	SRM	AMSA		SRM
Planetary Environment, Protection Habitability	AMSA	SRM	SRM		AMSA				SRM	SRM			
Data Synthesis, Analysis, and Visualization			SRM	AMSA					SRM	SRM			
Navigation and/or Formation Flying		SRM	SRM	SRM	SRM			SRM	SRM	SRM			SRM
		SRM	SRM		SRM	SRM		AMSA		SRM			SRM
SRM Identification of AMSA Support	None	None	Partial	None	None	Some		None	Major	Major	None		Some

● Areas where SRMs either mentioned modeling or the topic area need in general

● Gaps, where SRMs did not mention modeling; nevertheless modeling should be applied

View of AMSA support indicates if an SRM explicitly identified how the AMSA CRMs would aid their goals.

Identified topics are based only on data within SRM documents.

Appendix B. Team Recommendations

1. NASA should define and implement the equivalent of Technology Readiness Levels for its models and simulations.
2. NASA should define and implement the equivalent of a CMM rating for its modeling and simulation processes.
3. NASA should establish a collection of logically connected repositories/libraries of its legacy and newly created models and simulations.
4. NASA should create a modeling and simulation VV&A curriculum and suite of short courses to catalyze adoption and spur training and education amongst its government, contractor, and academic community.
5. NASA should invest in technology research and development that addresses limitations in modeling and simulation methodologies, tools, and techniques for VV&A to include the quantification and management of uncertainty; formal methods; and derivation, assessment, and recalibration of physical/behavioral models.
6. The Department of Defense has recognized the value and need to use modeling and simulation constructs within its system development and mission operations. As such, it has formalized an organizational infrastructure for modeling and simulation that NASA should be able to significantly leverage through tailored adoption.
7. NASA should actively participate in professional societies and standard bodies engaged in the formulation and proliferation of VV&A methodologies and techniques for modeling and simulation to ensure its needs can influence this community's direction. These forums can be used to leverage commercial and industrial practices.

Appendix C. Contributors: Presentations to the AMSA Team

Presentation Title	Presenter	Organization
November 30, 2004:		
Virtual Immersion into Data	William Campbell	NASA – GSFC
Distributed Space Systems	George Davis	Emergent Space Tech.
Goals and Challenges	Mark Gersh	Lockheed Martin
Mission Design	Cindy Kurt	United Space Alliance
Automated Design Systems	Jason Lohn	NASA – ARC
Experimentally Validated Simulation	Doun Van Gilder	AFRL, VPI, UCLA, JPL
SRNL Capabilities	Michael Williams	Savannah River Nat'l Lab
New Trajectories	Martin Lo	NASA JPL
UGS/Team Center Capabilities	Aaron Johns	UGS
Coupled Science Models	Dave Smith	Boeing
Parallel Meshing	Charles Norton	NASA – JPL/GSFC
Health Management Systems	Sanjay Garg	NASA – GSFC
Technology Infusion Assessment Sys	Trygve Magelssen	Futron Corporation
January 6, 2005:		
NASA Planetary Exploration Needs	Jim Cutts	NASA – JPL
	Jim Robinson	NASA – HQ
NASA Supercomputing	Walt Brooks	NASA –ARC
Ocean Modeling & Data Assimilation	Ichiro Fukumori	NASA – JPL
Solid Earth Modeling	Andrea Donnellan	NASA – JPL
Advanced Visualization	Erik DeJong	NASA – JPL
Integrated Optical Systems	Marie Levine-West	NASA – JPL
Earth System Modeling Framework	Cecelia DeLuca	NCAR
Space Weather Modeling Framework	Quentin Stout	Univ. of Michigan
Industrial Modeling	Ron Fuchs	Boeing
FEM	Michael Ortiz	CIT
Sandia Modeling and Simulation	Carl Peterson	Sandia
Engineering Modeling at NGST	Karen Fucik	NGST
Engineering & Modeling Data Center	Ricky Rood	NASA – GSFC
Nano-technology	Paul von Allmen	NASA – JPL
February 10, 2005:		
NASA Universe Needs	Jim Breckinridge	NASA – JPL
Web-centric Modeling and Simulation	J. Mark Pullen	George Mason Univ.
Planetary Atmospheres	Robert Tolson	Univ. of NC
Observing Sys Simulation Experiments	Bob Atlas	NASA – GSFC
NASA Sun-Earth Needs	Don Anderson	NASA – HQ
Future Computing Architectures	Larry Smarr	UC – San Diego
Climate Modeling	Jim Kinter	COLA
Stellar Atmospheres	Thierry Lanz	NASA – GSFC
Data Driven Application Systems	Frank Lindsey	NASA – HQ
Dynamic Data Driven Application Sys	Frederica Darema	NSF – CISE
Galaxy Interactions	Romeel Davé	Univ. of AZ

Appendix D Architectural Assumptions and Impact

Key architectural decisions affecting AMSA

Rather than consider the impact of NASA architectural decisions on Advanced Modeling, Simulation and Analysis (AMSA), AMSA can and should be used as a primary tool in guiding NASA leadership as these decisions are made. AMSA will illuminate which missions will return what type and quality of science data; show the technical capabilities of various mission concepts; and identify technical challenges and risks of those mission concepts.

The table below indicates some of the architectural decisions that NASA might make that would affect the future AMSA needs.

Decision	AMSA Impact
Manned Moon Missions	Increase priority of models for radiation effects (on humans) and space weather forecasts over current modeling for humans in LEO. Increase criticality of human safety, thus increasing priority of Anomalous Behavior Models (14.3.2). Increase importance of terrain modeling, surface planning and operations, in-space and surface vehicle design, radiation tolerant electronics, human health monitoring related to solar weather and storms, in-space assembly.
Manned Mars Exploration	• Increase priority of models for radiation effects (on humans) and space weather forecasts over current modeling for humans in LEO. Increase criticality of human safety, thus increasing priority of Anomalous Behavior Models (14.3.2). Increase need for long-duration spacecraft design, trajectory and propulsion design, solar weather and storms, planetary atmosphere modeling, surface science investigations and field analysis, radiation effects modeling, high bandwidth communications, antennas, electromagnetics, in-space assembly.
Robotic Mars Exploration	Increase modeling for long-range traverse and path planning, hardware design for extreme environments, autonomy, multi-path communications, and scientific data analysis of remote systems.
Robotic Deep Space Exploration (Jupiter Icy Moons, Europa, Pluto, etc.)	Require better models for TPS design (radiation-dominated aeroheating) for atmospheric entry systems at outer planets/moons. Increase need for complex navigation and trajectory optimization, spacecraft survivability in extreme environments, deep space communications, and scientific data analysis of remote systems.
Search for Origin of Life	Increase need for biological modeling, planetary protection and habitability, precision formation flying modeling. Increase the need for modeling and simulation of large structures, deployable structures, advanced materials and metrology modeling.

Space-Based Astronomy	Increase need for modeling of astronomical phenomena (accretion disks, galaxy evolution, planetary formation, gravitational waves, etc...) and identification of astronomical objects (brown dwarfs, etc...). Increase the need for modeling and simulation of large structures, advanced materials and metrology modeling.
Development of Heavy-Lift Launch Vehicles	Reduce priority of Robotics Assembly/Servicing Models (since the current ESMD plan is to use existing, lower capacity launchers, and do extensive on-orbit assembly of modular systems). Increase need for structural, thermal, fluid, and atmosphere dynamics modeling.
Development of Nuclear Space Propulsion and Power Systems	Increase the need for High power instrument design, trajectory design and optimization, long-duration science objective missions. Develop deployment and shielding technology for surface nuclear power systems
Earth Science	Increase the need for radar system end-to-end modeling. Require completion of integrated earth models and understanding of Earth as a complex system, forecast of anthropogenic effects.

Appendix E. Acronyms

AFL	Astrobiology Field Laboratory
AI	Artificial Intelligence
CEV	Crew Exploration Vehicle
CMBPoL	Cosmic Microwave Background Polarization
COTS	Commercial Off The Shelf
EDL	Entry, Descent, Landing
ESSP	Earth System Science Program
FIR	Far Infrared
GEC	Geospace Electrodynamic Connections
HWIL	Hardware in the loop
InSAR	Interferometric Synthetic Aperture Radar
JIMO	Jupiter Icy Moons Orbiter
JWST WFS&C	James Webb Space Telescope Wavefront Sensing & Control
JWST/MIRI	James Webb Space Telescope Mid-Infrared Instrument
LISA	Laser Interferometer Space Antenna
L1	Earth libration point orbit
MAXIM	Micro Arcsecond X-Ray Imaging Mission
MER	Mars Exploration Rover
MHD	Magnetohydrodynamic
MS&A	Modeling, Simulation and Analysis
MSL	Mars Science Laboratory
MSR	Mars Sample Return
NPP	NPOESS Preparatory Project
NPOESS	National Polar-orbiting Operational Environment Satellite System
PFF	Precision Formation Flying

SAFIR	Single Aperture Far-InfraRed Telescope
SAR	Synthetic Aperture Radar
SDO	Space Dynamics Observatory
SEC Mag	Sun Earth Connection Magnetometry Misions
SI	Stellar Imager
SIM	Space Interferometry Mission
SPECS	Sub-millimeter Probe of the Evolution of Cosmic Structures
SR	Sample Return
TPF-C	Terrestrial Planet Finder-Coronagraph
TPF-I	Terrestrial Planet Finder-Interferometer
TPS	Thermal Protection System
TRL	Technology Readiness Level
VV&A	Verification, Validation and Accreditation
VISE	Venus In-situ Exploration
VR	Virtual Reality
WISE	Wide Field Infrared Survey Explorer

Appendix F. Level 1 Roadmaps

Science applications

Capability	**IOC date**	**Mission driver**	**Mission launch date**
Mars weather prediction model	2012	Mars EDL Precursor	2014
Mars surface model	2012	MSR	2014
Giant Planet Radiation model	2010	SDO	2010
Solar Energetic Particle model components	2010	SDO	2010
Geospace	2010	SDO	2010
Disk accretion / Planet Formation Model	2020	SAFIR	2020
Composition	2009	NPP	2009
Carbon Cycle Model	2009	NPP	2009
Radiance based assimilation	2012	NPOESS	2012
Solid Earth Model	2007	InSAR	2012

Operations applications

Capability	IOC date	Mission driver	Mission launch date
Human-machine interface model	2009	CEV	2014
Human behavior model	2009	CEV	2014
Parameterized subsystem behavior model	2009	CEV	2014
Air transportation system model	2011	Aero/ASP	2011
Aviation system vulnerability model	2020	Aero/AvSSP	2020
Business Model (Technology Portfolio Investments Models and Cost Models)	2007	ESMD Lunar/ Mars Explorers	2015
Process/Operations Staffing Models	2007	MSL	2011

Engineering applications

Capability	IOC date	Mission driver	Mission launch date
Precision interferometer/ thrusters models	2007	LISA	2010
Aerodynamic decelerator models	2009	MSR	2013
EDL Control	2009	VISE	2013
Advanced Thermal models	2010	Solar orbiter	2014
Aircraft noise and emissions models	2011	Vehicle Systems	2014
Radiation shielding models	2011	CEV	2014
Precision wave optics and wave front control models, deployable structures	2010	TPF-C	2014
Formation flying	2015	TPF-I	2019
Digital flight in earth & planetary atmospheres	2012	Aero/VSP & Mars Precursors	2015
Solar sail / navigation	2018	L1 Diamond	2023
Aerothermal / Thermal protection system design	2022	Titan SR	2027

Appendix G. Level 2 Roadmaps

A description of needed capabilities required versus time is shown below.

Science Integration

Science	**Today's Capability**	**2010–2015**	**2016–2020**	**2021–2025**
Sun-to-Earth space environment model for space storms & SEP events	25 Re, millions of cells, kinetic solutions with 1 billion particles	Predictive Sun-to-Earth space environment model to provide 3 hr. forecasts	Interactive, predictive Sun-to-Earth space environment model to provide 24 hr. forecasts.	Interactive, predictive Sun–heliosphere space environment model to provide 72 hr. forecasts for space storms & SEP events.
Comprehensive planetary hazard models to support human exploration	Static, parametric Mars atmosphere model.	Simulation of Martian atmosphere and near-surface winds.	Simulation of dust transport and storms. Predictions of atmospheric or subsurface transport of biohazards.	Weather forecasting for atmospheric density, near-surface winds, and dust storms. Predictive models for ionizing radiation at the surface.
Crustal dynamics models for earthquakes and plate motion	Millions of interactions (Green's functions), fault length scales of several km	Predictive simulation of interacting active faults in a California-size region at a scale of 1 km.	Predictive simulation of interacting active faults in a California-size region to provide 2 yr. forecast of earthquakes larger than 5.	Predictive simulation of interacting active faults in a California-size region to provide 6 mo. forecast of earthquakes larger than 4.
Coupled air–sea–land model for weather and climate simulations	1 degree grid atmosphere for climate .1 degree ocean.	Probabilistic predictions of future climates and transitional climate change at 100's km. resolution	Integrated Earth system model with interactive hydrology, dynamic vegetation, and biogeochemistry, with 100 km resolution.	Earth system modeling suite, using comprehensive data assimilation systems and observations from space-based Earth-monitoring systems.
Cosmological and galactic dynamics models	3D MHD problems w/ 10 million cells and multiple species	Interpret spectroscopic data gathered by a range of spacecraft.	Predict ionizing fluxes (ionization of Local ISM, nebular models, and the re-ionization of the early Universe).	Predict spectra of extra-solar planets to help design of new NASA missions.

Operations Integration

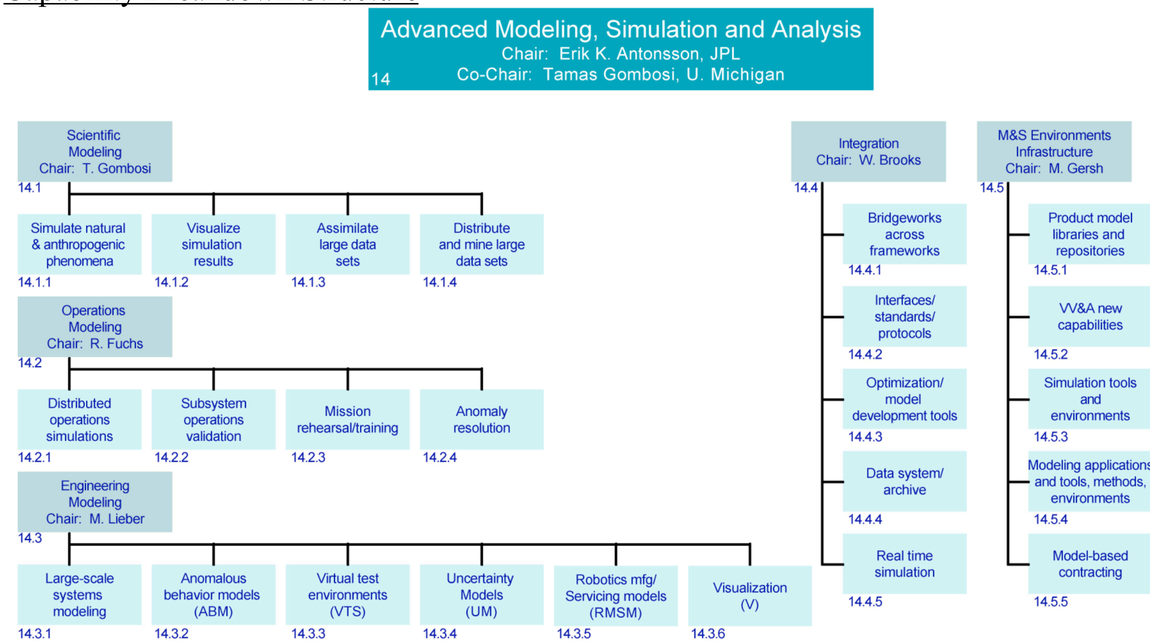
Operations	Today's Capability	2010–2015	2016–2020	2021–2025
Distributed operations simulations	Simulators at the individual system level; Manual interfaces between components	Prototype high bandwidth comm.. tools integrated with information management systems	Coupled, distributed simulators with software systems and tools allowing generalized mission support	Distributed ops model Integrated into the Interplanetary Network (IPN) framework.
Mission rehearsal / Training	Stand-alone mission specific simulators; Purpose-built single task trainers	Improved human-machine models, human behavior models	Multi-task trainers, coupled operations at distant sites	In-situ astronaut/robot training in-flight during Mars missions
Anomaly resolution	Limited to mission-specific tools	Operational data assimilation in system models	Integrated anomaly scenario evaluation	
Subsystem operations validation		Generalized, parameterized models of s/c subsystems	Test data models, data assimilation into operations models	

Engineering Integration

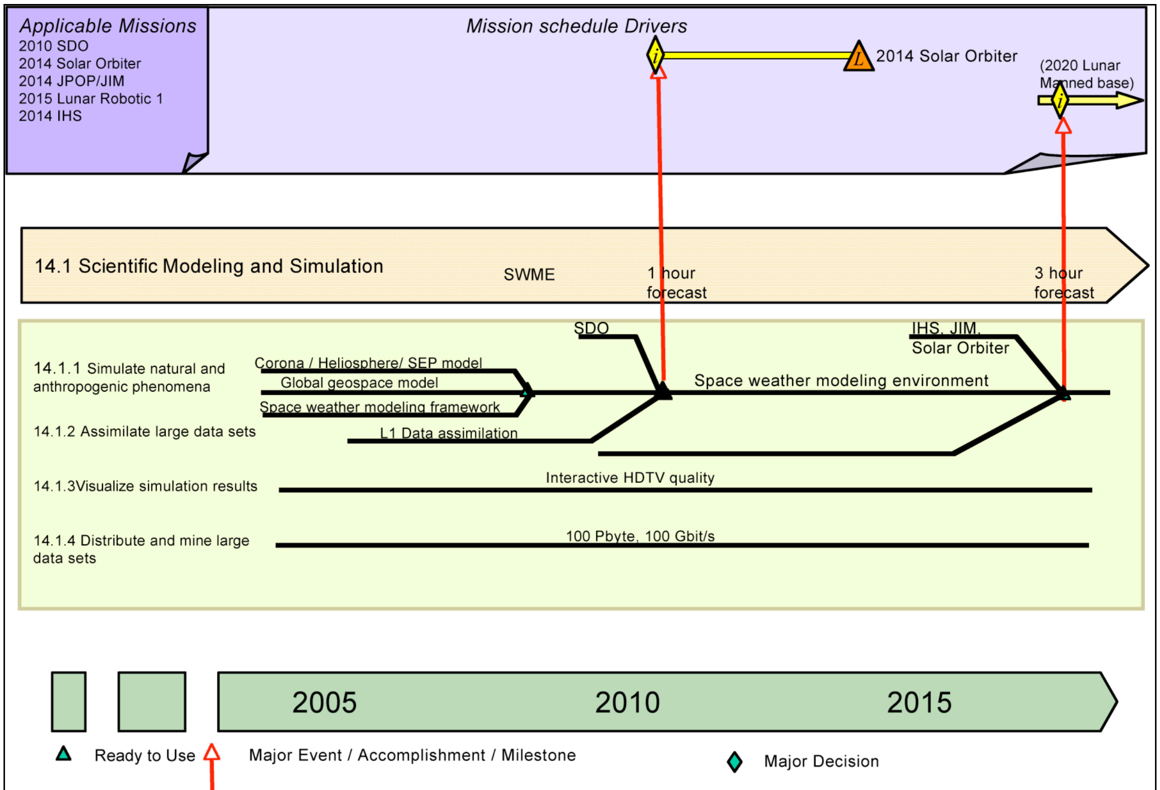
Engineering	Today's Capability	2010–2015	2016–2020	2021–2025
Large-scale system modeling	Bucket-brigade data transfer, significant discipline modeling, limited integrated system modeling	Cradle-to-grave models, rapid model deployment, integrated cost models	Seamless model evolution through design phases, integrated risk models	Distributed MDO, advanced data management, integrated cost/ risk/performance
Virtual test environment	Fit tool for manufacturing.		Robotic optical assembly.	Expansive HWIL, auto sys ID update
Uncertainty models	Probabilistic uncertainty propagation tools	Extensive uncertainty characterization	Uncertainty bounds in the validation domain	Uncertainty bounds in the predictive domain
Anomalous behavior models	Some SW analysis tools	Subsystem AI agent of doom	Full system AI agent of doom	Real-time isolation and resolution
Robotics manufacturing, servicing models	Rudimentary space-based servicing models	Human exploration hazard models	Robotic optical assembly and alignment	Human-robotic models for Exploration.
Visualization technology	3-D, single discipline analysis	Multidisicplinary design space exploration tools	Design space exploration agents	Holographic, dynamic, multiscale visualization

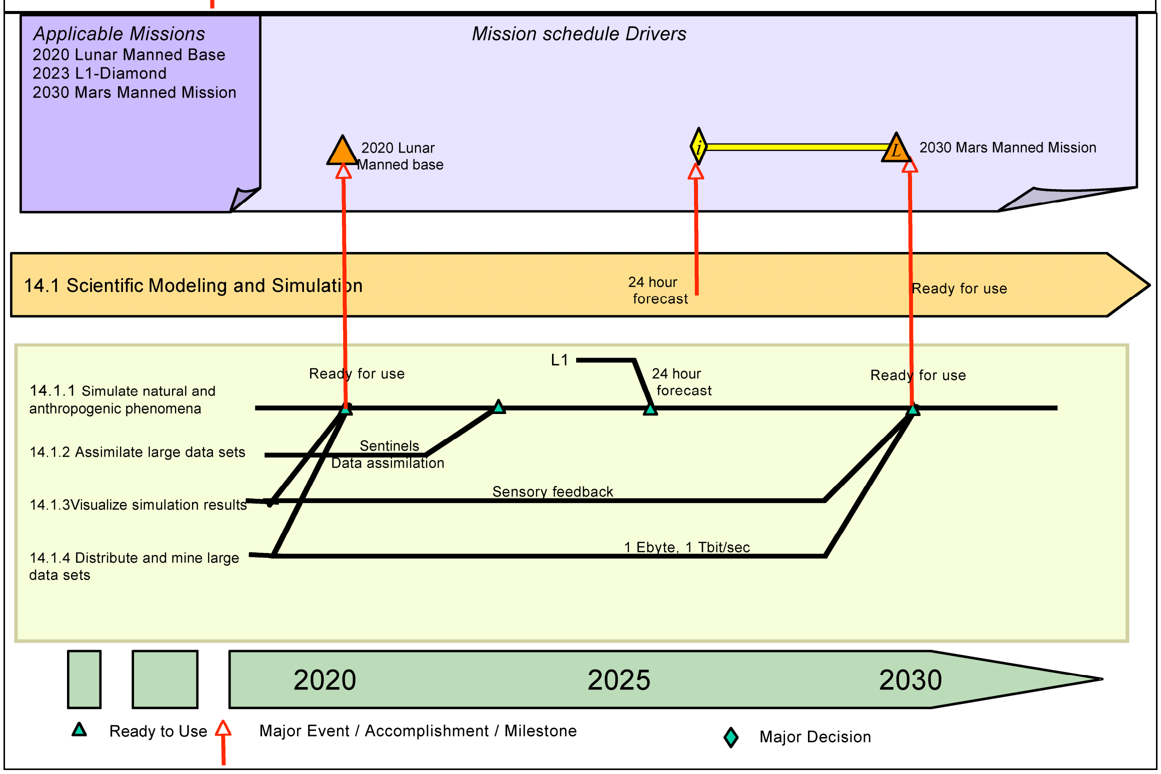
Level 2 Integration wiring diagrams are shown below:

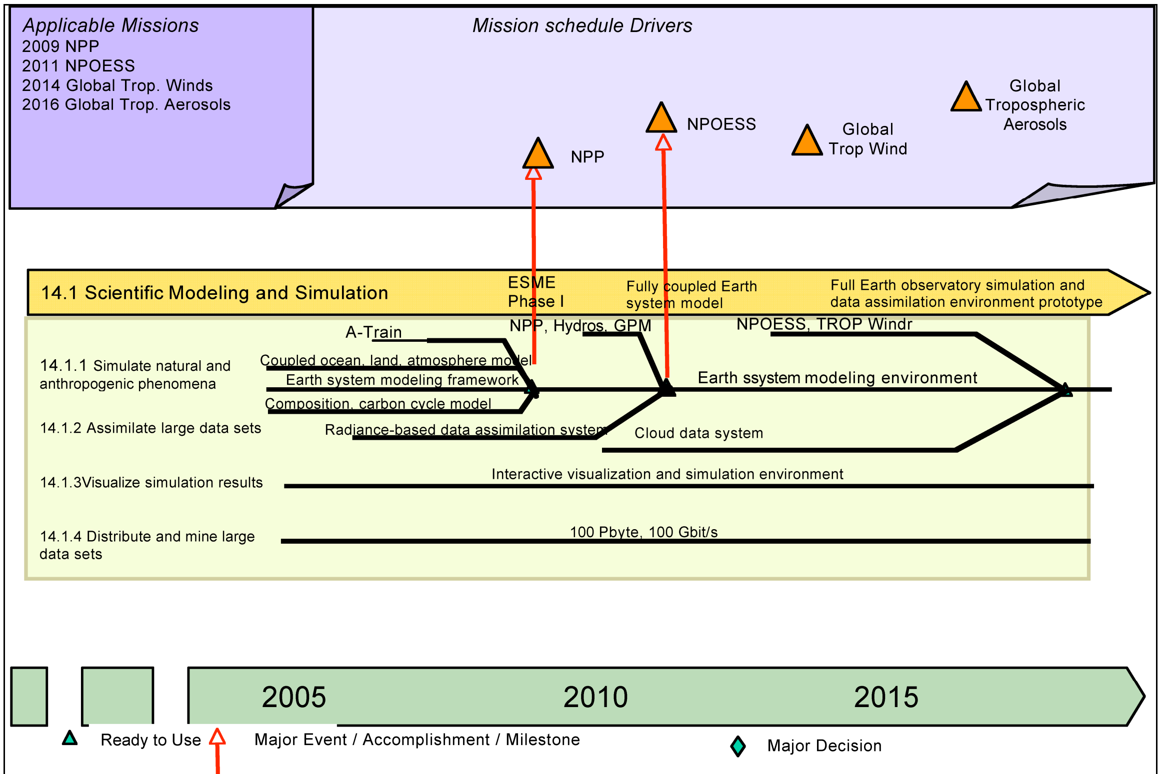
<u>Capability Breakdown Structure</u>

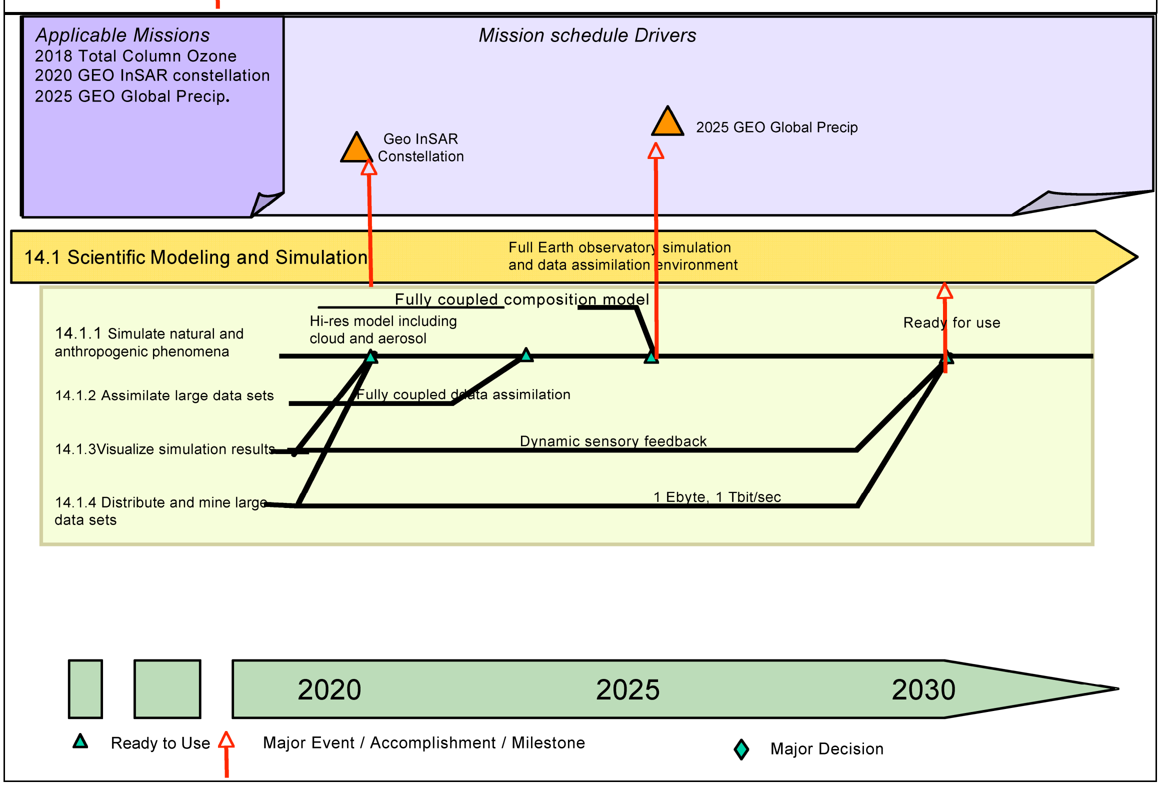


Science

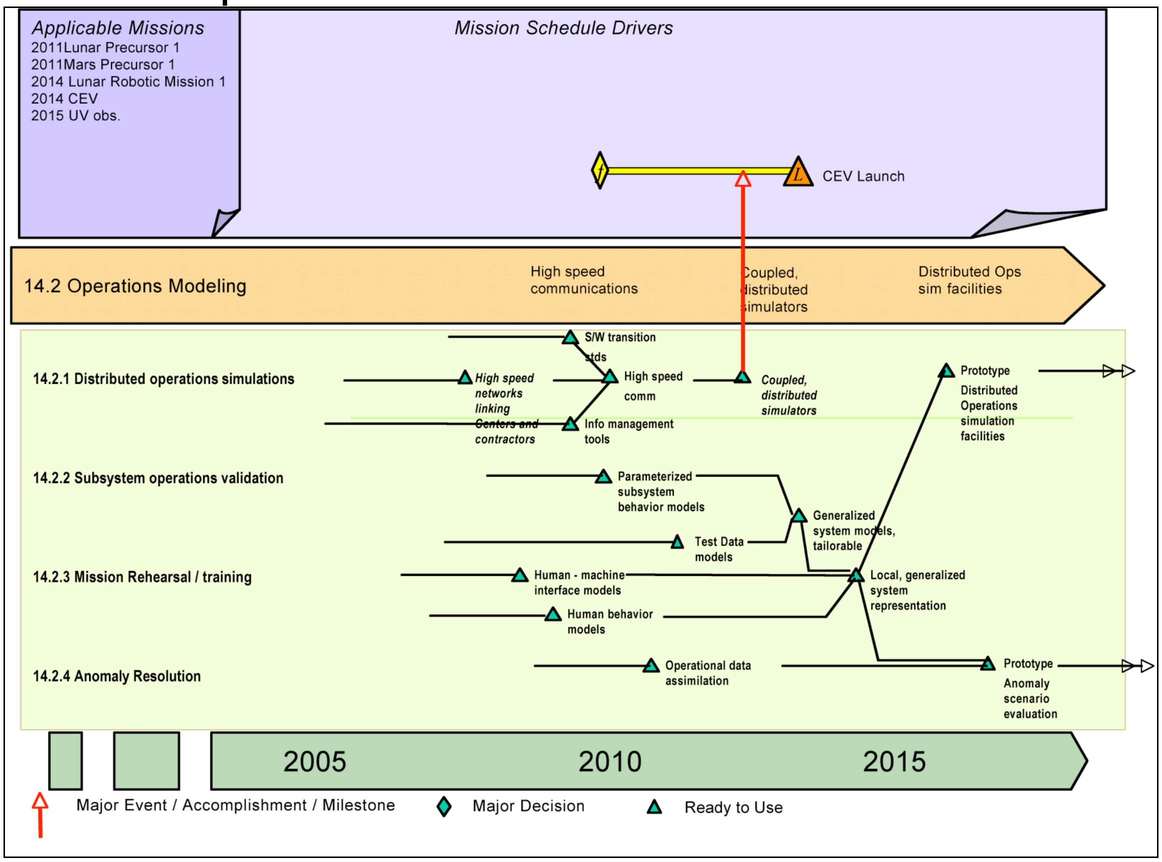

Applicable Missions
2010 SDO
2014 Solar Orbiter
2014 JPOP/JIM
2015 Lunar Robotic 1
2014 IHS
Mission schedule Drivers
2014 Solar Orbiter
(2020 Lunar Manned base)
14.1 Scientific Modeling and Simulation
SWME
1 hour forecast
3 hour forecast
14.1.1 Simulate natural and anthropogenic phenomena
Corona / Heliosphere/ SEP model
Global geospace model
Space weather modeling framework
SDO
IHS, JIM, Solar Orbiter
Space weather modeling environment
14.1.2 Assimilate large data sets
L1 Data assimilation
14.1.3Visualize simulation results
Interactive HDTV quality
14.1.4 Distribute and mine large data sets
100 Pbyte, 100 Gbit/s
2005
2010
2015
Ready to Use
Major Event / Accomplishment / Milestone
Major Decision

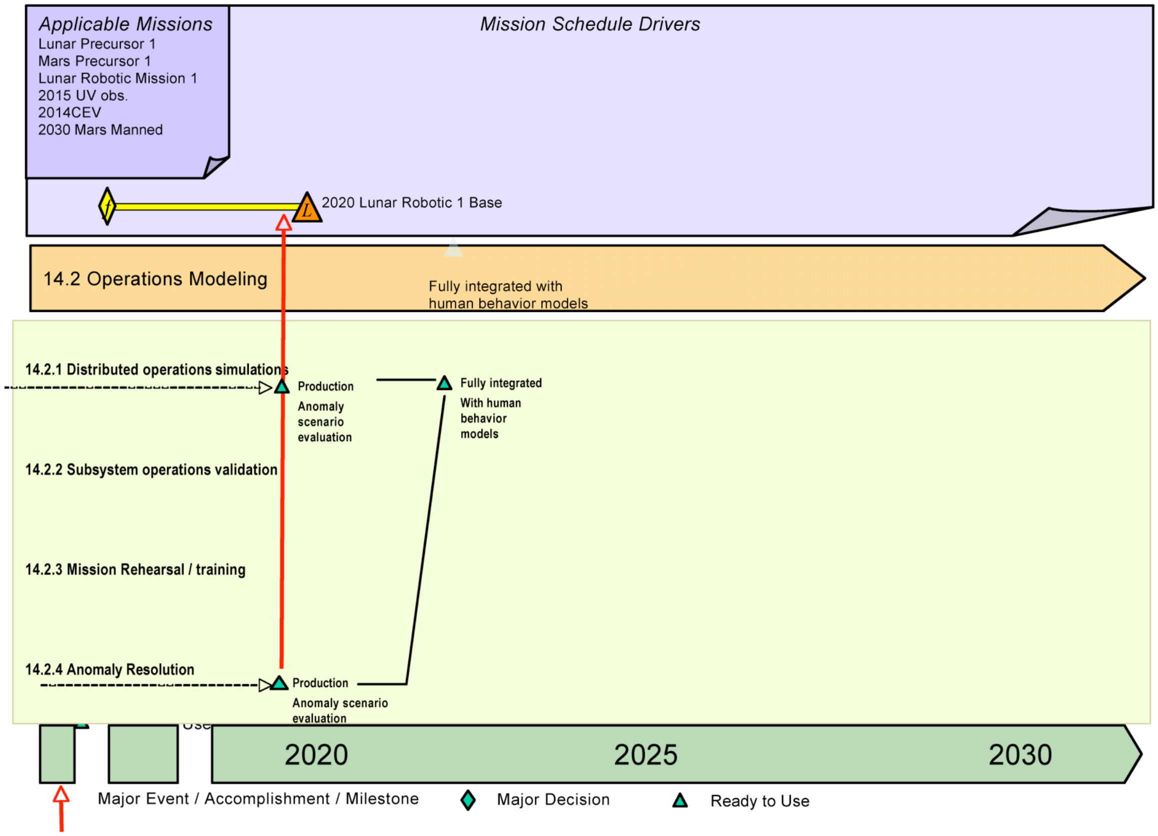

Applicable Missions
2020 Lunar Manned Base
2023 L1-Diamond
2030 Mars Manned Mission
Mission schedule Drivers
2020 Lunar Manned base
2030 Mars Manned Mission
14.1 Scientific Modeling and Simulation
24 hour forecast
Ready for use
14.1.1 Simulate natural and anthropogenic phenomena
Ready for use
L1
24 hour forecast
Ready for use
14.1.2 Assimilate large data sets
Sentinels
Data assimilation
14.1.3Visualize simulation results
Sensory feedback
14.1.4 Distribute and mine large data sets
1 Ebyte, 1 Tbit/sec
2020
2025
2030
Ready to Use
Major Event / Accomplishment / Milestone
Major Decision


Applicable Missions
2009 NPP
2011 NPOESS
2014 Global Trop. Winds
2016 Global Trop. Aerosols
Mission schedule Drivers
NPP
NPOESS
Global Trop Wind
Global Tropospheric Aerosols
14.1 Scientific Modeling and Simulation
ESME Phase I
Fully coupled Earth system model
Full Earth observatory simulation and data assimilation environment prototype
A-Train
NPP, Hydros, GPM
NPOESS, TROP Windr
14.1.1 Simulate natural and anthropogenic phenomena
Coupled ocean, land, atmosphere model
Earth system modeling framework
Composition, carbon cycle model
Earth ssystem modeling environment
14.1.2 Assimilate large data sets
Radiance-based data assimilation system
Cloud data system
14.1.3Visualize simulation results
Interactive visualization and simulation environment
14.1.4 Distribute and mine large data sets
100 Pbyte, 100 Gbit/s
2005
2010
2015
Ready to Use
Major Event / Accomplishment / Milestone
Major Decision

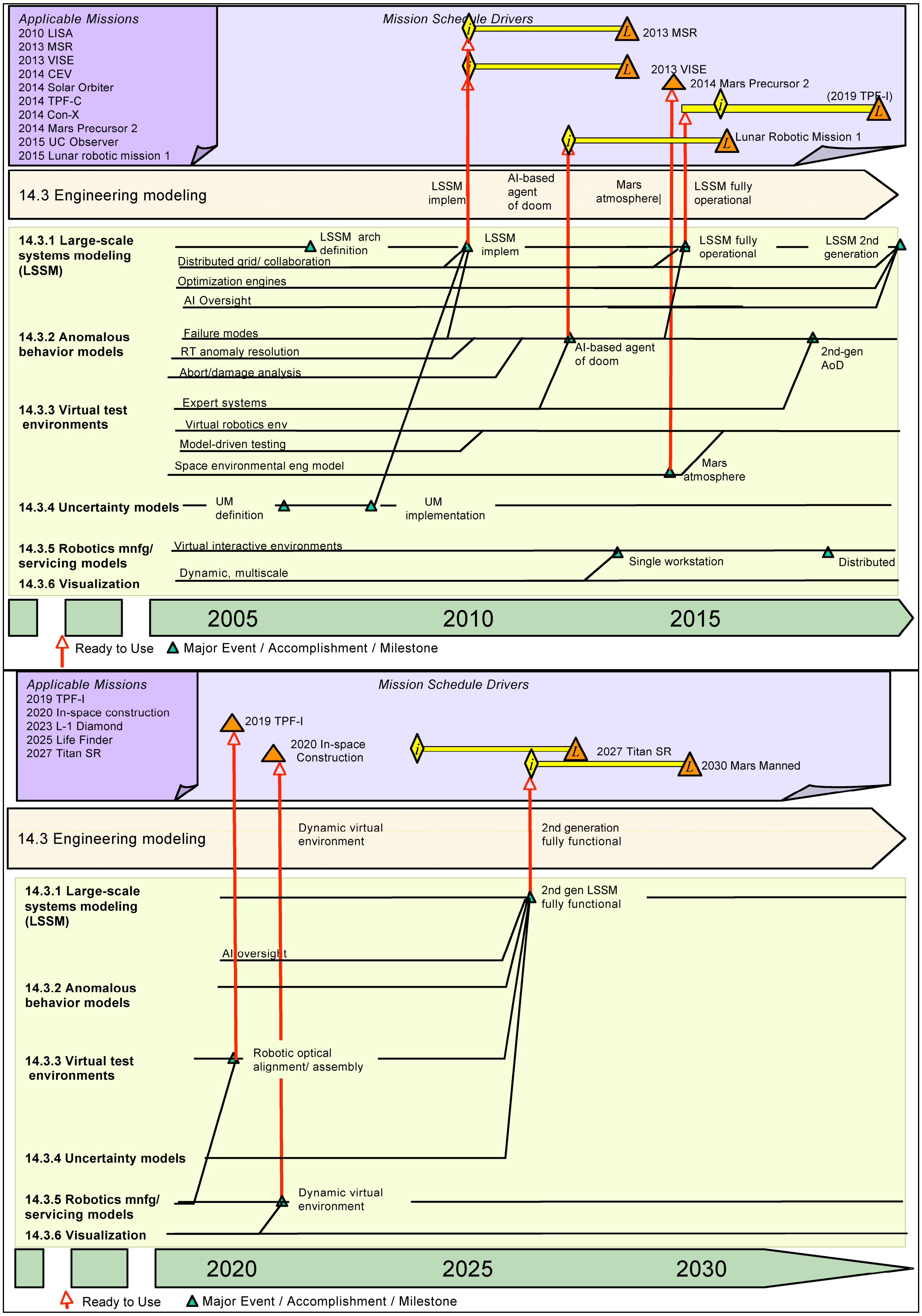

Applicable Missions
2018 Total Column Ozone
2020 GEO InSAR constellation
2025 GEO Global Precip.
Mission schedule Drivers
Geo InSAR Constellation
2025 GEO Global Precip
14.1 Scientific Modeling and Simulation
Full Earth observatory simulation and data assimilation environment
Fully coupled composition model
Hi-res model including cloud and aerosol
Ready for use
14.1.1 Simulate natural and anthropogenic phenomena
14.1.2 Assimilate large data sets
Fully coupled data assimilation
14.1.3Visualize simulation results
Dynamic sensory feedback
14.1.4 Distribute and mine large data sets
1 Ebyte, 1 Tbit/sec
2020
2025
2030
Ready to Use
Major Event / Accomplishment / Milestone
Major Decision

Operations

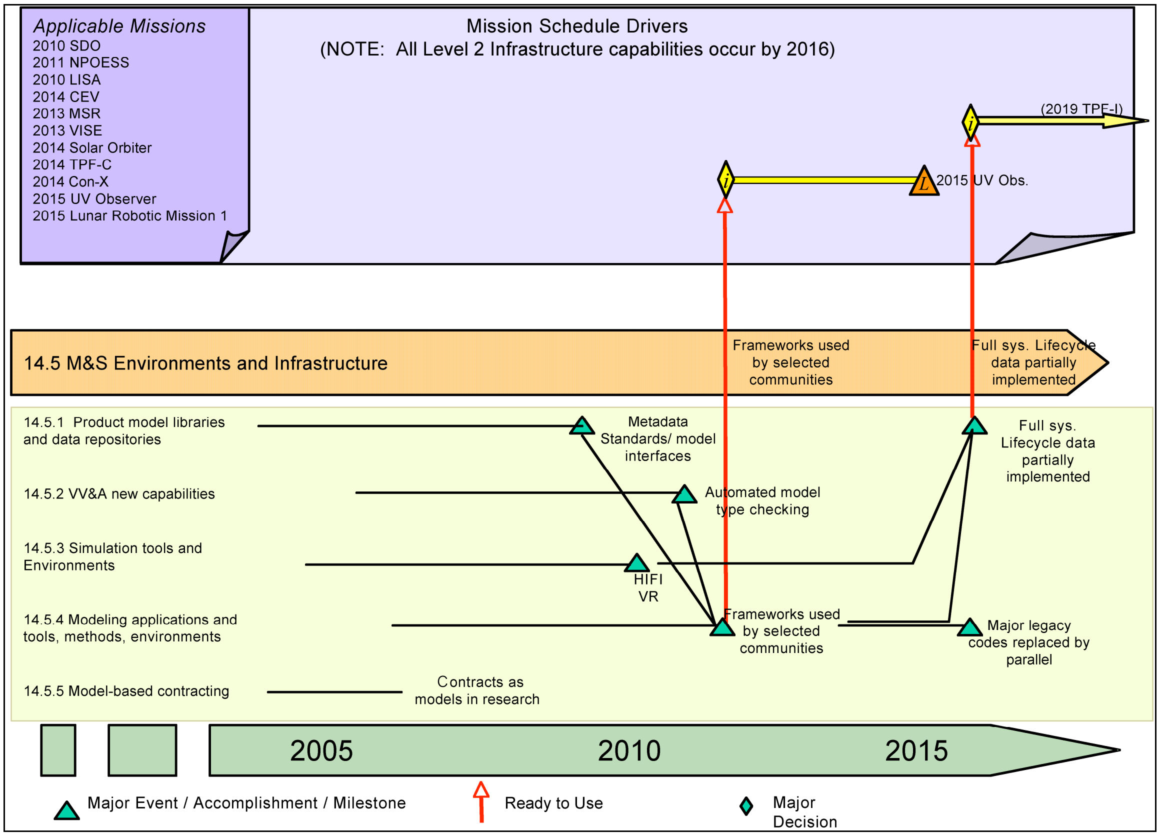

Applicable Missions
2011Lunar Precursor 1
2011Mars Precursor 1
2014 Lunar Robotic Mission 1
2014 CEV
2015 UV obs.
Mission Schedule Drivers
CEV Launch
14.2 Operations Modeling
High speed communications
Coupled, distributed simulators
Distributed Ops sim facilities
14.2.1 Distributed operations simulations
S/W transition stds
High speed networks linking Centers and contractors
High speed comm
Coupled, distributed simulators
Info management tools
Prototype Distributed Operations simulation facilities
14.2.2 Subsystem operations validation
Parameterized subsystem behavior models
Generalized system models, tailorable
Test Data models
14.2.3 Mission Rehearsal / training
Human - machine interface models
Local, generalized system representation
Human behavior models
14.2.4 Anomaly Resolution
Operational data assimilation
Prototype Anomaly scenario evaluation
2005
2010
2015
Major Event / Accomplishment / Milestone
Major Decision
Ready to Use


Applicable Missions
Lunar Precursor 1
Mars Precursor 1
Lunar Robotic Mission 1
2015 UV obs.
2014CEV
2030 Mars Manned
Mission Schedule Drivers
2020 Lunar Robotic 1 Base
14.2 Operations Modeling
Fully integrated with
human behavior models
14.2.1 Distributed operations simulations
Production
Anomaly scenario evaluation
Fully integrated
With human behavior models
14.2.2 Subsystem operations validation
14.2.3 Mission Rehearsal / training
14.2.4 Anomaly Resolution
Production
Anomaly scenario evaluation
2020
2025
2030
Major Event / Accomplishment / Milestone
Major Decision
Ready to Use

Engineering



Infrastructure



Appendix H. Level 3 Roadmaps

Integration capabilities needed for level 3 capabilities

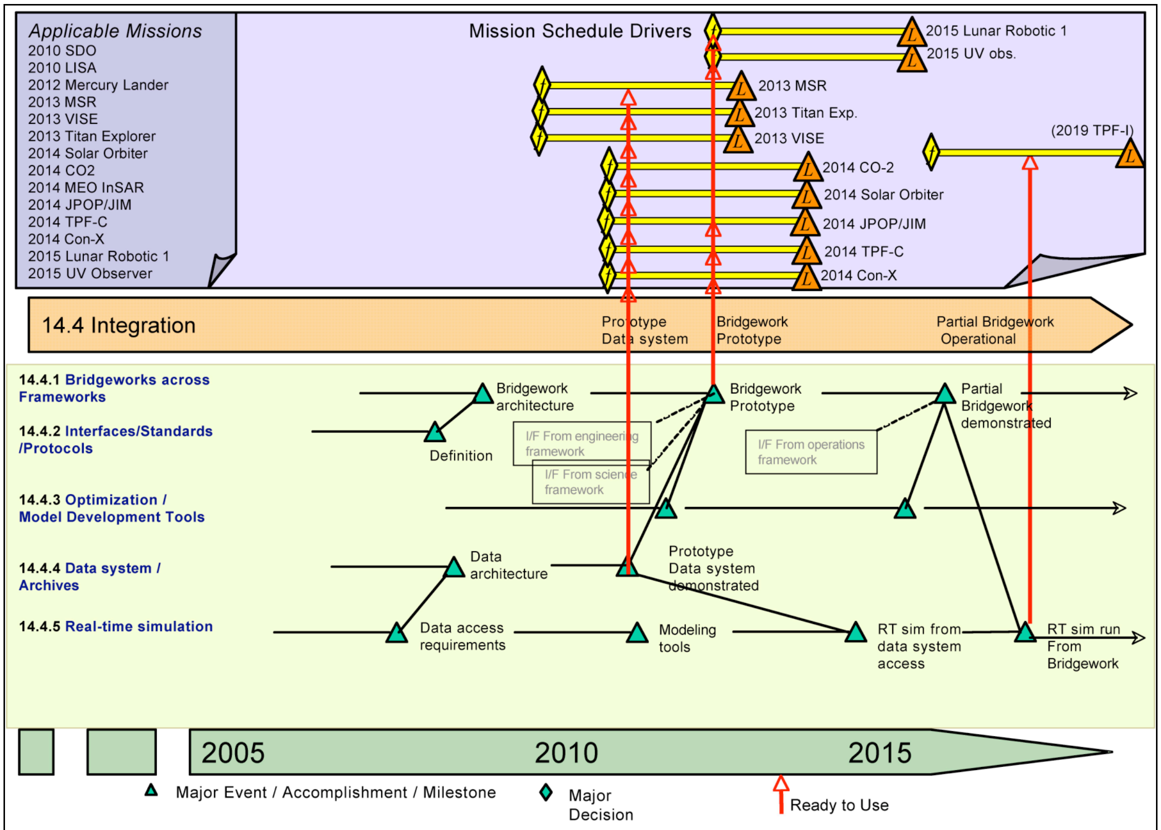
Integration	Today's Capability	2010–2015	2016–2020	2021–2025
Optimization tools	In limited use, primarily in Engineering	Engineering optimization linked to decision support tools	Sci. Eng and Ops separately linked to decision support tools	Portfolio management uses Sci-Eng-Ops optimization
Bridgeworks to integrate frameworks	Non-existent	Architecture defined, prototype demonstrated	Bridgework in general use integrating science, engineering	Bridgework in general use, integrating Sci. Eng and Ops
Interfaces / standards/ protocols	Exist in limited domains.	Defined for bridgework, compatible with bridgework architecture	Applied in implementation of bridgework	Maintained as needed for new data types. Extend across Interplanetary Network (IPN) for distributed ops.
Data architectures/ archives	Broadly used, generally not distributed,	Distributed, rapid retrieval access demonstrated	Applied in implementation of bridgework	Interplanetary data management across IPN
Real-time simulation	Specific hard-wired applications	Data access requirements defined	Demonstrated, driven from generalized agency database	Demonstrated, with model feedback to engineering and science

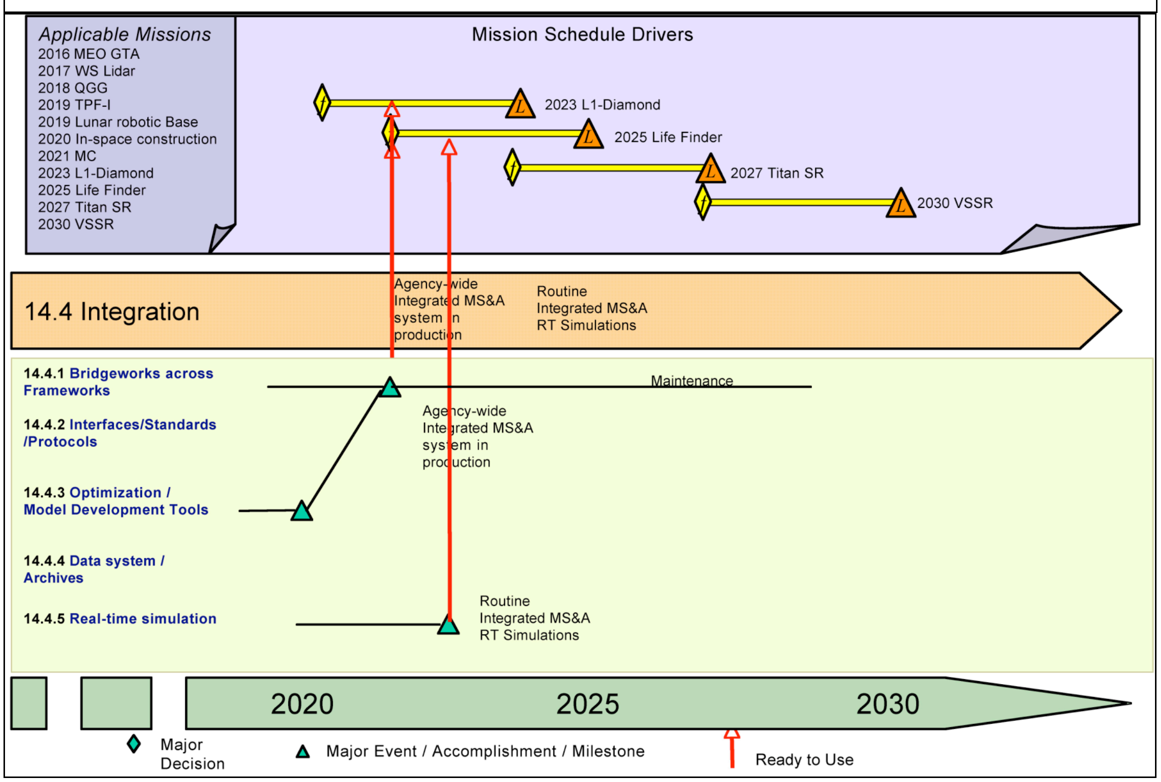
The timeline for the development of supporting infrastructure capabilities is shown below. Table terms: (black added in level 2, red added in level 3)

Infrastructure, supporting:	**Today's Capability**	**2010–2015**	**2016–2020**	**2021–2025**
Product model libraries and data repositories	Individualized meta data models and model libraries. Distributed data repositories	Meta data Standards. Model interfaces. Logical Data Architecture. Full data life cycle	Full system life cycle implemented for selected model communities	Full system life cycle for all mission critical modeling communities
Verification, Validation & Accreditation new capabilities	No process. No use of automation. Ad hoc unit-level complexity	Automated model type checking and simulation discontinuity checking. Multi-domain declarative and semantic taxonomy interchange standards	Widespread CMMI 5-level type ratings throughout industry. Automated calibration of models from physical test	Market exchange of models & sims based upon maturity and ratings. Automated generation of model and simulation code from high level, CONOPs-driven specification tools
Simulation tools and environments	Virtual reality demo projects. Data assimilation typically ad hoc manner.	High fidelity VR Mature science-based unit data assimilation for single data modes. Simulations run in software frameworks	Use of hifi VR with systems-level data assimilation incorporating restricted data modes	Systematic use of hifi VR using system of system models with science-based assimilated multimodal real-time data
Modeling applications and tools, methods, environments	Demo frameworks. Some parallel codes available, most based on legacy codes.	Frameworks used by selected communities. All new codes are written for software environment with parallelization.	Major legacy codes replaced by scalable parallel ones which run in software environment.	Systematic use by all MS&A developers for full lifecycle of NASA missions. Complete complex models run efficiently on highly parallel systems.
Model-based Contracting	Contracts as models in research stages.	Contracts written so that process artifacts are as electronic models.	Contracts require process artifacts represented as a model set. Customer rqmts V&V'd using models	Solicitations use models to reflect the expected behavior of a procured (acquired) system or portion of a system.

Roadmaps for the above capabilities are shown below

Agency-wide Integration





Agency-wide Infrastructure