

# The Advanced Modeling, Simulation and Analysis Capability Roadmap vision for engineering

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## ABSTRACT

This paper summarizes a subset of the Advanced Modeling Simulation and Analysis (AMSA) Capability Roadmap that was developed for NASA in 2005. The AMSA Capability Roadmap Team was chartered to “To identify what is needed to enhance NASA's capabilities to produce leading-edge exploration and science missions by improving engineering system development, operations, and science understanding through broad application of advanced modeling, simulation and analysis techniques.” The AMSA roadmap stressed the need for integration, not just within the science, engineering and operations domains themselves, but also across these domains. Here we discuss the roadmap element pertaining to integration within the engineering domain, with a particular focus on implications for future observatory missions. The AMSA products supporting the system engineering function are mission information, bounds on information quality, and system validation guidance. The Engineering roadmap element contains 5 sub-elements: (1) *Large-Scale Systems Models*, (2) *Anomalous Behavior Models*, (3) advanced *Uncertainty Models*, (4) *Virtual Testing Models*, and (5) space-based *Robotics Manufacture and Servicing Models*.

**Keywords:** Modeling and simulation, analysis and design, integrated modeling, technology roadmap

## 1. INTRODUCTION

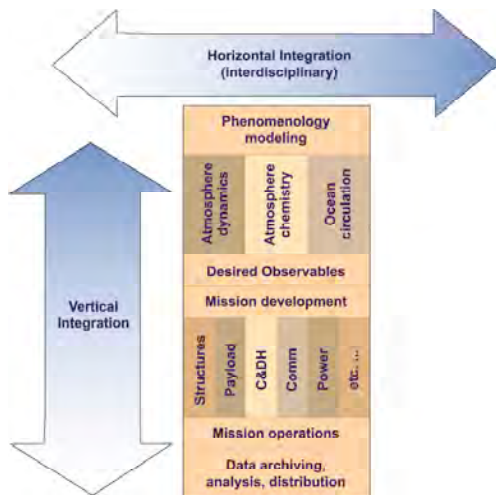
In late 2004 NASA established approximately two dozen teams, composed of individuals from government, industry and academia, to develop 30-year strategic and capability roadmaps<sup>1</sup> to support the NASA missions in Science, Exploration, Space Operations and Aeronautics Research. The completed roadmaps (6 Strategic Roadmaps and 15 Capability Roadmaps<sup>2</sup>) were submitted to NASA in May 2005. One of these teams, the NASA Capability Roadmap Team for Advanced Modeling, Simulation and Analysis (AMSA) was chartered to “To identify what is needed to enhance NASA's capabilities to produce leading-edge exploration and science missions by improving engineering system development, operations, and science understanding through broad application of advanced modeling, simulation and analysis techniques.” The context of this charter was to identify capabilities that are needed to be available to everyone (NASA itself as well as its industry and university partners) responsible for the design, development and operation of NASA missions. The theme of the AMSA roadmap, as illustrated in Figure 1, was greatly enhanced integration, not just within the science, engineering and operations domains themselves (horizontal integration), but also across these domains (vertical integration).

The AMSA Capability Roadmap had five major elements: Science Modeling, Operations Modeling, Engineering Modeling, Integration, and M&S Environments and Infrastructure. The first three elements deal with capabilities for the different types of horizontal integration, the fourth with the vertical integration capabilities, and the fifth with cross-cutting capabilities. This paper summarizes the Engineering element of the AMSA Capability Roadmap, with a particular focus on implications for future observatory missions. (Note that there was a separate Capability Roadmap Team that dealt with Systems Engineering as well as Cost and Risk models; hence, these important engineering topics were not within scope of the AMSA Capability Roadmap.)

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As the 2004-2005 roadmapping results were supplanted by the priorities of the new NASA management, this paper should not be construed as representing the official position of NASA, but merely the perspectives circa early 2005 of the AMSA Capability Roadmap Team members themselves.



**Figure 1. Integration Theme of the AMSA Capability Roadmap**

## **2. AMSA CAPABILITY ROADMAP BACKGROUND AND OVERVIEW**

The AMSA Capability Roadmap team was co-chaired by Erik Antonsson and Tamas Gombosi. The team consisted of 19 members: 7 from NASA, 5 from industry, and the remainder from other government laboratories and industry. A complete list of team members and their affiliations (at the time of the roadmapping work) is provided in Appendix A. The authors of this paper are the team members that focused on the Engineering element of the roadmap.

A public workshop was held on November 2005 in Washington DC, at which 17 presentations were given to the co-chairs of the teams; an additional 31 white papers were submitted for consideration. The full AMSA team met several times from January through May of 2005. To expand the knowledge base of the team, an additional 25 invited speakers made presentations to the full AMSA team. In addition the ASMA Capability Roadmap Team had some insight into the detailed hardware roadmaps emerging simultaneously from the 12 Capability Roadmap Teams that focused on needed developments in instruments, launch vehicles, entry systems, etc. (See, for example, the summary of the Advanced Telescopes and Observatories Capability Roadmap<sup>3</sup>.) The NASA Science Mission Directorate, representing Headquarters, provided most of the coordination and direction for the AMSA Capability Roadmap activity. The roadmap consequently focused very strongly on capabilities needed for future science (as opposed to exploration systems or aeronautics research) missions. Although the submitted roadmap contained some conjectures about capabilities for exploration systems or aeronautics research missions, both directorates have undergone dramatic replanning activities in the past year. Hence, this paper will mainly focus on portions of the AMSA Capability Roadmap that support NASA's science missions (as they were understood in early 2005).

The AMSA Capability Roadmap Team was supplied with Design Reference Missions, which in the case of the Science Mission Directorate, were the missions envisioned over the next several decades that this roadmap should support. Table 1 provides a partial list of these Design Reference Missions.

<b>Launch Year</b>	<b>Mission</b>
2009	NPOESS Preparatory Project
2010	Solar Dynamics Observatory
2010	National Polar-orbiting Operational Environmental Satellite System (NPOESS)
2010	Laser Interferometer Space Antenna (LISA)
2013	Global Tropospheric Wind
2013	Mars Sample Return
2013	Venus In Situ Explorer (VISE)
2014	Solar Orbiter
2014	Jupiter Polar Orbiter with Probes (JPOP)/Jupiter Interior Mission (JIM)
2014	Terrestrial Planet Finder-Coronagraph (TPF-C)
2014	Constellation-X
2015	Large-Aperture UV Optical Observatory
2016	Global Tropospheric Aerosols
2018	Total Column Ozone
2019	Terrestrial Planet Finder-Interferometer (TPF-I)
2020	Geosynchronous Earth Orbit Interferometric Synthetic Aperture Radar
2020	Constellation
2020	In-Space Construction
2023	L1-Diamond
2025	Geosynchronous Global Precipitation
2025	Life Finder
2027	Titan Sample Return

**Table 1. Representative Science Design Reference Missions for AMSA Capability Roadmap**

### **3. ENGINEERING MODELING, SIMULATION AND ANALYSIS TODAY**

NASA’s engineering functions span from high-level system analyses to detailed component design and development. (Recall that in the context of the AMSA Capability Roadmap, there is a distinct operations element.) Current NASA missions are supported by engineering tools that are significantly advanced over those available 20 years ago. This increased capability has been enabled not just by the obvious improvements in computer hardware and system software, but also by great strides in first-principles-based discipline models and commercial software tools that facilitate large-scale integration applications, such as end-to-end system modeling.

As is apparent from recent and proposed missions, e.g., JWST and TPF, NASA has indeed exploited early design trades and extensive modeling and simulation to lower risk before selecting a particular design and the contractors to carry out the manufacture and testing of the system. Despite these advances new missions are still straining modeling resources to support system engineering decision processes and accurately predict performance. While usually effective for the high-risk environment in which NASA operates, this sometimes contributes to dramatic failures, and has also limited the development of innovations that would measurably improve our engineering capabilities. And, while all organizations wrestle with how to stay competitive in their business, 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 in a number of key areas relevant to future science missions.

The singular factor that most contributes to the limitations of today’s system models is *complexity-the complexity of the systems themselves as well as the complexity of the models of the systems*. Although our system models have undoubtedly increased in complexity, they have nonetheless not kept pace with the increased complexity of the systems themselves (and our confidence in these complex system models has lagged even further behind). The increased system complexity is driven by the increased coupling between the constituent subsystems, which has often proven necessary in

order to achieve the desired system performance. This system complexity is addressed in the models through end-to-end model architectures and increased fidelity in the discipline models. However, there are some serious shortcomings to the current practice of model development.

A persistent challenge is model validation. For one thing, the current practice of developing the model concurrently with the hardware typically allows minimal time for validation of the model. This delay in model realization and validation translates into a large financial risk since 90% of mission costs are committed within the first 10% of the development cycle and changes are very costly<sup>4</sup>. Moreover, full system models are rarely themselves validated; rather isolated components of the full system are validated by comparison to specific discipline model results and with subsystem tests such as modal testing. The methods of data management and model correlation are not well established and frequently rely upon *ad hoc* procedures. Very little automation exists between testing and model updating. For example, models are currently employed to estimate the ambient environment effect and total ionizing dose limitation that spacecraft electronics can withstand. These models then drive experiments on physical parts. Although such tests guide experiments the results are not currently fed back toward improving the capability of the models. Both empirical and analytical methods must be improved to address this aspect of model validation. Finally additional limitations of current modeling are the lack of dynamic coupling between the performance models and science models and programmatic issues such as cost and schedule. 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.

A related problem is that large uncertainties are associated with most system models. As an example, certain aspects of the space environment (e.g., Mars atmosphere) are so poorly modeled (or inherently variable) that large design margins must be carried. Currently the instrument design process is managed by error budgets, which are evaluated by covariance propagation models. However, consistent methodologies and approaches and the ability to handle large-scale systems has not been firmly established and varies significantly. These shortcomings can be cast into the larger arena of uncertainty and margin management. Quantifying uncertainties and linking these to assessments of risks via probabilistic margin assessment needs to become part of the standard practice, but the mathematical foundations are weak in some areas and current tools are inadequate.

There are certainly other system-level limitations facing NASA and industry. One is the lack of a unified framework for end-to-end system models that not only facilitates the integration of the various discipline models at all needed levels of fidelity, but also the capturing of the uncertainty, analysis/verification, and validation processes for the discipline and system models. Integrated full-breadth modeling capabilities are rare except for very low fidelity and largely empirical cases. Data flow between commercial design, and analysis packages has been amply demonstrated, but the process is far from seamless and often requires human intervention and development of specialized data translators. Models of advanced technologies that can be used in system-level assessments for technology investments are weak.

At the discipline level, model fidelity is already adequate in some areas, e.g., deep space navigation, for design decisions on complex systems. But in many other areas, however, this is not the case. For instance, NASA has a capability to model portions of a spacecraft/lander electromagnetic interference environment. Full design optimization of antenna multipath and near-field EM interference on the complete spacecraft with realistic geometry, however, is not currently possible due to issues of model maturity compared to recent advances in physics, lack of engineering model integration, limitations of desktop-based analysis tools, and a poor ability to perform iterative high fidelity design trade-space exploration based on a seamless concept-to-flight modeling and simulation analysis capability. Such limitations are general in nature and apply equally well to many other engineering disciplines.

A common thread to many of these obstacles is that since there is little or no commercial market for many of the tools that NASA needs for its missions, development of specialized capabilities must necessarily be sponsored by NASA.

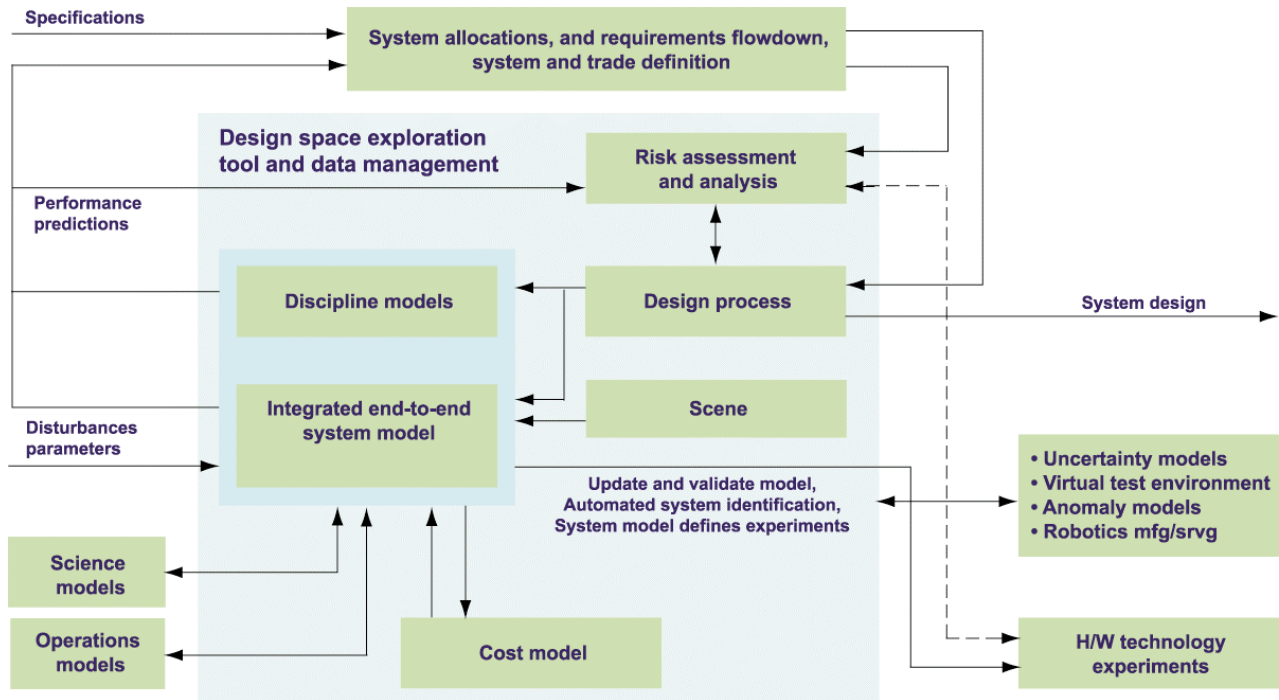
#### **4. FUTURE ROLE OF ENGINEERING MODELING, SIMULATION AND ANALYSIS**

The AMSA Capability Roadmap provided three options for investment. Level 1 dealt with improving these discipline-modeling capabilities that were most critical to the Design Reference Missions. Level 2 addressed horizontal, cross-discipline, integration in the Engineering domain, recognizing that many of the future missions proposed in the Design Reference Missions set will require integration of extremely complex technologies, which will challenge management and system engineering. Level 3 focused on vertical integration— across Science, Operations and Engineering. In this

paper we summarize the Level 2 Engineering element of the AMSA Capability Roadmap, which had the following five sub-elements:

- Large-scale systems models (LSSMs), 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 multilevel models, with an open but controlled architecture that allows distributed resources and computing.
- Anomalous behavior models (ABMs) for proactive consideration of low-probability but high-risk events. These models, which are today typically reserved for post-mortem investigations, should become more embedded in 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 (UMs). 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 (VTMs) 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.

In Figure 2 we show a functional representation of this concept. (Note that in accordance with the vertical integration theme of the roadmap, we include the linkage to the Science and Operations models.) 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.



**Figure 2. Functional diagram of proposed Large-Scale-System Modeling to support future missions.**

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 ( $\mu$  analysis,  $H^\infty$  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 Department of Energy's Accelerated Strategic Computing 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.

To increase the effectiveness of these tools, we propose earlier incorporation of the system modeling activities. This follows a recent trend by NASA to conduct multiple studies of architecture, requirements flowdown and cost in Pre-Phase A and Phase A studies. A diagram illustrating the temporal aspects from initial mission definition to on-orbit operations is shown in Figure 3. A rough outline of a developmental timeline to reach these goals for integration of these tools into a coherent framework is shown in Table 2. The linkage of Level 2 of the Engineering element of the AMSA Capability Roadmap to some Design Reference Missions is shown in Figure 4 and Figure 5.

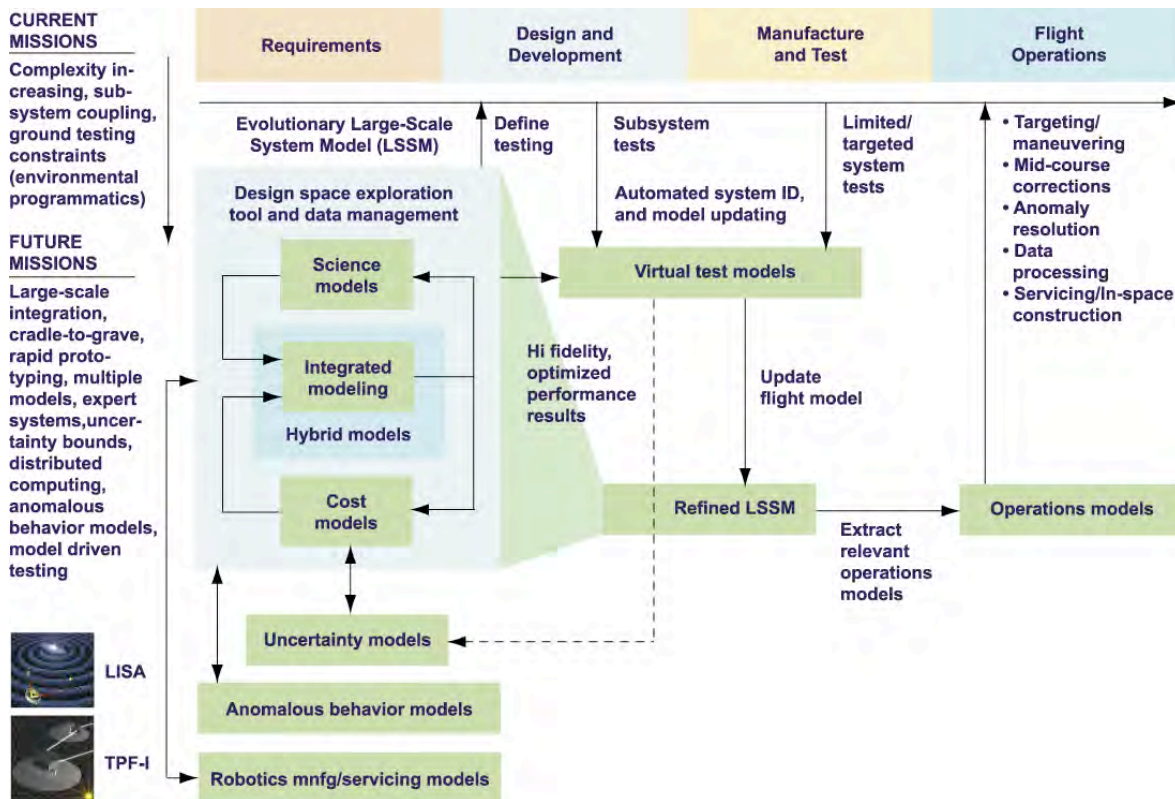


Figure 3. Conceptual diagram of early incorporation of system models into the engineering process.

Engineering	Today's Capability	2010-2015	2016-2020	2021-2035
Large-scale system modeling	Bucket-brigade Developing integrated system modeling, significant discipline modeling & optimization, approximate models. (TRL=3)	Cradle-to-grave models, rapid model deployment, 1st-generation embedded data management, integrated cost models, selected advanced discipline models, MDO.	Seamless model evolution through design phases, integrated risk models, design traceability, additional advanced discipline models, agent-based.	Distributed, MDO, environment for optimization, advanced data management, cost/risk integrated, science and operations, cradle-to-grave models, rapid prototyping, integration of other model types.
Virtual test environment	Widely varies, not baseline approach. Fit tool for manufacturing. (TRL=3,4)		Robotic optical assembly and alignment.	Expansive HWIL, max modeling/ min testing, auto sys ID/ model update, order of magnitude reduction I&T.
Uncertainty models	Probabilistic uncertainty propagation tools. Some uncertainty characterization. (TRL=3-6)	Non-probabilistic uncertainty tools. Expanded uncertainty characterization.	Tools for rigorous uncertainty bounds in the validation domain.	Tools for rigorous uncertainty bounds in the predictive domain. Input uncertainties fully characterized.
Anomalous behavior models	Typical using current models with some add-ons as mishap investigation. (TRL=2-5)	Subsystem AI agent of doom. High-fidelity abort and damage analysis.	Full system AI agent of doom.	Explore full failure/ anomaly mode space during design. AI agent of doom. Real-time isolation and resolution.
Robotics mnfg/ servcg (MS) models	Commercial mainly, minimal space-based modeling (servicing). (TRL=3-6)	Human exploration hazard models.	Robotic optical assembly and alignment.	Virtual toolset enabling dynamic assessment of designs for space/planetary-based MS.
Visualization technology	3-D, small-scale dynamic visualization, single discipline analysis.	Multidiscipline analysis, design space exploration.	Interactive design steering, design space exploration agents.	Hologram, instant visualization of dynamic events at multiple scales.

**Table 2. Rough outline of plan to develop additional modeling resources for mission support.**

## 5. CONCLUDING REMARKS

This paper has presented the perspective of the members of the Advanced Modeling, Simulation and Analysis Capability Roadmap Team on the AMSA needs in the engineering domain to enhance the performance, reduce the cost, reduce the risk and thereby increase mission assurance for future science missions. We find it timely that a recent National Science Foundation Report<sup>3</sup> has identified a national need for increased capability in AMSA (Simulation-Based Engineering Science in the NSF report terms) that is far broader than the NASA science mission need that was the focus of our roadmap. Two of the three major recommendations of the NSF report are particularly germane here:

2. “Formidable challenges stand in the way of progress in SBES research. These challenges involve resolving open problems associated with multiscale and multi-physics modeling, real-time integration of simulation methods with measurement systems, model validation and verification, handling large data, and visualization. ...”

3. “There is strong evidence that our nation’s leadership in computational engineering and science, particularly in areas key to Simulation-Based Engineering Science, is rapidly eroding. ...”

## ACKNOWLEDGEMENT

Although the four authors on this paper had the assignment of leading the Engineering element of the AMSA Capability Roadmap, we had the benefit of the perspectives and suggestions of all the members of the team. We are grateful to all their contributions and especially to the team co-chairs, Erik Antonsson and Tamas Gombosi.



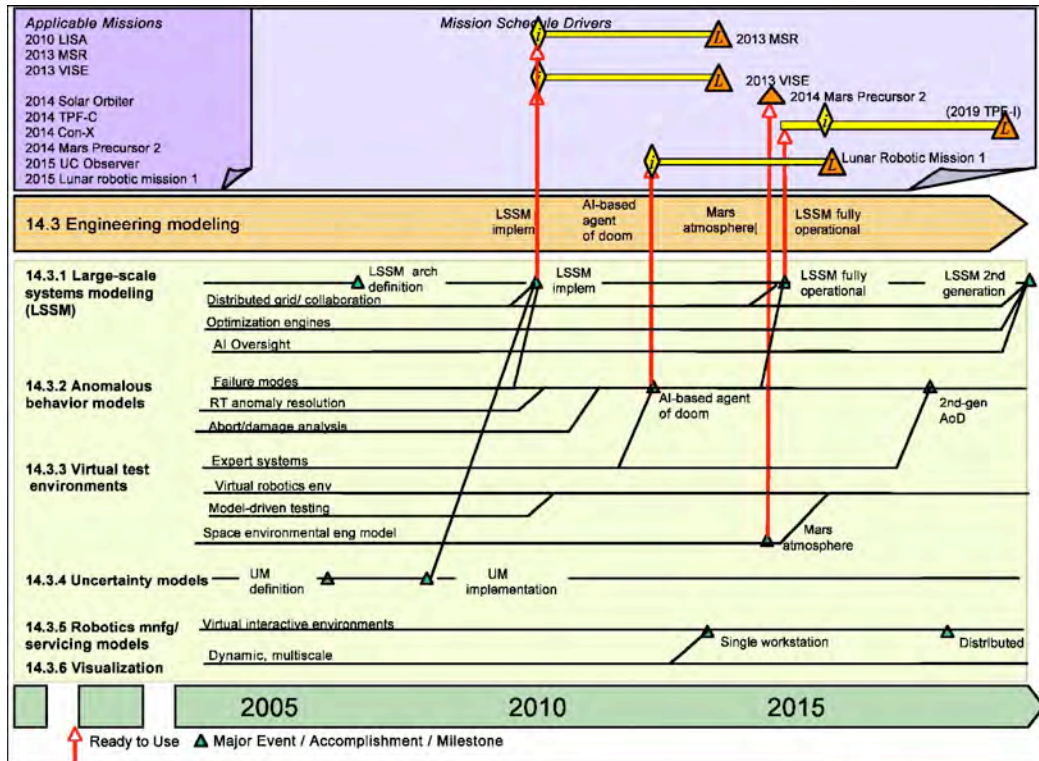


Figure 4. Near-Term AMSA Engineering Capability Roadmap

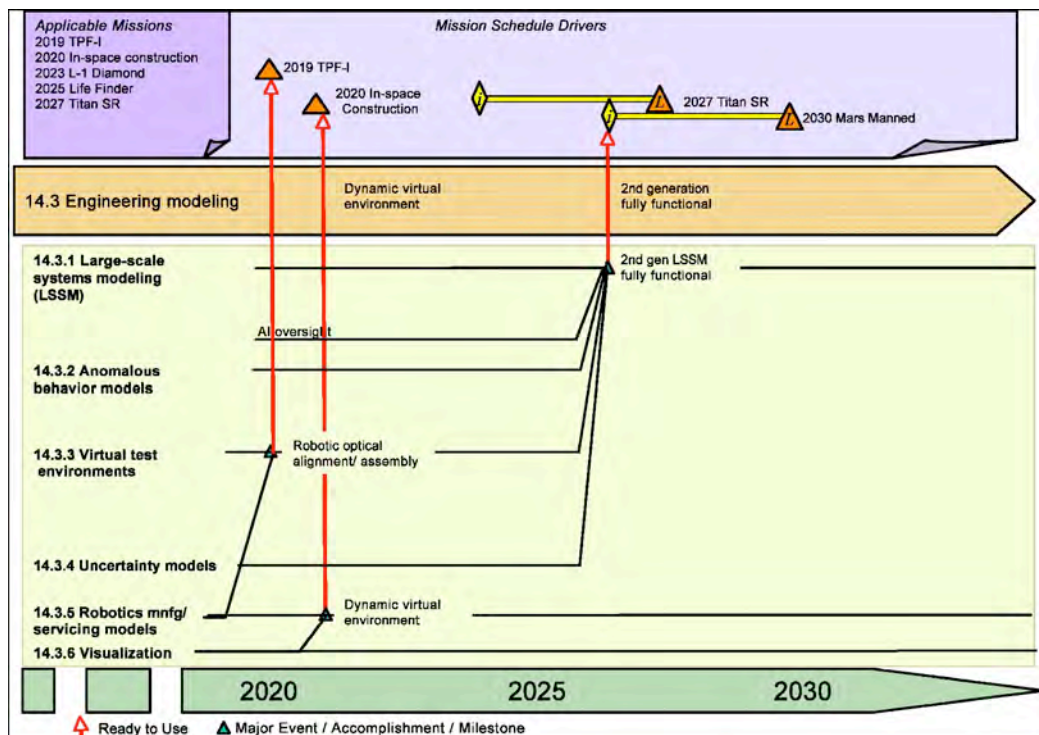


Figure 5. Far-Term AMSA Engineering Capability Roadmap



## REFERENCES

1. Rita Willcoxon, Briefing to ARTWG/ASTWG on NASA's Capability and Strategic Roadmap Activities, January 11, 2004 (available at [http://advrangetech.ksc.nasa.gov/Media/05\\_APIO\\_Brief\\_.pdf](http://advrangetech.ksc.nasa.gov/Media/05_APIO_Brief_.pdf))
2. NASA Capability Roadmaps Executive Summary, May 22, 2005 (available at <http://pweb.ae.gatech.edu/people/rbraun/classes/spacesystems06/Reference/NASARoadmap.pdf>)
3. Feinberg, L. D., "NASA capabilities roadmap: advanced telescopes and observatories", UV/Optical/IR Space Telescopes: Innovative Technologies and Concepts II, SPIE Proceedings Vol. 5899 (SPIE, Bellingham, WA, 2005)
4. Revolutionizing Engineering Science through Simulation, Report of the National Science Foundation Blue Ribbon Panel on Simulation-Based Engineering Science, February 2006 (available at [http://www.ticam.utexas.edu/events/SBES\\_Final\\_Report.pdf](http://www.ticam.utexas.edu/events/SBES_Final_Report.pdf))

Note: The three PDF documents above were publicly accessible at the cited URLs at the time of this conference.

## APPENDIX. AMSA CAPABILITY ROADMAP TEAM

**NASA Co-Chair:** Erik K. Antonsson, Jet Propulsion Laboratory & California Institute of Technology

**External Co-Chair:** Tamas Gombosi, Univ. Michigan

### **Team Members:**

Walt Brooks, NASA Ames; Dave Bader, Lawrence Livermore; Karen Fucik, Northrop-Grumman; Ron Fuchs, Boeing; Mark Gersh, Lockheed-Martin; Tsengdar Lee, NASA Headquarters; Loren Lemmerman, Jet Propulsion Laboratory; Mike Lieber, Ball Aerospace; Steve Meacham, National Science Foundation; Charles Norton, Jet Propulsion Laboratory; Carl Peterson, Sandia; Irene Qualters, Merck; Dan Reed, Univ. North Carolina; Ricky Rood, NASA Goddard; John Rundle, Univ. California, Davis; Quentin Stout, Univ. Michigan; Tom Zang, NASA Langley

### **Team Liaison Members:**

Jan Aitkins; NASA Ames /Roadmap Coordinator; Steve Prusha, Jet Propulsion Laboratory/System Engineering, Cost and Risk Capability Roadmap Team; Harley Thronson, NASA Science Mission Directorate