Interim Report of a Review of the Next Generation Air Transportation System Enterprise Architecture, Software, Safety, and Human Factors

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Computer Science and Telecommunications Board

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Preface

The Next Generation Air Transportation System (NextGen) is an effort begun in 2003 whose goals include improving the capacity, efficiency, and safety of the U.S. air transportation system and also enabling reduction in noise, pollution, and energy use. The Federal Aviation Administration (FAA), and various stakeholders, including equipment providers, airlines, and contractors, are currently implementing both near-term and midterm capabilities of this effort.

Section 212 of the FAA Modernization and Reform Act of 2012, Public Law 112-95 (Box P-1) called for an examination of NextGen's enterprise architecture and related issues by the National Research Council (NRC). The project that was a result of this call was funded by the FAA. The Committee to Review the Enterprise Architecture, Software Development Approach, and Safety and

BOX P-1 FAA Modernization and Reform Act of 2012, Public Law 112-95

SEC. 212. EXPERT REVIEW OF ENTERPRISE ARCHITECTURE FOR NEXTGEN.

(a) REVIEW.—The Administrator of the Federal Aviation Administration shall enter into an arrangement with the National Research Council to review the enterprise architecture for the NextGen.

(b) CONTENTS.—At a minimum, the review to be conducted under subsection (a) shall—

- (1) highlight the technical activities, including human- system design, organizational design, and other safety and human factor aspects of the system, that will be necessary to successfully transition current and planned modernization programs to the future system envisioned by the Joint Planning and Development Office of the Administration;
- (2) assess technical, cost, and schedule risk for the software development that will be necessary to achieve the expected benefits from a highly automated air traffic management system and the implications for ongoing modernization projects; and
- (3) determine how risks with automation efforts for the NextGen can be mitigated based on the experiences of other public or private entities in developing complex, software-inten-sive systems.

(c) REPORT.—Not later than 1 year after the date of enactment of this Act, the Administrator shall submit to the Committee on Transportation and Infrastructure of the House of Representatives and the Committee on Commerce, Science, and Transportation of the Senate a report containing the results of the review conducted pursuant to subsection (a).

BOX P-2 Statement of Task

As stipulated in Sec. 212 of the FAA Modernization and Reform Act of 2012, PL 112-95, a National Research Council study would review the enterprise architecture, software development approach, and safety and human factor design aspects of the Next Generation Air Transportation System (NextGen). An ad hoc committee will conduct a study and prepare a report that will (1) highlight the technical activities, including human-system design and testing, organizational design, and other safety and human factor aspects of the system, that will be necessary to successfully transition current and planned modernization programs to the future system envisioned by the Joint Planning and Development Office of the Administration and obtain necessary certifications and operational approval; (2) assess technical, cost, and schedule risk for the software development that will be necessary to achieve the expected benefits from a highly automated air traffic management system and the implications for ongoing modernization projects; and (3) determine how risks with automation efforts for the NextGen can be mitigated based on the experiences of other public or private entities in developing complex, software-intensive systems, particularly for life-critical, real-time operational systems, and including past aviation system development programs. The committee will issue a brief interim report within 12 months providing an initial assessment focusing on software development challenges and a final report within 18 months providing a full assessment of the issues listed above.

Human Factor Design of the Next Generation Air Traffic System was formed under the auspices of the NRC's Computer Science and Telecommunications Board in 2012 to conduct the study. The statement of task for the study committee can be found in Box P-2.

The study committee has received a number of briefings on NextGen efforts, particularly as related to the study's focus on enterprise architecture, software development approach, safety, and human factors. For the purposes of this interim report, the committee offers a brief encapsulation of some of the areas of focus and concern it has been discussing up to this point in the study process. The original focus of this interim report was expected to be on software development challenges, per the statement of task (see Box P-2). Based on what it has learned so far, coupled with the fact that software development is affected by every stage (from conception to deployment and maintenance) of system development and integration, the committee has reframed that discussion around the challenges of system architecture for software-intensive systems. Chapter 1 offers context and background information, Chapter 2 briefly discusses numerous and complex constraints to which the FAA and NextGen are subject, and Chapter 3 describes the committee's emerging areas of focus and concern, along with some of the questions that have been under discussion thus far in the study process. Committee biographies can be found in Appendix A. A list of briefers from meetings prior to the release of this interim report can be found in Appendix B.

The committee thanks the FAA staff and the other experts who took the time to brief the committee. The committee also thanks the reviewers who made many thoughtful comments and also had several suggestions regarding additional topics to explore. The committee expects to receive additional briefings and inputs and explore those and other topics further and is reliant on timely availability of FAA staff and information to do so. The committee expects to issue its final report with findings and recommendations in 2014.

David E. Liddle, *Chair*
Committee to Review the Enterprise Architecture, Software Development Approach, and Safety and Human Factor Design of the Next Generation Air Transportation System

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Laura Haas, IBM Corporation,
Norman Fujisaki, Independent Contractor, Broadlands, Virginia,
Barbara Liskov, Massachusetts Institute of Technology,
Amadeo Odoni, Massachusetts Institute of Technology,
Amy Pritchett, Georgia Institute of Technology,
William Scherlis, Carnegie Mellon University,
Edmond Soliday, United Airlines (ret.),
John Swainson, Dell, Inc., and
John Tracy, The Boeing Company.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Peter M. Banks, Red Planet Capital Partners. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

Summary

Section 212 of the Federal Aviation Administration (FAA) Modernization and Reform Act of 2012, Public Law 112-95 (see Box P-1), calls for an examination by the National Research Council (NRC) of the Next Generation Air Transportation System's (NextGen's) enterprise software development approach and safety and human factor design. This interim report of the Committee to Review the Enterprise Architecture, Software Development Approach, and Safety and Human Factor Design of the Next Generation Air Transportation System briefly describes issues that have surfaced so far in the study.

NextGen aims to overhaul the nation's air transportation by introducing technological improvements—including use of the Global Positioning System and digital communications—and procedural changes that exploit those technologies. Its goals include improved monitoring and management of aircraft, shortened routes, better navigation around weather, time and fuel savings, reduced delays, and increased system capacity.

This endeavor is constrained by operational and capacity factors as well as political, economic, cultural, and technical factors. These reflect the diverse interests of stakeholders as well as the FAA's own history and organizational culture. The FAA and the United States rightly pride themselves on an excellent safety record. But organizational culture can affect how quickly process and technological change can happen. The technical realities and constraints to which NextGen programs are subject include the particular capabilities of legacy hardware, legacy software, costs of certification, and the challenges of human-systems integration and aligning operational procedures with revised or enhanced technological capabilities.

Several key issues that have emerged from the committee's work thus far are discussed below. Because the committee's data gathering and analysis is still incomplete, the observations and emphases in this report may not be mirrored in the committee's final report.

- *Understanding and managing benefit and cost expectations.* The committee is concerned about the alignment among (1) the overarching vision for NextGen, (2) the expected benefits and the risks to achieving those benefits, and (3) the estimated costs (and who bears those costs).

Because all three are subject to change as the context and underlying assumptions change, and it is to be expected that all three would have changed since the launch of NextGen. But the committee is concerned that these changes were not fully reflected in the briefings it has received or the documents it has reviewed and that there are not clear mechanisms to track these changes over time or to make them known to stakeholders. Also, risks to achieving the anticipated benefits on the expected schedule are not clear to the committee, because the sources of uncertainty in the value framework delivered to the users and the development risks confronted by the developers are not well prioritized or well quantified, and the evolutionary commitments for the short, medium, and long term are not well articulated. In an effort to understand these and related issues better, the committee will explore further the vision for NextGen and how it has changed over time and the risks and benefits analysis for NextGen.

- *Architecture.* In the federal government, an "enterprise architecture" is a "management best practice" designed to "promote mission success by serving as an authoritative reference, and by promoting functional integration and resource optimization with both internal and external service partners."[1] (The term is also used sometimes in industry, with a similar meaning.) The enterprise architecture defined for NextGen addresses these matters, but does not, in the committee's view, address key technical and performance parameters and relationships (including organizational and human factors considerations) that are essential for managing system development. Thus, the committee has expanded its focus to also explicitly encompass system architecture. A system architecture specifies how all of the parts of a large-scale software-intensive system fit together and interact and provides a framework in which incremental changes can be made while maintaining overall system integrity. The committee intends to examine NextGen system architecture efforts and their implications for program success.
- *System integration and software development approaches.* The committee is focused on the existing and anticipated processes for integrating new capabilities into the U.S. National Airspace System (NAS) and NextGen over time. Regarding system integration, the committee has been seeking information about the incremental build plan for NextGen and how new capabilities will be integrated, the existing and anticipated NextGen architecture, and the primary desired behaviors and attributes that drove efforts toward this architecture.

  The development of a software-intensive system includes requirements elicitation and analysis, specification, architecture definition, design, coding, testing and analysis, and evolution. Historically, the trade-offs captured in requirements elicitation, specification, and architecture have proven to be strong indicators of success in reducing risks and uncertainties, especially in larger, more complex software systems such as those being developed for NextGen. The committee is particularly interested in the quantified measures and expert engineering judgments of software change costs that have been encountered so far as well as trends—how these change costs are increasing or decreasing over time.
- *System safety.* In considering the system safety aspects of NextGen, two factors are key: (1) the development of NextGen provides an opportunity to introduce new air traffic control (ATC) safety capabilities, and (2) the development of NextGen requires that historic safety performance of ATC systems be maintained or improved. The committee is seeking to

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[1] Office of Management and Budget, *The Common Approach to Federal Enterprise Architecture,* Washington, D.C., available at http://www.whitehouse.gov/sites/default/files/omb/assets/egov_docs/common_approach_to_federal_ea.pdf, May 2012.

understand the FAA's safety management system process and implications for the development and deployment of anticipated NextGen capabilities.

- *Human factors, automation, and decision support tools.* The scale, heterogeneity, and complexity of NextGen mean that there will be many upgraded or new systems, all being developed under different programs, at different stages of implementation, being tested at different airports, and coming online at different times. This is understandable given the complexity and scale of the NextGen effort. However, experience has shown that human factors and human-system integration challenges arise when different systems and different people interact. The committee is interested in current and anticipated automation and decision-support capabilities, along with plans for managing their integration and the transitions from existing tools and processes to NextGen.
- *System security.* The designers and developers of any software- and communications-intensive system deployed today must grapple with questions of system security.[2] Understanding the security risks and threats and developing appropriate threat models and mitigations are challenges endemic across government and industry. NextGen is no exception—indeed, the safety-of-life implications and the vital economic importance of air travel make security of NextGen and the NAS critically important. As various programs and components of the national airspace are modernized, upgraded, and transformed, the security implications of the changes will need to be taken into account. The committee is concerned about the plans, processes, and mechanisms for managing cybersecurity in NextGen and the national airspace, including impacts of security on safety.
- *Unmanned aircraft system integration.* Unmanned aircraft systems (UAS) pose numerous procedural and technical challenges and introduce new requirements; they also will involve both safety and security challenges. NextGen will need to be designed and operated to manage, accommodate, and integrate this new class of aircraft. The committee is concerned about current and anticipated plans for safe integration of UAS into the NAS, recognizing that planning for UAS implementation has just begun.
- *Spectrum management.* The committee is interested in current and anticipated plans with regard to spectrum management for the NAS and NextGen.

The long-term vision for NextGen is ambitious. Some aspects of NextGen are anticipated to be transformational. Other, no less critical, short- and medium-term initiatives provide a foundation for implementing the longer-term vision and enable critically needed modernization of aging elements of the NAS. In the committee's view, both of these elements are critically important.

The study committee will receive additional briefings about these and other aspects of NextGen in order to fulfill its task. A final report, with the committee's findings and recommendations, is anticipated in 2014. In that report, although it may not address each of the questions raised in this interim report, the committee expects to say more about each of the above topics.

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[2] Here the committee refers to what some call cybersecurity—system, data, and communications security—which is distinct from the physical security required for airport and aircraft operation, provided in part by the Transportation Security Administration.

1

Introduction

The U.S. National Airspace System (NAS) is widely acknowledged to be both safe and reliable. However, runway capacity (particularly at the busiest U.S. airports—referred to as the "Metroplex" airports), the current operational model, and the evolved NAS constrain flight patterns and operations in ways that limit the net capacity of the U.S. air space and limit options for improving efficiency. Although technological and procedural improvements have been introduced into the system over the years to increase capacity, reduce delays, and improve safety, elements of the NAS rely on outdated technology, and the system has not been significantly changed to take advantage of available information and communications technologies or to enable major improvements in how the airspace is organized and managed. Furthermore, the NAS exists in a complex political, organizational, and economic milieu that imposes its own constraints and demands as well.

In 2003, an effort to transform the air transportation system was announced, and the Joint Planning and Development Office was established to develop the Next Generation Air Transportation System (NextGen). NextGen refers to a set of programs and initiatives to be coordinated into an evolving overall transportation system aimed at a continuing transformation of the NAS. NextGen aims to overhaul the U.S. air transportation system through a combination of procedural and technological improvements. It is intended to make use of extant capabilities along with key enabling technologies such as satellite navigation systems and a digital communications infrastructure to share real-time information, making it possible to shorten routes, navigate better around weather, save time and fuel, reduce delays, increase capacity at airports not already capacity-limited, and improve capabilities for monitoring and managing of aircraft. The Federal Aviation Administration (FAA), working with a wide range of stakeholders, is currently working toward both near-term and midterm capabilities.[1]

NextGen efforts will almost certainly increase the amount, complexity, and safety-criticality of NAS systems and corresponding enterprise and system architectures. The development of

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[1] More information about NextGen can be found in the NextGen Implementation Plan 2013 on the FAA's website at http://www.faa.gov/nextgen/implementation/.

large-scale, software-intensive systems is widely recognized to be challenging and risky (in terms of cost, schedule, and system performance), and there have been both "extraordinary successes and colossal failures"[2] in developing and deploying systems in both the private and public sector. Efforts related to the national air transportation system are especially challenging owing to its large scope and scale (and difficulty tends to increase nonlinearly as systems scale up in complexity, features, and quality goals), the multiple entities that interconnect with it (such as airlines, aircraft manufacturers, and airport operators), and the human-systems interactions associated with piloting and controlling. Cost and time estimates associated with the acquisition of large, software-intensive systems are notoriously overoptimistic—in part due to the misalignment of near-term goals and incentives with long-term goals and incentives. In addition, in any complex environment, new or upgraded systems require careful attention to the co-development of appropriate new business processes and to human-systems integration considerations and related issues such as organizational design, development of new concepts of operation, system usability, and user training.

The committee has received a number of briefings on NextGen efforts, particularly as related to the study's focus on enterprise architecture, software development, safety, and human factors. In this interim report, the committee outlines some of the topics it has examined so far in the study process. Chapter 2 describes some of the constraints faced by NextGen efforts. Chapter 3 outlines major themes and areas of focus and concern that have emerged thus far in the committee's work. The final report—anticipated in mid-2014—will provide more in-depth analysis, along with findings and recommendations.

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[2] National Research Council, *Achieving Effective Acquisition of Information Technology in the Department of Defense*, The National Academies Press, Washington, D.C., 2010, p. ix.

2

Constraints

There are numerous complex constraints on the design and operation of the U.S. National Airspace System (NAS) to which the Federal Aviation Administration (FAA) and its stakeholders are subject. The FAA is well aware of these constraints—some of which may affect development of systems and some of which may bear on ultimate benefits and outcomes. In the committee's view, it is helpful to keep these often challenging constraints, which include legacy commitments already made, in mind when planning, assessing, or evaluating Next Generation Air Transportation System (NextGen) efforts.

OPERATIONAL AND CAPACITY CONSTRAINTS

One of the goals for NextGen is to improve efficiency and reduce congestion in the NAS. FAA's Aerospace forecast projects that the U.S. aviation industry will grow from 731 million passengers in 2011 to 1.2 billion in 2032.[1] Congestion in the NAS tends to be localized to certain regions. Using 2012 FAA Air Traffic Activity Data for 21.7 million commercial air operations, more than 56 percent (12 million) of these involved the so-called Metroplex airports.[2] Although there are opportunities to increase runway efficiency, such as less separation, parallel approaches, and so on, the realizable benefits of such are not yet clear. For example, wake vortex separation requirements may limit separation reduction, and local community resistance to noise and night flights may limit the introduction of new approach routes or extended hours that would increase the capacity of existing runways. In addition to all of this is uncertainty about what the future capacity needs will be given uncertainties about travel demand and fuel and other operational costs.

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[1] FAA, FAA Aerospace Forecast: Fiscal Years 2012-2032, available at http://www.faa.gov/about/office_org/headquarters_offices/apl/aviation_forecasts/aerospace_forecasts/2012-2032/media/2012%20FAA%20Aerospace%20Forecast.pdf.

[2] FAA, Air Traffic Activity Systems, Airport Operations, available at http://aspm.faa.gov/opsnet/sys/Airport.asp.

POLITICAL, ECONOMIC, AND CULTURAL CONSTRAINTS

The NAS is a national infrastructure to which significant resources are devoted. As such, it has numerous stakeholders, and there are few individuals or businesses in the country that do not have an interest in or expectations regarding its performance. Thus, the NAS, the FAA, and NextGen efforts are subject to significant scrutiny—not only from users (such as trade groups, airlines, airports, and affiliated labor groups), but from Congress, other federal agencies, and the flying public as well. And as a federal agency, the FAA must operate within the federal political environment and under whatever financial and performance constraints and expectations are produced within it.

External stakeholders, such as those listed above, have a variety of interests, demands, and constraints. Agreement, or at least rough consensus, on requirements will be important (albeit challenging to achieve). Some NextGen programs and components will undoubtedly have implications for the workforce—controllers, safety specialists, and pilots. The capacity, skill sets, size, and expectations of the associated workforces will need to be taken into account when developing and deploying new or changed capabilities.[3] NextGen's benefits are expected to accrue to stakeholders; however, many of those benefits (such as increased automatic communication between aircraft) cannot be fully realized without participation and (sometimes costly) adoption by the relevant stakeholders.[4] In addition, although many of the NextGen advances should benefit participants in the NAS writ large, the fact that some of the benefits may accrue to competitors could be a disincentive to participation by private entities. Thus, for some NextGen goals, the FAA is caught in a bind due to the distributed costs of deployment and the uncertainty of those costs if broad deployment does not occur. The expectation that economic benefits will sufficiently motivate airline equipment purchases may be misplaced, calling into question whether the anticipated voluntary uptake will occur.

In addition to external political considerations, as a large organization, the FAA has its own organizational culture that has developed over time. The FAA and the United States rightly pride themselves on a devotion to safety and an excellent safety record to match. At the same time, a conservative safety culture can affect how quickly process and technological change can happen—a challenge in an arena where technologies change rapidly. An historic culture of safety and responsibility—especially one that has resulted in a strong safety record—may inhibit the adoption of new technologies or increased automation that could potentially result in net improvements in both safety and efficiency. Recognizing and taking into account the tensions among competing goals in an organization is critical to ensure progress.

TECHNICAL CONSTRAINTS

The technical realities and constraints to which NextGen programs are subject run the gamut from the capabilities of legacy hardware to costs of certification to the challenges of large-scale system integration. The great majority of the tasks facing NextGen involve software and information and communications technology—the systems architecture has implications for how software

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[3] The 2007 National Research Council report *Human-System Integration in the System Development Process: A New Look* (The National Academies Press, Washington, D.C.) explores iterative development processes suitable for systems that have intensive human interaction and with humans having functional roles within the system (e.g., pilots, controllers, and so on.)

[4] For example, ADS-B must be installed not only in larger commercial aircraft, but also in smaller general aviation aircraft to make full use of the system everywhere and there are costs (financial and also process) associated with deploying this technology. (Automatic dependent surveillance-broadcast (ADS-B) is an aircraft tracking technology that relies on the global positioning system (GPS) and a datalink to broadcast (ADS-B Out) and receive (ADS-B In) data.)

components are developed and integrated and for how corresponding operational procedures are developed, refined, and deployed. Higher levels of software automation and integrity and fault tolerance will likely be needed, along with more reliable integration of aircraft and ground systems and processes. Future needs also include more flexibility and agility in systems and processes to deal with a dynamic and uncertain environment coupled with, wherever possible, reduction of uncertainties in the system (e.g., improved weather forecasting, tracking of wake vortices, wind shear, and so on).

Avionics systems and any upgrades or changes to them require time and resources for certification and, ultimately, integration. In addition, most avionics systems must have international backing and agreement in order to achieve substantial deployment, so rapid introduction of new technologies that might benefit the national airspace may not be possible.

For certain capabilities, decisions will need to be made about whether to deploy new software or whether software emulators running on new hardware may be sufficient.[5] In addition, as capabilities are developed and deployed, ensuring that potential avenues of future improvement—such as in the areas of communications, authentication, and spectrum management—are not closed off prematurely will be important.

Aligning operational procedures with revised or enhanced technological capabilities is critical to the success of any technology advances. Ensuring clear processes and plans for any changes to the operational infrastructure, such as the development of procedures and airspace that take full advantage of the new technical capabilities of NextGen, will be important. Given the human-intensive nature of operating the national airspace, there are also challenges related to design for organizations and to human-system integration, including robustness of the combined human-machine interaction, along with human factors concerns with the implementation of new technical functions. The anticipated benefits of NextGen will depend on commensurate changes in the airspace and how all of these challenges are managed.

The bulk of NextGen software and system development is done under a variety of contracts, thus obliging the FAA (or another contractor) to act as the system integrator. The structure of the network of supplier relationships and incentives to create and deploy NextGen will bear on development and deployment. A systems architecture serves as an integration blueprint that demands careful specification of the behaviors and interfaces of the components, effective tracking of contractor efforts, and continuous integration and testing of in-progress and completed components. Moreover, the importance of human-systems interaction and human factors in NextGen has implications for how the work is contracted. Notably, it is challenging to make measureable, quantifiable specifications for human factors—such as ensuring that the contractor makes a product that is truly effective and usable from the point of view of the controller. Thus, delegation of detailed design to contractors has implications for these and related aspects of NextGen. More generally, in the management of architecture, there is a natural tension between the client (FAA) and the supplier (various contractors) with regard to architecture leadership. Architectural leadership also requires senior management attention to constraints, incentives, and design participation by suppliers. Ineffective leadership can result in a diffusion of responsibility, which can result in perverse incentives for suppliers. Diffusion of responsibility might also lead to a vague, ineffective architecture or to different interpretations by different actors (client, various vendors). If the architecture leadership is weak or dispersed, it could lead to an overall system with no architecture or a flawed architecture.

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[5] Similar efforts were undertaken in the late 1990s for the FAA's Host Computer System. See FAA, Host and Oceanic Computer System Replacement Program, available at http://www.faa.gov/news/press_releases/news_story.cfm?newsId=6419, 1999.

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Emerging Topics of Focus and Concern

In this Chapter, the committee outlines several topics and areas of focus and concern that have emerged from its data gathering efforts so far. The committee will provide its findings and recommendations in its final report. Some of the questions that have been raised and discussed at briefing sessions are noted here, clustered roughly according to topic. Note that these preliminary observations, questions, and topics are raised as part of the committee's information-gathering efforts and may not reflect the emphases that will be given to topics in the committee's final report, and the committee does not anticipate addressing every question and issue outlined here in the final report. This chapter concludes with a brief comment about the importance of modernization.

UNDERSTANDING AND MANAGING BENEFIT AND COST EXPECTATIONS

The committee is concerned about the alignment among (1) the overarching vision for the Next Generation Air Transportation System (NextGen), (2) the expected benefits and the risks to achieving those benefits, and (3) the estimated costs (and who bears those costs). Because all three are subject to change as the context and underlying assumptions change, it is to be expected that all three would have changed since the launch of NextGen. But the committee is concerned that these changes were not fully reflected in the briefings it has received or the documents it has reviewed and that there are not clear mechanisms to track these changes over time or to make them known to stakeholders. The vision, the benefits, and the costs of NextGen are all models (that is, predictions) of a future state with many sources of uncertainty. The risks to achieving the anticipated benefits on the expected schedule are not clear to the committee, because of uncertainty in the value framework delivered to the users and stakeholders. In addition, the development risks confronted by the developers are not well prioritized or well quantified, and the evolutionary commitments for the short, medium, and long term are not well articulated.

In an effort to understand these and related issues better, the committee will explore further the vision for NextGen and how it has changed over time and the risks and benefits analysis for NextGen and how those analyses have changed over time. Examining the state changes of the vision from its original inception to the current baseline provides a window into how the predictions of the benefits have performed since NextGen was first envisioned.

More generally, the committee is concerned about how uncertainty in this large, complex undertaking is understood, managed, and synthesized into more predictable plans and expectations. The FAA is correctly taking an incremental approach to system development. The committee seeks to ascertain how the FAA channels the validated learning in previous increments into better predictions of benefits, costs, and outcomes. Focusing on FAA's approach to programmatic, engineering, and operational risk for NextGen, the committee requested information on the following: the FAA's assessment of each of these types of risk, how risk assessment is done, ongoing or anticipated mitigation strategies and how those are built into the development process, and expectations for how these risk profiles will change in the medium and long term. The committee has not been able to elicit a clear articulation of the significant risks perceived within the NextGen systems and software or how the FAA would quantify or monetize these risks to substantiate the priority ordering and anticipated schedule. Specific questions the committee will explore further include the following:

- What is the largest source of NextGen benefits today? What is the largest source of benefits expected to be in the future?
- What are the most uncertain benefits planned in the FAA's NextGen system and software capability?
- What are the most significant uncertainties in NextGen requirements that drive development risk?
- What are the most significant uncertainties in NextGen design and system architecture?
- What are the most significant uncertainties in the planned sequence of milestone expectations?
- What measures and metrics will be used to quantify and steer risk management priorities?

The committee wants to better understand the FAA's perspective on the uncertainty in the upsides (benefits) and the downsides (programmatic risks). The FAA could quantify these uncertainties by modeling the benefits and risks as probability distributions of possible outcomes. Even if these distributions were represented as simple triangular distributions (best case, worst case, expectation), it would provide the committee with a set of critical priorities and a quantified model of the perceived uncertainties.

ARCHITECTURE

The committee's statement of task (see Box P-2) asks for an examination of the NextGen enterprise architecture. The committee interprets this use of the term "enterprise architecture" to mean the Office of Management and Budget requirement that every government agency have an enterprise architecture designed to "promote mission success by serving as an authoritative reference, and by promoting functional integration and resource optimization with both internal and external service partners."[1] The enterprise architecture is thus focused on business structures and processes,

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[1] See Office of Management and Budget, The Common Approach to Federal Enterprise Architecture, Washington, D.C., May 2012, available at http://www.whitehouse.gov/sites/default/files/omb/assets/egov_docs/common_approach_to_federal_ea.pdf. The term "enterprise architecture" does not have a single definition and is used by others outside the federal context with slightly different meaning. Peter Weill at MIT defines an enterprise architecture as "the organizing logic for key business processes and IT capabilities reflecting the integration and standardization requirements of the firm's operating model" (Page 2 of P. Weill, "Innovating with Information Systems: What Do the Most Agile Firms in the World Do," presented at the Sixth e-Business Conference, Barcelona, Spain, March 2007, available at http://www.iese.edu/en/files/6_29338.pdf.) Maier and Rechtin observe that

and the NextGen enterprise architecture[2] addresses these matters. However, enterprise architecture is only one piece of the architectural definition that is needed for NextGen.

Any large-scale, software-intensive systems endeavor requires a technical and systems architecture that specifies how all of its parts fit together and interact, which can be used in a dynamic way to help inform and drive decision making.[3] The systems architecture of the NAS would encompass the technical and operational aspects of the system and its components—individual avionics systems, communications facilities, ground equipment, airport facilities, routes, approach procedures, personnel roles and training, and so on. In addition to addressing the technical enablement of the full set of functional capabilities, a system architecture also addresses "nonfunctional" attributes such as critical quality attributes, management of variabilities (that is, anticipated changes over a system lifetime), roles of services vendors, and alignment with organizational and supply-chain structure.

The committee's discussions have focused on both the particulars of the enterprise architecture as well as the technical and systems architecture. Questions and topics related to these architectures that have been discussed thus far include the following:

- Who are the specific intended users of the various architectures, and what types of decisions are they expected to influence?
- What are the processes for managing architecturally significant decision making within the NextGen effort? Are these processes explicitly managed, or is architecture more of an emergent outcome from a multiplicity of separate processes—and one that may, or may not, have the necessary technical and structural attributes?

Given the enormous range of activities within NextGen, considerations related to the congruence of system architecture and organizational (and supply-chain) architecture are likely to be significant, prompting the following questions:

- How does the architecture address the goal of risk mitigation, and how is this determined?

"If we take an enterprise to be an organization with a defined mission, . . . the practice of enterprise architecture would concern itself largely with business strategy and business processes" (M. Maier and E. Rechtin, The Art of Systems Architecting, Third Edition, CRC Press, Boca Raton, Fla., 2009, p. 353).

[2] Mike Hritz, Role of Enterprise Architecture NextGen, Briefing to the Committee Review the Enterprise Architecture, Software Development Approach, and Safety and Human Factor Design of the Next Generation Air Transportation System, March 2013. See also The National Airspace System Enterprise Architecture at https://nasea.faa.gov.

[3] Chapter 3 of National Research Council, *Critical Code: Software Producibility for Defense* (The National Academies Press, Washington, D.C., 2010, pp. 68-69) offers a useful description of architecture and its importance*:*

> Just as in physical systems, architectural commitments comprise more than structural connections among components of a system. The commitments also encompass decisions regarding the principal domain abstractions to be represented in the software and how they will be represented and acted upon. The commitments also include expectations regarding performance, security, and other behavioral characteristics of the constituent components of a system, such that an overall architectural model can facilitate prediction of significant quality-related characteristics of a system that is consistent with the architectural model. Architecture represents the earliest and often most important design decisions—those that are the hardest to change and the most critical to get right. Architecture makes it possible to structure requirements based on an understanding of what is actually possible from an engineering standpoint—and what is infeasible in the present state of technology. It provides a mechanism for communications among the stakeholders, including the infrastructure providers, and managers of other systems with requirements for interoperation. It is also the first design artifact that addresses the so-called non-functional attributes, such as performance, modifiability, reliability, and security that in turn drive the ultimate quality and capability of the system. Architecture is an important enabler of reuse and the key to system evolution, enabling management of future uncertainty. In this regard, architecture is the primary determiner of modularity and thus the nature and degree to which multiple design decisions can be decoupled from each other. Thus, when there are areas of likely or potential change, whether it be in system functionality, performance, infrastructure, or other areas, architecture decisions can be made to encapsulate them and so increase the extent to which the overall engineering activity is insulated from the uncertainties associated with these localized changes.

- How, for example, is the system architecture designed to accommodate novel uses of the airspace such as unmanned aircraft systems?
- How are the interplays between security and safety and between efficiency and safety in the system architecture being dealt with and assured?
- To what extent are technological requirements and specifications for near-term systems developed to accommodate future needs, and how is this managed in the overall systems architecture?
- How are changing requirements and changing stakeholder needs expressed, modeled, and accommodated over time?
- How are process or technology innovations suggested or developed by local area experts (e.g., at individual towers), contractors, or other stakeholders within the NAS vetted for potential impacts and potential wider adoption/implementation, and can the system architecture flexibly accommodate such innovations? The committee is particularly interested in examples of where these sorts of accommodations have been accomplished.

SYSTEM INTEGRATION AND SOFTWARE DEVELOPMENT APPROACHES

The committee is focused on the existing and anticipated processes for integrating new capabilities into the system over time. Regarding system integration, the committee has been seeking input about the incremental build plan for NextGen and how new capabilities will be integrated, including the NextGen target architecture and the primary desired behaviors and attributes that drove efforts toward this target architecture. As discussed above, understanding the primary constraints (economic, technical, political, physical, human, and so on) that bound decisions will be important to aligning the evolving NextGen vision with near- and long-term benefits.

The development of a large-scale, software-intensive system includes requirements elicitation and analysis, specification, architecture definition, design, coding, testing and analysis, and evolution. Historically, the trade-offs captured in requirements elicitation, specification, and architecture have proven to be strong indicators of success in reducing risks and uncertainties, especially in larger, more complex software systems such as those being developed for NextGen.

The committee is particularly interested in quantified measures and expert engineering judgments of software change costs (e.g., requirement change, design change, code change, regression test cycle, bug fix, build time, or others) and trends (how are these change costs increasing or decreasing over time). More abstractly, the committee will examine further how the FAA characterizes its software posture. The following considerations have been discussed: How to characterize and quantify the “mass” of software to be developed, and how to characterize and quantify the cost of the software to be developed. With respect to contractors in particular, the committee has been discussing and learning about how technical and system requirements and expectations (as well as changes) are communicated to and from the FAA, what the underlying technical and architectural assumptions are and how they are made explicit, and how testing and integration is managed.

A particular program or enabling technology can be used as an exemplar to consider some of these issues. With regard to the major NextGen programs, the committee is interested in their detailed technical specifications and operational dates. For the Data Communications program, for example, these areas would include what modes of digital data will be supported (i.e., protocols, bandwidth, security, availability, reliability, and so on) and what the expected aircraft equipage rates will be. In general, the requirements for a given program—what the new capability will be used for in the medium and long term, and more generally the current status of the program and projected timeline for its implementation, are of interest. Equipment cost expectations—both for commercial carriers and general aviation users—will also play a role in uptake in some situations. For a given program, the general questions about uncertainties and risk apply as well: What have been the biggest challenges (technical, process, operational, or organizational)? and What are current uncertainties and risks and anticipated mitigation plans?

SYSTEM SAFETY

In considering the system safety aspects of NextGen, two factors are key: (1) the development of NextGen provides an opportunity to introduce new air traffic control (ATC) safety capabilities, and (2) the development of NextGen requires that historic safety performance of ATC systems either be maintained or improved. The committee is seeking to understand the FAA's safety management system process and implications for the development and deployment of anticipated NextGen capabilities so as to understand how these two factors are being addressed.

The committee is focused on the safety objectives that the FAA has for NextGen, the processes and techniques by which the FAA expects these objectives to be met, any safety indicators and metrics used in an ongoing way in the development process, and any preliminary NextGen safety data and associated analyses that are currently available. In order to understand the basis for the safety objectives for NextGen, the committee is interested in learning more about the following: the safety objective defined for the current ATC system, the current mechanism for safety assessment for the NAS, the status of assessed safety metrics in the NAS, and how current safety assessment mechanisms and procedures might change as NextGen capabilities continue to be put in place.

Safety is not a system property that can be added after basic functionality has been addressed. Safety is an emergent property that derives from careful design at all levels. Thus, the committee is interested to learn what techniques are included in the NextGen architecture, design, and implementation to mitigate residual risk. The committee also notes that comprehensive hazard identification is a critical input to the safety-engineering process. The committee is interested to learn what specific techniques are being used to undertake hazard identification and estimate residual risk at each phase of deployment. In briefings to the committee, quantification of various safety items has been summarized. The committee expects to further explore what quantification approaches are being used in NextGen to estimate probabilities of hazardous states and the role of quantification in deployment decisions for NextGen features and capabilities.

Other air traffic control systems throughout the world have been upgraded and have added novel capabilities over time. The committee also plans to explore the following: to what extent the safe-design concepts and safety-assessment techniques planned for NextGen are consistent with and compatible with those used by other agencies around the world (such as the United Kingdom's Civil Aviation Authority, Eurocontrol, and the International Civil Aviation Organization) and to what extent the safety technology and associated experience elsewhere have been reviewed by and considered for adoption by the FAA.

HUMAN FACTORS, AUTOMATION, AND DECISION SUPPORT TOOLS

Experience has shown that human factors challenges arise when different systems and different people interact. The scale, heterogeneity, and complexity of NextGen mean that there will be many upgraded or new systems and operational procedures, all being developed under different programs, at different stages of implementation, tested at different airports, and coming online at different times. This is understandable given the complexity and scale of the NextGen effort. The committee is interested in understanding the current and anticipated automation and decision-support capabilities and how users of the airspace will be trained, including plans for managing the transitions from existing tools and processes to NextGen, recognizing that it is difficult to specify a priori design, and guidelines for human-systems interaction.

With regard to roles and boundaries in human-systems interactions, there is generally a shift, from human to system, taking place in the interpretation of sensor data and, increasingly, decisions and actions based on that data.[4] This has profound significance for the design of the NextGen system. It applies both to piloting and to controller responsibilities—raising issues that connect policy, user-experience design, and usability evaluation. It also creates challenges for capability assurance, because some of rules of engagement previously belonging in the human domain, and typically relatively informally modeled, may need to be formalized to the point where there can be assurance that system behavior will respect these rules. There are trade-offs to be studied between enacting desired mission goals through changing the human (selection, training, staffing) and changing the technology.

Thus far, the committee has been exploring some of the topics and questions in this area, asking, At what level of management is the responsibility to ensure that critical human factors considered? and At what stage in the system development process does the human factors team become involved, and what is their method of involvement? The committee will explore examples of past human-factors recommendations that have been integrated into the system (or not) and why they were (or were not) integrated. The committee will also explore the differences between current ATC technologies and processes and anticipated NextGen ATC technologies and processes with regard to needed skill sets and knowledge requirements for controllers and pilots. A large cadre of controllers will be retiring soon, so the committee is interested in understanding what measures are being taken to analyze the job skills required for ensuring that new controllers understand and make use of the computer-based systems being introduced in NextGen.

Because human performance capabilities and risks are difficult to quantify in engineering terms sufficient to specify requirements, human factor aspects of new system designs must be evaluated by means of human-in-the-loop simulations (HITLSs). One issue is how and when to use HITLSs, and with what simulator fidelity. Experience has shown that at initial stages of system design, much understanding of the issues can be gleaned from relatively simple part-task HITLSs.

New computer-based decision aids are bound to make controllers more dependent on the computer advice given. Questions include, How is that expected to affect policies for assigning authority and responsibility of controllers? What types of automation of capabilities are anticipated in the near and long term, what capabilities exist for human override of automation, and what changes are anticipated in the future? NextGen assumes a level of teamwork between sector controllers, flow controllers, tower controllers, and pilots—much greater than in current ATC. The committee is interested in what means are being used to ensure that all parties to the cooperation are seeing the picture in the same way in an adequate time window.

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[4] National Research Council, *Human-System Integration in the System Development Process: A New Look,* The National Academies Press, Washington, D.C., 2007.

SYSTEM SECURITY

The designers and developers of any software- and communications-intensive system deployed today must grapple with questions of system security.[5] Understanding the security risks and threats and developing appropriate threat models and mitigations are challenges endemic across government and industry. NextGen is no exception; indeed, the safety of life implications and the vital economic importance of air travel make the security of NextGen and the NAS critically important. As various programs and components of the national airspace are modernized, upgraded, and transformed, the security implications of the changes will need to be taken into account.

The committee is concerned about the plans, processes, and mechanisms for managing system security in the national airspace. Some of the topics and questions in this area the committee has been exploring thus far include the following: the threat model, how it is being validated, and how threats will be monitored over time as context and adversaries change; the scope and focus of security concerns for NextGen and how they are accommodated in the system architecture; and the FAA's assessment of its most significant security risks and challenges and what plans are in place to address them. For example, is there a well-articulated a process for addressing security attributes as early as possible in the process, as opposed to relying on process compliance and intensive after-the-fact acceptance evaluation?[6] Programmatically, questions to consider further include these: Where does overall responsibility for security reside? and How are cybersecurity considerations managed and addressed in the various programs of NextGen (such as ADS-B and DataComm)? Finally, the committee believes it will be important to understand how NextGen and the NAS cope with the insider threat—that is, authorized users of the systems with malicious intent.

UNMANNED AIRCRAFT SYSTEM INTEGRATION

Unmanned aircraft systems pose numerous procedural and technical challenges and introduce new requirements; they also will involve both safety and security challenges. NextGen architectures will need to be designed to manage, accommodate, and integrate this new class of aircraft. Depending on what rules are promulgated with respect to unmanned aircraft systems (UAS) in the airspace, integration of UAS will likely require that the NAS accommodate a wider spectrum of aircraft weights and sizes; aircraft operating over a larger range of flight profiles using non-traditional routes; and a larger variety of aircraft with a broader range of capabilities.[7] Additional challenges include managing differences between see-and-avoid capability (the capability traditionally provided by human pilots) and sense-and-avoid operation; autonomous operation of UAS, either as part of a mission profile or as a result of the loss of a command link; and ensuring efficient communication with the UAS crew. Operational expectations within the NAS would almost certainly have to change. For example, procedures to ensure adequate separation of UAS from other aircraft and recovery of safe flight for manned aircraft in the event of a loss of separation will be important.

Perhaps most critically, failure modes of UAS will differ substantially from the failures modes of manned aircraft, affecting safety, reliability, and security analyses. For instance, vulnerabilities may exist in the command and control link—How should a UAS behave if it loses communications capability along that link or is spoofed or jammed? The committee is concerned about current and

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[5] Here the committee refers to what some call cybersecurity—system, data, and communications security, which is distinct from the physical security required for airport and aircraft operation, provided in part by the Transportation Security Administration.

[6] See, for example, M. Howard and S. Lipner, The Security Development Lifecycle, 2006.

[7] Unmanned aircraft systems could operate from altitudes of a few hundred feet to perhaps 50,000 feet with dwell times potentially beyond 24 hours. The ability of a typical UAS to maneuver is also severely limited, complicating collision avoidance.

anticipated plans for safe integration of UAS into the NAS, recognizing that planning for UAS implementation has just begun. Questions include: What are the key factors that will guide FAA work in this space, and what is the projected time line for policy decisions and any associated implementation? What design and architectural decisions (if any) have been or will need to be taken in NextGen to accommodate UAS of varying flight profiles, capabilities, and weights and types?

SPECTRUM MANAGEMENT

One of the FAA's most valuable capital assets is its allocated spectrum. The management and use of this asset in the future will need to be a critical element of the systems architecture. It takes significant time and effort to achieve international agreement and standardization before any changes can be made to the allocation of the spectrum. Aircraft equipage considerations require standardization and implementation to be coordinated worldwide; otherwise, international flights would be required to carry multiple sets of equipment for different parts of the world. Spectrum efficiency is also important. Like other entities that manage government-held spectrum, the FAA is under pressure to share spectrum and to use it more efficiently.[8] The 108-137 MHz very-high-frequency (VHF) and 960-1215 MHz ultrahigh-frequency airbands, which are used for navigation aids, precision approach systems, and voice communications, are used inefficiently by modern standards, having been allocated in a different technology era. Most notable is the continued use of amplitude modulation (AM) channels for voice communication. But the transition to efficient digital voice, low-cost, high-performance data radios and the shutdown of some radars and old VHF navigation equipment to free up spectrum will be a challenging process. The committee is focused on current and anticipated plans with regard to spectrum management for the NAS and NextGen.

THE IMPORTANCE AND NECESSITY OF MODERNIZATION

FAA's NextGen efforts are broadly aimed at transforming U.S. airspace, and toward that end, there are significant modernization opportunities along the way. Opportunities to replace and upgrade aging equipment are certainly within the scope for NextGen and offer the potential to reduce the risk of failure, to reduce maintenance costs, and to enhance capabilities. Modernization efforts also afford opportunities to increase the flexibility and extensibility of existing software-intensive systems to allow for incremental advancement over time. The trade-off between the near term and long term is, in part, about delivering economic benefits in the near term while taking compatible near-term steps that support longer-term transformation of the system. NextGen aims to deliver near-term benefits for its user community (which has a near-term planning horizon driven by business objectives) while establishing and retaining a focus on longer-term transformative changes in the system. The challenge is balancing evolutionary changes with revolutionary changes and aligning these changes with the most significant problems that most critically require solutions.

The long-term vision for NextGen is ambitious. Some aspects of NextGen are anticipated to be transformational. Others, no less critical, are important and necessary modernization efforts and can pave the way for potential eventual transformations. An ambitious long-term vision for NextGen includes short- and medium-term initiatives that will (1) provide a foundation for the

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[8] Two Presidential Memoranda in recent years have emphasized the importance of wise spectrum management: June 28, 2010, "Unleashing the Broadband Revolution" (http://www.whitehouse.gov/the-press-office/presidential-memorandum-unleashing-wireless-broadband-revolution), and June 14, 2013, "Expanding America's Leadership in Wireless Innovation" (http://www.whitehouse.gov/the-press-office/2013/06/14/presidential-memorandum-expanding-americas-leadership-wireless-innovatio).

longer-term vision and (2) enable critically needed modernization of aging elements of the NAS. In the committee's view, both of these elements are critically important.

The study committee will receive additional briefings about these and other aspects of NextGen in order to fulfill its charter. A final report, with the committee's findings and recommendations, is anticipated in 2014. In that report, although it will not necessarily address each of the questions raised here in this preliminary snapshot, the committee expects to say more about each of the above topics.

Appendixes

A

Biographies of Committee Members and Staff

David E. Liddle, *Chair***,** has been a partner at U.S. Venture Partners, a Silicon Valley-based venture capital firm since 2000. He co-founded Interval Research Corporation, a Silicon Valley-based laboratory and incubator for new businesses focusing on broadband, consumer devices, interaction design, and advanced technologies, where he served as president and CEO between 1992 and 1999. Previously, Dr. Liddle co-founded Metaphor Computer Systems, Inc., in 1982 and served as its president and CEO until 1991. He has also held executive positions at Xerox Corporation and IBM. Prior to co-founding Interval with Paul Allen, Dr. Liddle founded Metaphor, which was acquired by IBM in 1991, which named him vice president of business development for IBM Personal Systems. His extensive experience in research and development has focused largely on human-computer interactions and includes 10 years at Xerox Palo Alto Research Center (PARC), from 1972 to 1982. He has been a director of MaxLinear, Sybase, Broderbund Software, Borland International, and Ticketmaster and is currently on the board of the New York Times Company and InPhi, Inc. His board involvement at U.S. Venture Partners includes AltoBeam, Karmasphere, and LineStream. Dr. Liddle served on the Defense Advanced Research Projects Agency (DARPA) Information Science and Technology Committee and as co-chair of the National Research Council's (NRC's) Computer Science and Telecommunications board. His contributions to human-computer interaction design earned him the distinction of senior fellow at the Royal College of Art. He is on the boards of SRI International, the College of Engineering at Stanford University and The Public Library of Science. Dr, Liddle earned a B.S. in electrical engineering at the University of Michigan and a Ph.D. in EECS at the University of Toledo, where his dissertation focused on reconfigurable computing machines and theories of encryption, encoding and signal recovery. He recently served as chair of the NRC study on wireless technology prospects and policy options, and on the subsequent PCAST study on realizing the full potential of government-held spectrum to spur economic growth. He is a type-rated Citation pilot with more than 2,000 hours in jets.

Steven M. Bellovin (NAE) is a professor of computer science at Columbia University, where he does research on networks, security, and especially why the two do not get along. He recently served as the chief technologist for the Federal Trade Commission. He joined the faculty at Columbia in 2005 after many years at Bell Labs and AT&T Labs Research where he was an AT&T fellow. He received a B.A. degree from Columbia University and his M.S. and Ph.D. degrees in computer science from the University of North Carolina, Chapel Hill. While a graduate student, he helped create Netnews; for this, he and the other perpetrators were given the 1995 Usenix Lifetime Achievement Award (The Flame). In 2007 he received the National Institute of Standards and Technology/National Security Agency National Computer Systems Security Award. He is a member of the National Academy of Engineering (NAE) and is serving on the Department of Homeland Security's Science and Technology Advisory Committee and the Technical Guidelines Development Committee of the Election Assistance Commission. He was a member of the Internet Architecture Board from 1996-2002 and was co-director of the Security Area of the Internet Engineering Task Forcefrom 2002 through 2004. Dr. Bellovin is the co-author of *Firewalls and Internet Security: Repelling the Wily Hacker,* and holds a number patents on cryptographic and network protocols. He has served on many NRC committees, including those on information systems trustworthiness, the privacy implications of authentication technologies, and cybersecurity research needs. He was also a member of the information technology subcommittee of an NRC study group on science versus terrorism.

John-Paul B. Clarke is an associate professor in the Daniel Guggenheim School of Aerospace Engineering with a courtesy appointment in the H. Milton Stewart School of Industrial and Systems Engineering and director of the Air Transportation Laboratory at the Georgia Institute of Technology. He received S.B., S.M. , and Sc.D. degrees in aeronautics and astronautics from the Massachusetts Institute of Technology (MIT). His research and teaching in the areas of control, optimization, and system analysis, architecture, and design are motivated by his desire to simultaneously maximize the efficiency and minimize the societal costs (especially on the environment) of the global air transportation system. Dr. Clarke has made seminal contributions in the areas of air traffic management, aircraft operations, and airline operations—the three key elements of the air transportation system—and has been recognized globally for developing, among other things, key analytical foundations for the Continuous Descent Arrival and novel concepts for robust airline scheduling. His research has resulted in significant changes in engineering methods, processes and products—most notably the development of new arrival procedures for four major U.S. airports and one European airport—and changes in airline scheduling practices. He is an associate fellow of the American Institute of Aeronautics and Astronautics (AIAA) and a member of the Airline Group of the International Federation of Operational Research Societies, Institute for Operations Research and the Management Sciences, and Sigma Xi. His many honors include the AIAA/AAAE/ACC Jay Hollingsworth Speas Airport Award (1999), the Federal Aviation Administration (FAA) Excellence in Aviation Award (2003), the NAE Gilbreth Lecturership (2006), and the 37th SAE/AIAA William Littlewood Memorial Lecture Award (2012).

George L. Donohue was granted the status of professor emeritus in 2010 and has been a professor of systems engineering and operations research at George Mason University since 2000. He has an M.S. and a Ph.D. in mechanical and aerospace engineering from Oklahoma State University and a BSME from the University of Houston. From 1994 to 1998, he was the associate administrator for research and acquisitions at the FAA and is the founding director of the Center for Air Transportation Systems Research in the Volgenau School of Engineering. Dr. Donohue is a former vice president of the RAND Corporation and director of PROJECT AIR FORCE (1989-1994). Previously he was the director of DARPA's Aerospace and Strategic Technology Office (1988-1989), a vice president of Dynamics Technology (1979-1984). He served as head of the Advanced Technology Division (1977-1979) and head of the Fluid Mechanics Branch (1973-1976) at the U.S. Naval Ocean System Center in San Diego, California. In the interim, he served as a program manger in DARPA's Tactical Technology Office (1976-1977). He has been awarded an NRC post-doctoral fellowship with the U.S. Navy (1973-1974), the Secretary of Defense Meritorious Civilian Service Medal (1977), the Air Traffic Control Association Clifford Burton Memorial Award (1998), and the Embry Riddle Aeronautical University Pinnacle Award for initiating the Alaska Capstone ADS-B Program (2007). He was named one of *Federal Computer Week's* top 100 Executives in 1997 and was also named one of the top 100 decision makers in Washington, D.C., by the *National Journal* in 1997. Dr. Donohue was chosen to head the U.S. Delegation to the International Civil Aviation OrganizationConference on Air Traffic Management Modernization in 1998. He is a member of Tau Beta Pi, Pi Tau Sigma, Omicron Delta Kappa, and Sigma Xi honorary societies. He is a fellow of AIAA and a licensed private pilot with a single-engine land rating. In addition to more than 60 published unclassified papers, he has been the principle author of two books on air transportation, the most recent is titled *Terminal Chaos: Why U.S. Air Travel is Broken and How to Fix It*. He has testified before Congress on both military and civil aviation issues on numerous occasions. Dr. Donohue is currently acting as an academic advisor to undergraduate and doctoral students. He is a member of the NRC's NASA Aeronautics Research and Technology Roundtable, and a member of the Mechanical and Aerospace Engineering Advisory Board, Oklahoma State University.

R. John Hansman, Jr. (NAE) is the T. Wilson Professor in the Department of Aeronautics and Astronautics at MIT, where he is head of the Humans and Automation Division. He also is director of the International Center for Air Transportation. His current research interests focus on advanced cockpit information systems, including flight management systems, air-ground datalink, electronic charting, advanced alerting systems, and flight crew situational awareness. Dr. Hansman received a Ph.D. from MIT. He holds six U.S. Patents and has authored more than 250 technical publications. He is also an internationally recognized expert in aviation meteorological hazards such as icing and windshear. He is a fellow of AIAA. He received the 1998 Bose Award for Excellence in Teaching, the 1997 FAA Excellence in Aviation Award, the 1994 AIAA Losey Atmospheric Award, the 1990 OSTIV Diploma for Technical Contributions, and the 1986 AIAA Award for Best Paper in Thermophysics. He recently served as co-chair of the MIT Presidential Task Force on Student Life and Learning. Dr. Hansman consults and serves as a member of numerous advisory and technical committees, including the Congressional Aeronautics Advisory Committee, the FAA Research and Development Advisory Committee, the FAA WAAS Independent Review Board, and the NASA Advanced Air Transportation Technologies Executive Steering Committee. He serves on several editorial boards, including *Air Traffic Control Quarterly*. He has more than 5,650 hours of pilot in-command time in airplanes, helicopters, and sailplanes, including meteorological, production, and engineering flight test experience.

Mats P.E. Heimdahl is the director of the University of Minnesota Software Engineering Center where he specializes in software engineering and safety critical systems. Dr. Heimdahl is the recipient of the National Science Foundation's CAREER award and University of Minnesota's McKnight Land-Grant Professorship, the McKnight Presidential Fellow Award, and the Award for Outstanding Contributions to Post-Baccalaureate, Graduate, and Professional Education. His research group, the Critical Systems Research Group, is conducting research in software engineering and is investigating methods and tools to help develop software with predictable behavior free from defects.

Research in this area spans all aspects of system development ranging from concept formation and requirements specification through design and implementation to testing and maintenance. In particular, he is investigating model-based software development for critical systems, focusing on how to use various static verification techniques to assure that software requirements models possess desirable properties, how to correctly generate production code from software requirements models, how to validate models, and how to effectively use the models in the testing process.

John C. Knight is a professor of computer science at the University of Virginia. He holds a B.Sc. (Hons) in mathematics from the Imperial College of Science and Technology (London) and a Ph.D. in computer science from the University of Newcastle upon Tyne. Prior to joining the University of Virginia in 1981, he was with NASA's Langley Research Center. He was the general chair of the 2000 International Symposium on the Foundations of Software Engineering (FSE), and general chair of the 2007 International Conference on Software Engineering (ICSE). He served as editor in chief of *IEEE Transactions on Software Engineering* from January 2002 to December 2005. He was honored by the IEEE Computer Society as the recipient of the 2006 Harlan D. Mills Award "for encouraging software researchers to focus on practical results as well as theory, and for critically analyzing their assumptions and evaluating their research claims." He was honored by the Association for Computing Machinery's (ACM's) Special Interest Group on Software Engineering (SIGSOFT) as the recipient of the 2008 Distinguished Service Award.

Leon J. Osterweil is a professor in the Department of Computer Science and co-director of the Laboratory for Advanced Software Engineering Research at the University of Massachusetts, Amherst. He served as dean of the College of Natural Sciences and Mathematics at the University of Massachusetts, as chair of the Information and Computer Science Department of the University of California, Irvine, and chair of the Computer Science Department at the University of Colorado, Boulder. Dr. Osterweil received the Outstanding Research Award for lifetime achievement in research and the Influential Educator Award, both from ACM SIGSOFT. His paper suggesting the idea of process programming was recognized as the Most Influential Paper of the 9th International Conference on Software Engineering, awarded as a 10-year retrospective. Dr. Osterweil has served on the editorial boards of several journals, including *IEEE Software, IEEE Transactions on Software Engineering,* and *ACM Transactions on Software Engineering and Methodology.* He has served as program chair for many conferences, including the 16th ICSE, and as general chair of the 28th ICSE and the 6th FSE. He was a member of the Software Engineering Institute's Process Program Advisory Board for several years following its inception and has been an advisor or consultant for such organizations as SAIC, MCC, AT&T, Boeing, KLA-Tencor, TRW, and IBM. He has been a keynote speaker at many conferences around the world. Dr. Osterweil is a fellow of the ACM and an ACM Lecturer.

Walker E. Royce is the chief software economist in IBM Software Group. He is a principal consultant and practice leader specializing in measured improvement of systems and software development capability. He is the author of three books: *Eureka! Discover and Enjoy the Hidden Power of the English Language* (2011), *The Economics of Software Development* (2009) and *Software Project Management, A Unified Framework* (1998). From 1994-2009, Mr. Royce was the vice president and general manager of IBM's Rational Services organization and built a worldwide team of 500 technical specialists in software delivery best practices and $100 million in consulting services. Before joining Rational/IBM, he spent 16 years in software project development, software technology development, and software management roles at TRW Electronics and Defense. Mr. Royce was a recipient of TRW's Chairman's Award for Innovation for his contributions in distributed architecture middleware and iterative software processes (1990) and was a TRW technical fellow. He received his B.A. in physics from the University of California and his M.S. in computer engineering from the University of Michigan.

Gavriel Salvendy (NAE) is professor emeritus of industrial engineering at Purdue University and chair professor emeritus and former head (2001-2011) of the Department of Industrial Engineering at Tsinghua University, Beijing, and P.R. of China. He is the author or co-author of more than 550 research publications, including more than 300 journal papers, and he is the author or editor of 42 books. His publications have appeared in seven languages. He is the major professor to 67 former and current Ph.D. students. His main research deals with the human aspects of design, operation, and management of advanced engineering systems. Dr. Salvendy is the founding editor of *International Journal on Human-Computer Interaction* and *Human Factors and Ergonomics in Manufacturing and Service Industries*. He was the founding chair of the International Commission on Human Aspects in Computing, Headquartered in Geneva, Switzerland. In 1990, he became the first member of either the Human Factors and Ergonomics Society or the International Ergonomics Association to be elected to the NAE. He was elected "for fundamental contributions to and professional leadership in human, physical, and cognitive aspects of engineering systems." In 1995, he received an honorary doctorate from the Chinese Academy of Sciences "for great contributions to the development of science and technology and for the great influence upon the development of science and technology in China" and is the fourth person in all fields of science and engineering in the 45 years of the Academy ever to receive this award. In 2006, he received the Friendship Award presented by the People's Republic of China—the highest honor the Chinese government confers on foreign experts. In 2007, he received the John Fritz Medal, which is the engineering profession's highest award, for his "fundamental international and seminal leadership and technical contributions to human engineering and industrial engineering education, theory, and practice." The journals *Ergonomics* (2003), *Computers in Industry* (2010), and *Intelligent Manufacturing* (2011) have published special issues in his honor. He is an honorary fellow and life member of the Ergonomics Society and a fellow of the Human Factors and Ergonomics Society, the Institute of Industrial Engineers, and the American Psychological Association. He has advised organizations in more than 31 countries on the human side of effective design, implementation, and management of advanced technologies in the workplace. He earned his Ph.D. in engineering production at the University of Birmingham, United Kingdom.

Thomas B. Sheridan (NAE) is the Ford Professor of Engineering and Applied Psychology, Emeritus, in the Department of Mechanical Engineering and the Department of Aeronautics and Astronautics at MIT, where he has spent most of his professional career serving as director of the Human-Machine Systems Laboratory. Dr. Sheridan's research interests are in experimentation, mathematical modeling, and design of human-machine systems in air, highway, and rail transportation, space and undersea robotics, process control, arms control, telemedicine, and virtual reality. He has authored and edited numerous books, co-founded the MIT Press journal *Presence: Teleoperators and Virtual Environments* and served on several editorial boards. Dr. Sheridan chaired and continues to serve on the NRC's Committee on Human Systems Integration and has served on numerous government and industrial advisory committees. Since retiring from MIT, he has served the U.S. government as a senior research fellow for the U.S. DOT Volpe Center and as chief system engineer for human factors for the FAA. He is a fellow of the Human Factors and Ergonomics Society and a recipient of their Paul M. Fitts and Arnold Small Awards and the President's Outstanding Career Award, as well as a former president of the society. He was elected to the NAE in 1995. Dr. Sheridan holds a bachelor's degree from Purdue University, an M.S. degree from the University of California, Los Angeles, and a Sc.D. degree from MIT.

Robert F. Sproull (NAE) recently retired as vice president and director of Oracle Labs, an applied research group that originated at Sun Microsystems. Since his undergraduate days, Dr. Sproull has been building hardware and software for computer graphics, clipping hardware, an early device-independent graphics package, page description languages, laser printing software, and window systems. He has also been involved in very-large-scale integration design, especially of asynchronous circuits and systems. Before joining Sun Microsystems in 1990 (acquired by Oracle in 2010), he was a principal with Sutherland, Sproull and Associates, an associate professor at Carnegie Mellon University and a member of Xerox PARC. He is a coauthor with William Newman of the early text *Principles of Interactive Computer Graphics.* He is also an author of the book *Logical Effort,* which deals with designing fast complementary metal-oxide–semiconductor circuits. He is a member of the NAE, a fellow of the American Academy of Arts and Sciences, and has served on the U.S. Air Force Scientific Advisory Board and as a technology partner of Advanced Technology Ventures. He is currently the chair of the NRC's Computer Science and Telecommunications Board, a director of Applied Micro Circuits, Inc., and an adjunct professor of computer science at University of Massachusetts, Amherst. Dr. Sproull received a B.A in physics from Harvard College and an M.S. and Ph.D. in computer science from Stanford University.

James W. Sturges is an independent consultant specializing in program management and systems engineering for very large, complex aerospace and defense systems. He retired in 2009 from Lockheed Martin Corporation where he had been director, engineering processes, and director, mission assurance. Prior to that he was vice president, engineering and total quality, at Loral Air Traffic Control/Lockheed Martin Air Traffic Management, and C3I strategic business area director for Loral Tactical Defense Systems, Arizona. He is an associate fellow and past member of the Standards Executive Council and chair of the Systems Engineering Technical Committee of AIAA and was twice chair of the Corporate Advisory Board for the International Council on Systems Engineering. Early in his career, he was a naval aviator, instrument instructor, and check pilot and was an anti-submarine warfare officer for the U.S. Navy. He has a B.A. from the University of North Carolina and an M.S. and aeronautical engineer degree from the Naval Postgraduate School at Monterey.

Elaine Weyuker (NAE) is an ACM fellow, an IEEE fellow, an AT&T fellow, and NAE member. Dr. Weyuker is currently an independent consultant specializing in software testing, reliability, and metrics, and a visiting scholar at the Center for Discrete Mathematics and Theoretical Computer Science of Rutgers, the State University of New Jersey. She is the author of 170 papers in journals and refereed conference proceedings. Prior to moving to the Research Division of AT&T Labs, she was a professor of the Courant Institute of Mathematical Sciences of New York University, was a faculty member at the City University of New York, a systems' engineer at IBM, and a programmer at Texaco. She served as chair of the ACM Women's Council from 2004 to 2012, is a member of the steering committee of the Coalition to Diversify Computing, a member of the Rutgers University Graduate School Advisory Board, and was a member of the board of directors of the Computing Research Association. Dr. Weyuker is or was a member of the editorial boards of *IEEE Transactions* *on Software Engineering*, *IEEE Transactions on Dependable and Secure Computing*, *IEEE Spectrum*, *Empirical Software Engineering,* and the *Journal of Systems and Software,* and she was a founding editor of *ACM Transactions of Software Engineering and Methodology*. She was the secretary/treasurer of ACM SIGSOFT and was an ACM national lecturer. Dr. Weyuker received a Ph.D. in computer science from Rutgers University, an M.S.E. from the University of Pennsylvania, and a B.A. in mathematics from the State University of New York, Binghamton.

Staff

Virginia Bacon Talati is a program officer for the Computer Science and Telecommunications Board (CSTB) of the NRC of the National Academies. She formerly served as a program associate with the Frontiers of Engineering program at the NAE. Prior to her work at the Academies, she served as a senior project assistant in Education Technology at the National School Boards Association. Ms. Talati has a B.S. in science, technology, and culture from the Georgia Institute of Technology and an M.P.P. from George Mason University, with a focus in science and technology policy.

Dwayne A. Day is a senior program officer for the NRC's Aeronautics and Space Engineering Board, has a Ph.D. in political science from the George Washington University. Dr. Day joined the NRC as a program officer for the Space Studies Board. Before this, he served as an investigator for the Columbia Accident Investigation Board, was on the staff of the Congressional Budget Office, and also worked for the Space Policy Institute at the George Washington University. He has held Guggenheim and Verville fellowships and was an associate editor of the German spaceflight magazine *Raumfahrt Concrete*, in addition to writing for such publications as *Novosti Kosmonavtiki* (Russia), *Spaceflight*, and *Space Chronicle* (United Kingdom). He has served as study director for several NRC reports, including *Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies* (2010), *Preparing for the High Frontier: The Role and Training of NASA Astronauts in the Post-Space Shuttle Era* (2011), *Continuing Kepler's Quest: Assessing Air Force Space Command's Astrodynamics Standards* (2012), *Recapturing NASA's Aeronautics Flight Research Capabilities* (2012), and *NASA's Strategic Direction and the Need for a National Consensus* (2012).

Jon Eisenberg is director of CSTB. He has also been study director for a diverse body of work, including a series of studies exploring Internet and broadband policy and networking and communications technologies. In 1995-1997 he was a AAAS Science, Engineering, and Diplomacy Fellow at the U.S. Agency for International Development, where he worked on technology transfer and information and telecommunications policy issues. Dr. Eisenberg received his Ph.D. in physics from the University of Washington and B.S. in physics with honors from the University of Massachusetts, Amherst.

Lynette I. Millett is associate director of CSTB. Ms. Millett has extensive experience as program manager, team leader, analyst, researcher, and writer with specific expertise in information technology policy. She is skilled in working with diverse and expert work groups and since 2000 has been developing, directing, and overseeing NRC studies and teams of national experts examining public policy issues related broadly to information technology, computing, software, and communications. Her portfolio at the NRC includes a suite of studies on computing research, the most recent being 2012's *Computing Research for Sustainability*; several examinations of government information technology and infrastructure needs, such as 2011's *Strategies and Priorities for Information Technology at the Centers for Medicare and Medicaid Services*; and in-depth examinations of privacy, identity and cybersecurity, including 2010's *Biometric Recognition: Challenges and Opportunities*. She has an M.Sc. in computer science from Cornell University, where her work was supported by graduate fellowships from the National Science Foundation and the Intel Corporation; and a B.A. in mathematics and computer science with honors from Colby College.

Eric Whitaker is a senior program assistant at CSTB. Prior to joining CSTB, he was a realtor with Long and Foster Real Estate, Inc., in the Washington D.C. metropolitan area. Before that, he spent several years with the Public Broadcasting Service in Alexandria, Virginia, as an associate in the Corporate Support Department. He has a B.A. in communication and theater arts from Hampton University

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Briefers to the Study Committee

MARCH 19, 2013

Steven Bradford, Federal Aviation Administration
Gerald Dillingham, Government Accountability Office
Michael Hritz, Federal Aviation Administration
Margaret Jenny, RTCA
Heather Krause, Government Accountability Office
Molly Laster, Government Accountability Office
Natesh Menikoth, Federal Aviation Administration
Michele Merkle, Federal Aviation Administration
Madhav Panwar, Government Accountability Office
Pamela Whitley, Federal Aviation Administration

MAY 8-9, 2013

Sherry Borener, Federal Aviation Administration
Edgar Calderon, Federal Aviation Administration
Vincent Capezzuto, Federal Aviation Administration
Rachel Carr, House Aviation Subcommittee, Minority Staff
Sean Cassidy, Air Line Pilot Association
Paul Fountain, Federal Aviation Administration
Giles Giovinazzi, House Aviation Subcommittee, Minority Staff
Tom Kramer, Aircraft Owners and Pilots Association
Paul Krois, Federal Aviation Administration
Andrew Lacher, MITRE
Natesh Manikoth, Federal Aviation Administration
Mike Matousek, House Aviation Subcommittee, Majority Staff

Jay Merkle, Federal Aviation Administration
Robert Nichols, Federal Aviation Administration
Simone Perez, House Aviation Subcommittee, Majority Staff
Andrew Rademaker, House Aviation Subcommittee, Majority Staff
Mike Riso, Professional Aviation Safety Specialists
Rich Swayze, Senate Commerce Committee, Majority Staff
Joseph Teixeira, Federal Aviation Administration
Dan Watts, Federal Aviation Administration
Holly Woodruff Lyons, House Aviation Subcommittee, Majority Staff
Dale Wright, National Air Traffic Controllers Association

AUGUST 6-7, 2013

Sherry Borener, Federal Aviation Administration
Steve Bradford, Federal Aviation Administration
Glen Dyer, Excelis
Fran Hill, Lockheed Martin
Mike Hritz, Federal Aviation Administration
Charles Keegan, Raytheon
Paul Krois, Federal Aviation Administration
Natesh Manikoth, Federal Aviation Administration
Roberto Ortiz, Federal Aviation Administration
Ron Stroup, Federal Aviation Administration
Jesse Wijntjes, Federal Aviation Administration