National Aeronautics and Space Administration

NASA AERONAUTICS

Strategic Implementation Plan

2019 Update

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The view from inside a NASA simulation lab used to test Urban Air Mobility technologies such as electric-powered vertical-takeoff-and-landing vehicle designs or airspace operations in and around cities.
Image credit: NASA

A Letter to the Reader

Five years ago, NASA's Aeronautics Research Mission Directorate published the first version of this Strategic Implementation Plan. Its purpose was – and still is – to describe how we intend to develop and advance technologies that meet the needs of the aviation community. Since then, we've seen emerging trends as new players enter the market and air travel seeks to reinvent itself in ways unimaginable even just half a decade ago. To keep pace and maintain U.S. leadership in aviation, our research must evolve as well.

With this updated plan we've reorganized our research portfolio – as described in the six strategic research thrusts – to reflect the ongoing input we've received from our industry partners and other stakeholders. Generally speaking, these modifications are designed to enable new, diverse aviation business models; recognize the complexity of integrating alternative propulsion systems with innovative subsonic aircraft designs; and focus attention on vertical takeoff and landing aircraft and their use of electric propulsion.

At the same time, the basic tenets of our strategic plan haven't changed: First, global demand for air travel will continue to grow and evolve. Second, technologies not traditionally associated with aviation are converging to create new possibilities in flight. Finally, the need for aviation to be sustainable and more environmentally friendly is as urgent as ever.

With this plan we hope to enable commercial supersonic flight over land, increased use of electric propulsion for large aircraft, subsonic aircraft designs not bound by traditional tube and wing configurations, and hundreds of vertical takeoff and landing vehicles safely flying people and packages within dense urban environments across the country – all of this handled by advanced airspace management systems developed by NASA's aeronautical innovators. The ultimate goal: Future air travel providing unprecedented mobility that will be safer, cleaner, and more efficient as it gets you to where you want to go faster than ever before.

Working with our many partners in the United States and throughout the world, we are committed to seeing this transformation take place. We remain open to new ideas, will watch for new trends to develop, and stay receptive to industry's needs. When the time is right, we will offer a new version of this plan based on that new knowledge, our accomplishments, lessons learned, and your input as well.

Mr. Robert Pearce
Associate Administrator
NASA Aeronautics Research Mission Directorate

Executive Summary

This Strategic Implementation Plan provides the NASA Aeronautics Research Mission Directorate (ARMD) vision for the next 25 years and beyond. It encompasses investigating a broad range of technologies to meet future needs of the aviation community, the Nation, and the world for safe, efficient, flexible, and environmentally sustainable air transportation. It is updated biennially. In this update, the most significant changes are refinement of ARMD's strategy and redefinition of two of the six Strategic Thrusts to more closely align the refined strategy with those Strategic Thrusts.

Envisioning the long-term plan for aeronautics research provides the basis for new concepts leading to industry innovation and societal benefits. The future holds new challenges for the aviation community, including the need to achieve continued growth that meets increasing global demand, safely integrate unmanned aircraft systems and other innovative vehicle concepts with myriad of applications, and proactively adapt to sometimes rapidly changing conditions. An overall key objective is to solve those challenges in ways that minimize adverse impacts on the environment.

An analysis of global trends in 2014 led ARMD in 2015 to identify three major trends, known in this plan as Mega-Drivers, which will shape NASA's aeronautical research plans during the coming years:

- Mega-Driver 1—Global Growth in Demand for High-Speed Mobility: Reflects rapid growth in traditional measures of global demand for mobility as well as new modes of transportation.
- Mega-Driver 2—Affordability, Sustainability, and Energy Use: Presents severe challenges in maintaining affordability while achieving sustainability.
- Mega-Driver 3—Technology Convergence: Points to convergence occurring in industry sectors such as materials, manufacturing, energy, and information and communication technologies that will transform aeronautical capabilities and air transportation options.

NASA's ARMD organizes its research portfolio around six Strategic Thrusts, which represent ARMD's prioritization of aeronautics objectives in response to the Mega-Drivers and feedback from the aviation community. The six Strategic Thrusts, and the future state they would yield when the aviation community applies our results into their operations, include:

1. Safe, Efficient Growth in Global Operations
    - Achieve safe, scalable, routine high tempo airspace access for all users.
2. Innovation in Commercial Supersonic Aircraft
    - Achieve practical, affordable commercial supersonic air transport.
3. Ultra-Efficient Subsonic Transports
    - Realize revolutionary improvements in economics and environmental performance for subsonic transports with opportunities to transition to alternative propulsion and energy.

4. Safe, Quiet, and Affordable Vertical Lift Air Vehicles
    - Realize extensive use of vertical lift vehicles for transportation and services including new missions and markets.
5. In-Time System-Wide Safety Assurance
    - Predict, detect and mitigate emerging safety risks throughout aviation systems and operations.
6. Assured Autonomy for Aviation Transformation
    - Safely implement autonomy in aviation applications.

Taken together, the six Strategic Thrusts represent a future of aviation that is safer, cleaner, more efficient, and provides more versatile mobility than today.

ARMD focuses on high-risk, high-payoff research investments that will enable the transformation of aviation to serve future needs, produce demonstrable benefits, and leverage technology advances outside of, as well as within, traditional aviation disciplines. Major technology emphases include electrified aircraft propulsion and the use of alternative energy; low-sonic-boom supersonic flight; fundamental research to enable routine, reusable airbreathing hypersonic flight; automation and autonomy; sustainable alternative jet fuels; and fostering new aviation applications in Urban Air Mobility (UAM). Collectively, these efforts, other technologies, and a focus on technology convergence will develop transformative solutions towards the ultimate goal of a safe, efficient, adaptive, scalable, and environmentally sustainable global aviation system.

Introduction

In 2015, the NASA Aeronautics Research Mission Directorate (ARMD) published the initial edition of this Strategic Implementation Plan (SIP), setting forth a vision for aeronautical research aimed at the next 25 years and beyond based on NASA's synthesis of the aviation community's view of the future of civil aviation.

This update reflects work that has been implemented to achieve the ARMD vision. In this update, Strategic Thrust definitions align more closely with a refined ARMD strategy. The most notable change can be found in Strategic Thrusts 3 and 4. In the 2017 edition of the SIP, Strategic Thrust 3 was divided into two parts: 3a was focused on subsonic transport and 3b on vertical lift. Strategic Thrust 4 involved alternative propulsion and energy. Now, Strategic Thrust 3 is dedicated to subsonic transports and Strategic Thrust 4 is all about vertical-lift-capable air vehicles. The research emphasis on alternative propulsion and energy is now incorporated into both Strategic Thrusts 3 and 4. Other Strategic Thrusts included smaller refinements.

Overview

Aviation is a critically important industry for the United States. It integrates the latest knowledge in advanced technologies developed over decades of concerted research. The mission of ARMD is to serve the future needs of civil aviation by conducting research into, and developing solutions for, the problems of flight. While the specific research problems have changed considerably since NASA's mission was written into the National Aeronautics and Space Act of 1958, aeronautical research remains as important now as it was in the early days of aviation.

The Domestic and Global Roles of Air Transportation

As a primary mechanism for physically connecting countries across the world, air transportation is an integral part of today's U.S. and global economies. Aviation enables U.S. enterprises to operate on a global scale, providing safe, high-speed transport of people and goods. It accounts for more than $1.6 trillion of U.S. economic activity each year and generates a positive trade balance—$82.5 billion in 2015. The aviation industry also supports nearly 11 million direct and indirect jobs, including more than one million high-quality manufacturing jobs.

Aviation benefits every individual. Nearly every product created and purchased today has been touched by aviation in some way. More than 21 million tons of freight were moved worldwide by U.S. air carriers in 2018, as well as nearly 889 million passengers. Domestic and foreign air travelers spent more than $771 billion in the U.S. economy on hotels, rental cars, and entertainment in 2014. In short, the U.S. aviation industry is critical to both economic and societal well-being.

Looking forward, global economic growth and urbanization are driving rapid increases in demand for aviation services, especially in the Asia-Pacific region and other high-growth areas. The International Air Transport Association (IATA) forecasts nearly a billion additional air passengers during the next six years, and demand for new aircraft and equipment is growing to keep pace. This expectation represents a substantial opportunity for U.S. economic growth and competitiveness, as well as providing a variety of benefits on a global scale.

The Role of Research in the U.S. Aviation Industry

Today, ARMD is making significant contributions to fundamental understanding in areas critical to the future of aviation, including technologies that will facilitate implementation of system-wide safety assurance, alternative sustainable jet fuels, vehicle efficiency improvements, and reduction of noise and harmful emissions such as nitrogen oxides (NOx). The future promises new roles for aviation.

Long-term aeronautics research provides the basis for new concepts that ultimately lead to industry innovation and value to society. For example, the potential for Unmanned Aircraft Systems (UAS) to serve myriad needs, from battling wildfires to retail distribution to delivering urgently needed medical supplies at remote locations, is becoming reality. ARMD focuses on research and technology development outside the economic and risk criteria that govern commercial investments, with emphasis on technologies to achieve public benefits such as safety assurance and environmental protection. NASA's many partners throughout the aviation community view ARMD as the stewards of the Nation's aeronautics research enterprise.

NASA Aeronautics Research Yesterday and Today

The year 2015 marked the 100th anniversary of the founding of NASA's predecessor, the National Advisory Committee for Aeronautics (NACA). Since that seminal event, aeronautics research has expanded from the fundamentals of flight to hypersonic air vehicles, from measuring the static performance of airfoils to understanding the behavior of complex human-machine systems, and from wood-and-canvas structures to adaptive shape-changing materials.

The history of NASA research begins with the establishment of the NACA on March 3, 1915, by a rider to the Naval Appropriations Act. The legislation chartered the new organization to "supervise and direct the scientific study of the problems of flight, with a view to their practical solution." Throughout the last century, research has involved a combination of empirical knowledge gained from ground and flight testing, development of theory and analytic methods, and confirmation by physical demonstration. This research has encompassed an ever-broadening array of technologies, enabling increased performance, enhanced safety, greater efficiency, and reduction of adverse environmental impact.

Initial NACA research focused on the physics of flight, with work involving wind-tunnel tests and flight tests of both models and full-scale aircraft. These tests and the development of theory addressing the aerodynamics of aircraft resulted in greatly increased aircraft speed, payload, and range. During the 1930s and 1940s, the NACA developed airfoil shapes for wings and propellers that found their way into the designs of many U.S. aircraft of the time, including several important World War II-era aircraft such as the P-51 Mustang.

This period also saw the expansion of NACA research into flying qualities to examine aircraft behavior as a human-machine system. In 1941, a pioneering NACA report, "Requirements for Satisfactory Flying Qualities of an Airplane," by Robert Gilruth, who went on to lead NASA's early efforts in space, defined the first set of requirements for the handling characteristics of an aircraft; this work grew into the Cooper-Harper handling-qualities scale for aircraft, which is still in use today.

After World War II, the NACA began to work on the goal of supersonic flight, working closely with the Air Force and Bell Aircraft to design the first supersonic airplane – the X-1 experimental aircraft. This collaboration marked the NACA's first effort in dealing with the initial design, construction, and flight testing of a research airplane. At the same time, refinement of theory led to further aerodynamic improvements, such as development of the swept-wing concept by Robert T. Jones in 1945 and invention of the area rule concept by Richard Whitcomb in 1951. Development of the axial flow compressor in the 1950s, which became the basis for modern turbojet and turbofan engines, reflected further expansion of the NACA's research horizons.

Following the 1958 Space Act, which established NASA as the successor to the NACA, aeronautics research expanded to address flight beyond Earth's atmosphere. The X-15 research aircraft set an altitude record of 354,000 feet in 1963 and a record speed of Mach 6.7 in 1967. Research topics supporting this and other efforts included compressible flow aerodynamics, high-temperature materials, aircraft structures, and reaction controls. Notable achievements include development of the widely used NASA Structural Analysis tools during the 1960s, and initial development and application of computational fluid dynamics (CFD) during the 1970s.

During the 1970s and 1980s, research in supercritical airfoils, winglets, riblets, laminar flow control, and propulsion enabled further advances in performance. These advances were embodied in a vigorous flight demonstration program that included the Quiet Short-haul Research Aircraft, XV-15 tiltrotor research aircraft, and X-29 forward-swept-wing flight research aircraft. In this period, the scope of aeronautics research grew to include a number of important safety and performance enhancements such as digital fly-by-wire controls, “glass cockpits,” airborne wind-shear detection, microwave landing systems, and head-up displays.

NASA’s research contributed significantly to a transformation of commercial air transportation following the introduction of jet airliners beginning in the 1960s. Aircraft cruise speed increased 70 percent between 1960 and 1990, and energy efficiency doubled in terms of passenger miles per unit of fuel consumed. In the United States, during the same period, accidents per departure dropped by 90 percent and annual passenger miles flown increased tenfold.

Accomplishments since 1990 demonstrate not only further expansion of ARMD’s research, but also a shift to treating aviation as a complex system of systems that integrates a wide variety of technologies to provide safe, efficient, and environmentally sustainable air transportation. These accomplishments include the following, among many others:

- Development of FutureFlight Central full-scale airport operations simulator, simulations of the National Airspace System (NAS), and development of air traffic control and air traffic management tools.
- Exploration of air vehicle and propulsion concepts for energy efficient aircraft, including flight demonstrations of the Blended Wing Body (BWB) X-48B testbed and initiation of research into electric propulsion technology.
- Integration of human factors, guidance, displays, and intelligent flight controls into safety research.
- Further research in aircraft structures, composites, and high-temperature materials.
- Flight demonstration of techniques to shape sonic boom signatures to reduce sonic boom intensity.
- Further development of physics-based and multidisciplinary tools for aircraft design and analysis.

These and other efforts have made significant contributions to the advancement of aviation in the United States and around the world. U.S. passenger miles continued to grow by more than 50 percent since 1990, while flying has become safer and aircraft have become quieter and more energy efficient. Thanks in large measure to technology features attributable to ARMD research, accident rates worldwide have continued to decline while commercial aircraft now entering service are 20 percent more energy efficient and have a noise footprint 60 percent smaller than the previous generation of aircraft.

NASA consistently undertakes research and development efforts that are outside the scale, risk, and payback criteria that govern commercial investments, with the purpose of proactively transitioning the research findings to the aviation community. NASA aeronautics research has delivered results producing substantial benefits for air transportation in the established ARMD focus areas of fundamental aeronautics, vehicle systems and configurations, air traffic management, and aviation safety. These results have transformed aviation to the benefit of the national economy, national defense, the traveling public, and the transportation industry, as well as fostering efforts to minimize environmental impacts. As an example, Figure 1 illustrates major features of modern commercial aviation that have been made possible by NASA aeronautical research.

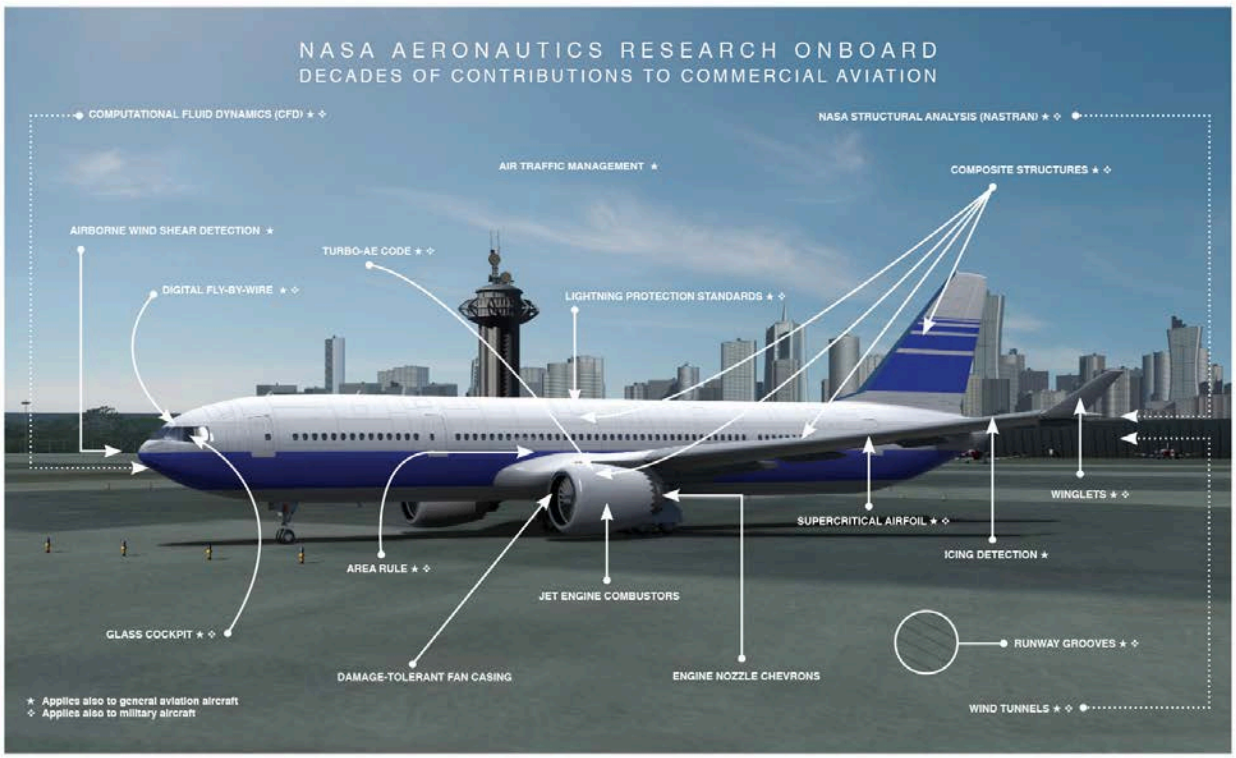

Figure 1. Applications of NASA research results in a modern commercial aircraft

This brief historical overview illustrates how ARMD research has produced large benefits by enabling transformative and far-reaching advances in aeronautics. Development of a sound knowledge base and advances in analysis and simulation have enabled NASA to expand its aeronautical research perspectives within necessarily constrained resources. The history of NASA aeronautics also underscores the continuing need to expand and adjust the scope of ARMD's research to address the public good, meet emerging needs of the aviation community, and exploit new technologies not previously associated with aviation. ARMD's strategy continues to focus on making efficient investments to enable the transformation of aviation to serve future needs, enable demonstrable benefits, and leverage technology advances both within and outside of traditional aviation disciplines.

NASA Aeronautics Vision for the 21st Century

U.S. leadership for a new era of flight

6 Strategic Thrusts

- Safe, Efficient Growth in Global Operations
- Safe, Quiet, and Affordable Vertical Lift Air Vehicles
- Innovation in Commercial Supersonic Aircraft
- In-Time System-Wide Safety Assurance
- Ultra-Efficient Subsonic Transports
- Assured Autonomy for Aviation Transformation

Figure 2. NASA Aeronautics Vision

NASA Aeronautics Strategy

While past NASA aeronautics research has provided the U.S. aviation industry with transformative technologies, recent global trends call for a shift in focus beyond traditional research areas. In defining NASA's approach to meeting future aviation needs, the *2018 NASA Strategic Plan* provides a bold strategic objective for ARMD (strategic objective 3.1): "Transform Aviation Through Revolutionary Technology Research, Development, and Transfer." ARMD is responding with an equally bold vision embodied in this SIP.

Figure 2 represents our vision for the 21st century: our high-risk, high-payoff research enables safer, cleaner, and more efficient air travel with unprecedented mobility.

ARMD's Strategic Planning Process

The SIP provides a basis to guide research across a wide range of technology initiatives, helping to sustain the Nation's aeronautical leadership and supporting U.S. industry's ability to meet the needs of global aviation markets.

ARMD's vision, therefore, addresses the wider roles of aviation and aviation research organizations on a global scale. In evaluating those roles, ARMD recognizes that some research needs do not require NASA's expertise, and other research needs that are within ARMD's range of expertise are more properly served by other research organizations. ARMD's research strategy aims to operate productively within that collaborative global research environment, building on current leadership while enabling revolutionary technological advances.

Table 1. Hierarchy of Elements that Guides ARMD's Aeronautics Research Planning

NASA's AERONAUTICAL RESEARCH ROLE

Address Research Needs within Three Overarching Trends Affecting Future Aviation

- Mega-Driver 1: Global Growth in Demand for High-Speed Mobility
- Mega-Driver 2: Affordability, Sustainability, and Energy Use
- Mega-Driver 3: Technology Convergence

ARMD's AERONAUTICAL RESEARCH TAXONOMY

STRATEGIC THRUSTS

ARMD Research is Organized into Six Strategic Thrusts

- Strategic Thrust 1: Safe, Efficient Growth in Global Operations
- Strategic Thrust 2: Innovation in Commercial Supersonic Aircraft
- Strategic Thrust 3: Ultra-Efficient Subsonic Transports
- Strategic Thrust 4: Safe, Quiet, and Affordable Vertical Lift Air Vehicles
- Strategic Thrust 5: In-Time System-Wide Safety Assurance
- Strategic Thrust 6: Assured Autonomy for Aviation Transformation

OUTCOMES

Outcomes are Defined in Terms of the Envisioned Future State

RESEARCH THEMES

Long-Term Research Areas that will Enable the Outcomes

TECHNICAL CHALLENGES

There are Specific Measurable Research Activities

The Mega-Drivers are three overarching global trends that shape, in large part, requirements of aeronautical research during the coming years. ARMD funds research that is both within the capabilities of NASA aeronautics expertise and resources, and beyond the capability of industry to invest (i.e., high-risk, high-payoff research).

The Strategic Thrusts represent ARMD's prioritization of aeronautics objectives in response to the Mega-Drivers and input from the aviation community. They are mutually supportive and evolve in response to changes in Mega-Drivers and community needs. Taken together, the Strategic Thrusts provide a glimpse into possible futures for aviation. In this update, the Strategic Thrusts represent a future of aviation that is safer, cleaner, and more efficient, while providing unprecedented advances in mobility. This possible future may be realized when NASA aeronautics research enables new technical capabilities, and the aviation community implements them into operational capabilities.

Outcomes associated with each Strategic Thrust signify the in-service capabilities and benefits envisioned through the eventual implementation of NASA's research in operations. They are measurable overarching aviation goals that are more than NASA alone can achieve. They are achieved through joint efforts across the aviation community. NASA aeronautics research is meant to enable each Outcome, but others – such as the Federal Aviation Administration (FAA), Department of Defense (DoD), industry, academia — have key roles in achieving the Outcome and realizing the community's view. In combination, the Outcomes from all six Strategic Thrusts articulate operational possibilities that span the interests and contributions of the entire aviation community.

The Outcomes are divided across the future into near-, mid-, and far-term time periods during which research results are transitioned from concept to practice:

- Near-term (2015-2025) Outcomes generally leverage partnerships to demonstrate feasibility of potential applications. They enjoy a greater degree of confidence within the aviation community and generally involve focused technology partnerships to enable the Outcomes.
- Mid-term (2025-2035) Outcomes are often in a transitional stage, aimed at a combination of new concepts and applications within the current system. They reflect applications of emerging technologies, initially within the paradigm of the existing aviation system, but often leading to transformative innovations responsive to future needs.
- Far-term (beyond 2035) Outcomes are more exploratory in nature, focusing on concept exploration and technology research. For these Outcomes, ARMD takes a greater role in performing and sponsoring concept exploration and fundamental research.

Research Themes represent ARMD's long-term research focus in particular technology areas required by the Outcome.

The Technical Challenges serve as the basis for planning research activities and measuring performance. In some cases, the output (technical solutions) from solving the Technical Challenges can be applicable to multiple Strategic Thrusts, which increases the effectiveness of our investment response.

Global Trends and Mega-Drivers

The three Mega-Drivers that emerged from the trend analysis (growth in air transportation demand, climate change, sustainable energy use, and technology convergence) structure ARMD's strategic response and shape major aeronautics research. ARMD has established six Strategic Thrusts based on an analysis[1] of how these global trends will potentially determine the future of aviation.

Mega-Driver 1: Global Growth in Demand for High-Speed Mobility

A century-long trend of migration into cities across the globe is now generating urban growth at a level equivalent to seven Chicago-sized cities per year, and two-thirds of the world's population will live in urban centers by 2050.[1] At the same time, there has been a trend toward higher-speed transport. In 1990, buses, automobiles, and railroads accounted for 91 percent of the world's traffic volume, leaving only 9 percent to the high-speed transport modes of air and high-speed rail. But growth in urbanization and wealth by 2050 could increase the demand for high-speed transport to more than 40 percent of the world's traffic volume.[2]

For example, the economies of both China and India have been growing more than twice as fast in a 20-year span as did the U.S. economy during its most economically expansive 50-year period (1900- 1950). As a result, these countries are expected to account for half of the world's middle-class population by 2050.[3] Since the urban middle class constitutes a major air transportation market, growth in this population segment will dramatically increase the need for greater, faster, and more efficient air mobility.

The IATA projects that the number of air passengers worldwide will double by 2034.[4] To support that growth in demand, high-technology aircraft, powered by advanced renewable energy sources, will serve intercontinental traffic through a dozen global gateways, connecting at 50 to 75 regional U.S. hubs with air service to local airports.

At the same time, surface traffic congestion in major urban centers has reached intolerable levels, leading to lengthy delays and a growing need for alternative transportation for people and time-critical goods within and between metropolitan areas. Responding to this surge in demand, the rise of UAM has seen cities around the world exploring the use of new air vehicles, such as electric Vertical Takeoff and Landing (eVTOL) air taxis, and small drones to deliver food and consumer goods. These vehicles also

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1 United Nations Department of Economic and Social Affairs. World Urbanization Prospects: The 2014 Revision.

2 Andreas Schafer et al. *Transportation in a Climate Constrained World*. MIT Press, 2009.

3 Karen Ward and Frederic Neumann. "Consumer in 2050: The rise of the EM [Emerging Market] middle class." HSBC Global Research, October 2012.

4 International Air Transport Association, "Total Passengers Set to Double to 7 Billion by 2034," Press Release No. 55. November 26, 2015.

will extend the reach of aviation to rural or otherwise hard to reach localities. This increasing diversity and density of operations will influence the course of aviation during the decades to come.

This expanded and increasingly distributed demand for air travel will require advanced technologies and operational concepts as well as increasing attention to performance requirements and interoperability to ensure safety. Rising demand also will have to be satisfied with efficient resource use to satisfy cost constraints and limit adverse environmental impacts.

Mega-Driver 2: Affordability, Sustainability, and Energy Use
Fuel is currently a significant driver of the cost of air transportation. According to IATA, fuel is the only major element of air transportation cost that has grown significantly over time. For example, prices of jet fuel rose by about a factor of six between the 1990s and 2012. Fuel made up only 10 percent of total airline costs in 1995, but it increased to almost 30 percent by 2011. Despite recent volatility in fuel prices, evidenced by a more than 50 percent reduction in the cost of jet fuel since the 2012-2013 peak, energy costs are projected to continue to rise over the long term, affecting affordability of air transportation and sustainability of current models of operation.

In terms of environmental impact, air transportation accounts for about two percent of the world's carbon dioxide (CO_2) emissions.[5] While this is a relatively small share, continued growth in air transportation could lead to larger effects. The industry has ambitious goals for reducing the generation of CO_2 to enable sustainable growth and address climate change. These goals are to improve system-level fuel efficiency by 1.5 percent per year through 2020; achieve carbon-neutral growth beyond 2020; and, by 2050, reduce CO_2 emissions to 50 percent of 2005 levels.[6] Achieving these goals will require affordable renewable fuels and new low-carbon propulsion system concepts, as well as energy-efficient aircraft and operations.

Mega-Driver 3: Technology Convergence
Technology convergence, widely defined as the combination of two or more different technologies in a single device or product, has historically played a major role in technological innovation. This seemingly simple definition, however, masks the fact that systems embodying convergent technologies have often led to radical changes in affected industries and supply chains, marketing and distribution, infrastructure, and uses of the system, along with wide economic and social ramifications.

Evolution of the internet and its uses provides an obvious, but far from unique, example. Past examples in aviation include convergence of analytical theory with computational capabilities and new materials

5 Data from United Nations Intergovernmental Panel on Climate Change, quoted by Air Transport Action Group http://aviationbenefits.org/environmental-efficiency/aviation-and-climate-change/. Accessed December 11, 2014.

6 International Air Transport Assoication. IATA Resolution on the "Implementation of the Aviation Carbon-Neutral Growth (CNG2020) Strategy." June 2013.

that have made possible today's air vehicles. Another example is the various technologies that have converged with the Global Positioning System and its applications for navigation and air traffic control.

A current example is UAS, which have brought in new producers, users, technologies, and missions, and raised new issues related to privacy, regulation, and airspace management. Today, rapid advances in energy, materials, manufacturing, and cyber-physical systems across a broad range of industries represent major examples of technology convergence that promise to transform aviation.

Sustainable alternative jet fuels and other renewable sources of energy for air vehicles will converge with technologies for energy storage, on-board electric power generation and distribution, and vehicle propulsion, as well as new ground infrastructure for energy distribution. Additionally, electric power distribution may allow efficient use of distributed propulsion, which could potentially change the way aircraft are designed and controlled, leading to new vehicle configurations with enhanced performance, improved energy efficiency, and reduced emissions.

New materials, such as composites with tailored strength properties and ceramics for high-temperature applications, will continue to replace customary metal structures and components. With these materials come new producers and new means of manufacture. Convergence with advanced computational methods, robotics, and vehicle design concepts will lead to widespread use of 3-D printing, automated assembly, monolithic structures, shape-changing and multifunctional materials, and other new capabilities to reduce weight, lower manufacturing cost, enhance production flexibility, and improve vehicle performance.

Cyber-physical systems convergence is transforming operational concepts as increasingly intelligent systems enable highly networked systems-of-systems, remote operations, and on-demand systems and services. These advances have promoted innovations such as distributed self-services, exemplified by check-in kiosks at airports, on-demand shared automobiles, and internet streaming. Machine autonomy and robotics could lead to autonomous on-demand aviation that would radically transform personal mobility and aviation services. The emergence of UAM is an early example of the transformation that could unfold in coming years.

Thus, technology convergence is expected to amplify the benefits of new concepts and technologies in existing as well as emerging aviation markets. However, technology convergence brings new risks and hazards that must be understood and mitigated, such as the creation of new potential safety issues. Technology convergence may also affect the future demand for aviation by enabling innovations such as high-fidelity, multisensory telepresence that could reduce the demand for air travel by partially substituting for physical transportation. In contrast, expanded telepresence, by increasing interactions among people separated by distance, might increase demand for aviation in ways that are hard to predict today – the historical impact of telephones and internet, increasing demand for travel by enabling connectivity to more people and over longer distances, are good examples of such an effect.

ARMD seeks to leverage rapid advancements in these technologies and standards across many sectors, as well as emerging operational concepts enabled by the convergence of these technologies, to develop revolutionary solutions for future aviation challenges.

Community Dialogue

In addition to strategic analyses and inputs from subject matter experts and senior stakeholders, ARMD's planning incorporates mechanisms for dialogue with the aviation community on a wide range of topics. To help identify important research areas and challenges of the future, ARMD has frequently engaged the aviation community to understand what its stakeholders believe are priority research areas. Regular discussions have engaged domestic and international partners and experts from industry, academia, and government. Interactions have included regular reviews of ongoing research by federal advisory committees and dialogue sessions with the National Research Council's Aeronautics Research and Technology Roundtable.

The aviation community's highest priorities for research are in safety, highly efficient aircraft, the evolution of the Next Generation Air Transportation System (NextGen), automation and autonomy, and the rapidly expanding UAM market. Recent community focus on UAM vehicles, airspace management of these vehicles, and infrastructure challenges has increased as the UAM market has shown the potential for profound changes to the aviation system. Facilitating advances in these areas will require the development of tools for more innovative virtual testing, and verification and validation of complex systems. Additionally, flight research continues to be a critical element in the maturation of technology, and it can help to establish strong public-private partnerships. Serving these expressed community needs forms an integral part of ARMD's research plans.

ARMD has engaged with the National Academies of Science, Engineering, and Medicine to perform detailed studies of national focus on the ARMD Strategic Thrusts and related topics. These studies provide in-depth information that help support ARMD detailed research planning and partnership development (links to completed studies are available at https://www.nasa.gov/aeroresearch/strategy). Additionally, ARMD recognizes that its research will affect, and be affected by, the work of a wide array of U.S. and international researchers. For that reason, ARMD places major emphasis on maintaining communications and collaborative relationships with the full range of researchers working in government agencies, industry, and academia.

Strategic Partnerships

Partnerships with other government, industry, academia, and foreign aeronautics agencies leverage ARMD's investments through joint efforts that complement NASA's internal capabilities, provide access to a wide range of technologies beyond the traditional aeronautics portfolio, and facilitate technology transfer to more mature states of development and eventual implementation. Integrated technology demonstrations typically include selected industry or government partners who contribute their own funding or knowledge. These partnerships also give ARMD deep insight into the goals and needs of the aviation community, as well as providing user feedback and facilitating industry engagement early in the technology development cycle.

ARMD collaborates closely with the FAA to support that agency's decision making and to improve the performance of the National Airspace System (NAS), as well as with the DoD and other government agencies to leverage technology investments. Industry partnerships allow rapid insertion of NASA aeronautics research results into air vehicles and subsystems, and NAS operations, tools, and processes. Partnerships with domestic academic institutions support cutting-edge research on emerging aviation technologies and on the education of new researchers in various fields of study. To help address the global nature of air transportation, ARMD also forges partnerships with a wide range of international government entities, such as the International Forum for Aviation Research (IFAR).

To broaden its perspective and impact, ARMD complements its formal partnerships by participating in various public forums, including conferences, industry days, working groups, and technical interchange meetings. These activities help to identify needs and areas of potential technical interest that could produce future partnership opportunities.

Representatives from industry, academia, and government engaged in discussions about NASA's plans to advance the development of a safe UAM ecosystem during a meeting convened by NASA. Image credit: NASA/Andrew Carlsen

Strategic Response

ARMD has formulated six Strategic Thrusts to organize and prioritize our response to the Mega-Drivers. They are summarized below. Detailed descriptions are presented later in this document.

Strategic Thrust 1: Safe, Efficient Growth in Global Operations

Within the United States, NextGen is the focus for a modernized air transportation system that will achieve much greater capacity and operational efficiency while maintaining or improving safety and other performance measures. ARMD will contribute specific research and technology to enable the continued development of NextGen and beyond to achieve safe, scalable, routine, high-tempo airspace access for all users. ARMD also will work with the emerging UAM ecosystem, developing concepts to enable a safe, scalable system for the growth of this new transportation sector. Projected growth in air travel will require a sustained focus on reducing risks to maintain acceptable levels of safety; to that end, ARMD will work with the FAA, the Commercial Aviation Safety Team (CAST), and others to perform research and contribute technology that addresses current and future safety risks. Similar ongoing international developments, such as the European Union's (EU's) Single European Sky Air Traffic Management Research (SESAR) effort, are being globally harmonized through the International Civil Aviation Organization (ICAO).

Strategic Thrust 2: Innovation in Commercial Supersonic Aircraft

Development of efficient, cost-effective, and environmentally compatible commercial supersonic transports could be a game changer for transcontinental and intercontinental transportation, providing an opportunity to maintain U.S. leadership in aviation systems and generate economic and societal benefits in a globally linked world. In order to achieve practical and affordable commercial supersonic air travel, ARMD will focus its research on advancing groundbreaking technologies that overcome barriers to reducing its environmental impact and realizing innovative economic efficiencies. Since overcoming these barriers likely will involve modifications to regulations and certification standards for supersonic flight, ARMD will conduct its research in cooperation with the FAA, ICAO, and other aviation regulatory agencies.

Strategic Thrust 3: Ultra-Efficient Subsonic Transports

Significant improvements in aircraft efficiency, coupled with reductions in noise and harmful emissions, are critical to realizing the aviation community's projections for growth while achieving greatly improved environmental sustainability. ARMD seeks to enable substantial efficiency gains along with a fundamental shift to innovative alternative energy-based propulsion systems through the electrification of aircraft propulsion in combination with sustainable alternative jet fuels and renewable energy. ARMD also is working to enable substantial reductions in time and cost to market of aircraft through advanced materials, structures, and manufacturing technologies and enhanced digitalization of the full aircraft life cycle. ARMD will work across government, the transport industry, and academia to develop critical technologies to enable revolutionary improvements in economics and environmental performance for subsonic transports. ARMD will actively seek opportunities to transition to alternative propulsion and energy for all categories of subsonic transports, including short-haul and regional aircraft as well as large commercial aircraft.

Strategic Thrust 4: Safe, Quiet, and Affordable Vertical Lift Air Vehicles

The aviation community expects new and cost-effective uses of aviation including advanced vertical takeoff and landing (VTOL) vehicles that could provide options for using air travel as part of daily activities through unprecedented accessibility and shorter door-to-door travel times compared to other modes of transportation. While this capability is expected to greatly increase the demand for air service and significantly increase the number of flights, this mode of air travel will only be practical if the advanced VTOL aircraft provide acceptable levels of safety while reducing its environmental footprint – especially with regard to noise – compared to existing VTOL aircraft. ARMD will work across government, transport industry, and academia to develop critical technologies to enable realization of extensive use of vertical lift vehicles for transportation services including new missions and markets associated with UAM.

Strategic Thrust 5: In-Time System-Wide Safety Assurance (ISSA)

ISSA is a safety net that utilizes system-wide information to provide alerting and mitigation strategies in time to address emerging risks. Moving forward, aviation safety needs to take advantage of modern information availability and intelligent systems. New operational concepts will change and diversify aviation and create the need for advanced safety capabilities that operate on a broad scale. ISSA will incorporate both advanced technologies and collaboration between humans and intelligent agents. ISSA must be both system-wide and distributed. Its vision is to predict, detect, and mitigate emerging safety risks throughout aviation systems and operations.

Strategic Thrust 6: Assured Autonomy for Aviation Transformation

Ever-increasing levels of automation and autonomy are transforming aviation, and this trend will continue to accelerate. ARMD will lead in the research and development of intelligent machine systems capable of operating in complex environments, including the safe integration of UAS in the NAS. Complementary methods will provide safety assurance, verification, and validation of these systems. To pave the way for increasingly autonomous airspace and vehicles, ARMD will explore human-machine teaming strategies. Advanced metrics, models, and testbeds will enable the effective evaluation of autonomous systems in both laboratory and operational settings to safely implement autonomy in aviation applications.

Strategy Implementation

NASA aeronautics research creates on-ramps for industry to realize various future states of aviation described in the six Strategic Thrusts. NASA ARMD's four program offices develop the Technical Challenges and ensure that NASA aeronautics work to enable the Outcomes is developed and maintained in response to this SIP. Research activities are executed within projects hosted among four of NASA's field centers in Virginia, Ohio, and California. The projects follow NASA-established protocols for formulating and executing NASA research and technology projects.

NASA's research activities are organized within these four programs:

- The Airspace Operations and Safety Program (AOSP) develops and explores fundamental concepts, algorithms, and technologies to safely increase throughput and efficiency of the NAS.

- The Advanced Air Vehicles Program (AAVP) conducts cutting-edge research that will generate innovative concepts, technologies, capabilities, and knowledge to enable revolutionary advances for a wide range of air vehicles.

- The Integrated Aviation Systems Program (IASP) conducts research on promising concepts and technologies at an integrated system level, with a focus on flight research and demonstrations. IASP works with AOSP and AAVP to forecast and plan for needed flight research and demonstrations in support of all Strategic Thrusts.

- The Transformative Aeronautics Concepts Program (TACP) cultivates multidisciplinary, revolutionary concepts that transform aviation. TACP explores new solution paths that leverage the convergence of traditional aeronautics disciplines with other emerging technologies.

Major risks to achieving the community Outcomes – and research activities designed to overcome them – are identified in the following sections detailing each Strategic Thrust. In addition, ARMD conducts crosscutting research in fundamental technologies that support multiple Strategic Thrusts. These crosscutting technologies are summarized later.

At NASA's air traffic management laboratory near the Dallas/Ft. Worth International Airport in Texas, researchers Al Capps (seated) and Paul Borchers demonstrate Airspace Technology Demonstration 2 tools that air traffic managers have been successfully testing since 2017 at the Charlotte Douglas International Airport in North Carolina to more efficiently direct departing traffic. Image credit: NASA / Jim Banke

Strategic Thrust 1:
Safe, Efficient Growth in Global Operations

The vision for Strategic Thrust 1 is to achieve safe, scalable, routine high-tempo airspace access for all users. It is developed using the community's vision based on priorities identified during dialogue and through strategic analyses. It includes the Outcomes the aviation community can expect from implementing the results of ARMD research.

Community's Vision

NextGen is the Nation's plan for a modernized Air Traffic Management (ATM) system that will achieve much higher levels of operational capacity and efficiency while maintaining or improving safety and other performance measures. Strategic Thrust 1 responds to the NextGen plan and, further into the future, the FAA vision to build on NextGen beyond 2025 to fully capture the opportunities enabled by cyber-physical systems research and other emerging technologies.[7] More efficient aircraft operations will reduce energy consumption, complementing Strategic Thrust 3 in offering options for environmentally sustainable aviation.

Throughout the time periods from 2015 to 2035 and beyond, Strategic Thrust 1 also responds to specific safety hazards associated with existing or new aircraft, such as near-term needs to reduce loss-of-control accidents of commercial transports and the long-term need to maintain safety of the NAS in the face of greater traffic volume and an increasing variety of vehicle types and missions.

Outcomes:

1. 2015-2025: Improve operational performance integrated across all phases of flight operations, known as "domains," for traditional stakeholders, and enable initial entry of new vehicles (ATM+1). This time frame will see enhanced domain efficiencies, supported cost savings, and reduced environmental impact.

2. 2025-2035: Increasingly autonomous and collaborative ATM and routine all-vehicle access and operations (ATM+2). This time frame will see incorporation of increasingly autonomous operations resulting in increased system efficiency, predictability, and reliability gains to further improve operations and support traffic growth, including full integration of UAS in the NAS.

7 "The Future of the NAS." Federal Aviation Administration, June 2016.

3. Beyond 2035: Dynamic autonomous trajectory services (ATM+3) and NAS transformation. This timeframe will see dynamic autonomous trajectory services enabled to yield rapid adaptation to meet user demand or respond to system perturbations. A diverse range of non-traditional vehicles and operations will be integrated into the NAS by means of a scalable, service-oriented architecture.

ARMD's Role

The technical focus of Strategic Thrust 1 is on future aviation system concepts, operations, and technologies. ARMD plays two primary roles within this Strategic Thrust. The first is to develop key safety and automation technologies and safety-management capabilities that enable and extend the benefits of the FAA's plans for NextGen and the future of the NAS. The second role is to look beyond current FAA plans by researching and developing innovative concepts and technologies to ensure that a long-term research base is in place to support future planning, enable transformative approaches to future operations, and safely extend the capabilities and range of uses of the NAS.

ARMD's research for near-term (2015-2025) applications will focus on early improvements in NAS efficiency by implementing ongoing technology development in individual ATM domains and laying the foundation for revolutionary advances for both ATM+2 and ATM+3. Research includes modeling and simulation, tools to test Trajectory Based Operations (TBO) and NextGen concepts, and focus on safety issues such as loss of control and hazard awareness and detection.

Research aimed at the mid term (2025-2035) will improve NAS efficiency and predictability by implementing gate-to-gate TBO, as well as continuing progress toward ATM+3 by providing enabling technologies, including: new ATM concepts, real-time predictive modeling and simulation tools integrated with safety assurance, and integrated safe autonomous UAS operations.

Exploratory research to support the far-term period (beyond 2035) will focus on a revolutionary global aviation system with high levels of autonomy and safety prognostics that demonstrate game-changing efficiencies and enable new markets and vehicles.

ARMD also plans for continued research in engine and airframe icing to enable air vehicles to safely fly into various types of icing environments. This research will include validated computational and experimental icing simulations, as well as complementary on-board icing sensing radar to enable avoidance of icing conditions and to facilitate safe operation of current and future air vehicle concepts addressed in Strategic Thrusts 3 and 4.

Table 2. Outcomes and Research Themes for Strategic Thrust 1

STRATEGIC THRUST 1: SAFE, EFFICIENT GROWTH IN GLOBAL OPERATIONS			
	2015	2025	2035
Outcomes	Improved NextGen Operational Performance in Individual Domains, with Some Integration Between Domains (ATM+1)	Increasingly autonomous and collaborative ATM and routine all-vehicle access and operations (ATM+2)	Beyond NextGen Dynamic Fully Autonomous Trajectory Services (ATM+3)
Research Themes	**Advanced Operational Concepts, Technologies, and Automation** Research and development of operational efficiency and enhanced access incorporating proactive safety risk management in operational domains. **Safety Management for Emergent Risks** Research and development of prognostic safety risk management solutions and concepts for emergent risks across all vehicles, airspace, and emerging markets. **Integrated Modeling, Simulation, and Testing** Development, validation, and application of advanced modeling, simulation, and testing capabilities to assess and enable scalable, integrated, end-to-end NextGen trajectory-based operations functionality, as well as seamless UAS operations and other future aviation system concepts and architectures. **Airspace Operations Performance Enablers** Advanced research to develop performance requirements and guidelines for enablers, including operational guidelines and standards for new vehicles, secure Communications, Navigation, Surveillance, and Information (CNSi) infrastructure requirements, and assuring reliability of safety critical software for integrated, end-to-end global airspace operations and emerging non-traditional markets.		

Major Outcome Risks Addressed by Planned Research

- Research will address overcoming limitations of modeling and testing capabilities used in the development and implementation of advanced solutions for improved capacity, efficiency, and safety.
- Research, development, and implementation of transformational technologies and systems for air traffic management and safety assurance will be critical for meeting projected demand of increased traffic volume and diversity of operations.

NASA's X-59 QueSST, an experimental piloted aircraft designed to fly faster than sound without producing the annoying – if not alarming – sonic booms of previous supersonic aircraft is taking shape.
Image credit: Lockheed Martin

Strategic Thrust 2:

Innovation in Commercial Supersonic Aircraft

The vision for Strategic Thrust 2 is to achieve practical, affordable commercial supersonic air transport. It is developed using the community's vision based on priorities identified during dialogue and through strategic analyses. It includes the Outcomes the aviation community can expect from implementing the results of ARMD research.

Community's Vision

Development of efficient, cost-effective, and environmentally sound commercial supersonic transportation could be a game changer for transcontinental travel. Such a development also would help to sustain U.S. leadership in aeronautical science and technology. The Outcomes for this Strategic Thrust represent an approach to supersonic research focusing on groundbreaking technologies that show promise of overcoming the environmental and operational barriers to supersonic commercial aircraft.

Environmental barriers include the adverse impacts of sonic boom noise, airport community noise, high-altitude emissions, and high-energy consumption. Successful supersonic commercial aircraft must overcome the current prohibition against supersonic flight over land that was imposed to prevent public annoyance from sonic booms. They also must contend with or avoid challenges associated with airport community noise and operationally inefficient subsonic flight segments required for integration with existing air traffic. Additionally, high fuel consumption and cost due to inefficient airframe aerodynamics and propulsion system performance results in poor operating efficiency and economics. Of all these barriers, sonic boom noise, which creates an unacceptable impact on both the environment and efficient operations, is viewed as the initial critical barrier to overcome.

Outcomes:

1. 2015-2025: Certification standards identified for supersonic commercial aircraft, including over land flight based on acceptable sonic boom noise, landing and takeoff noise and emissions appropriate for technical and economic viability. The market is opened to new supersonic aircraft for fast point-to-point transportation, with defined standards for manufacturers to measure their product readiness for market entry and without introduction of a new noise annoyance.

2. 2025-2035: Introduction of affordable, low-boom, low-noise, and low-emission supersonic transports. A new market for fast point-to-point transportation will be served by environmentally compatible small supersonic aircraft, creating new business and job growth opportunities.

3. Beyond 2035: Increased mission utility and commercial market growth of supersonic transport fleet. A variety of air transportation markets will be served by supersonic aircraft with capacities as large as 200 passengers that offer rapid travel with competitive economics and reduced environmental impact.

ARMD's Role

The viability of commercial supersonic service depends on permissible supersonic flight over land and the ability to satisfy the same environmental constraints as those imposed on subsonic aircraft. ARMD's initial

The X-59 Quiet SuperSonic Technology, or QueSST, wing assembly is lifted by a crane and moved to another area of the manufacturing floor in preparation for wing skin installation. The aircraft is under construction at Lockheed Martin Skunk Works® in Palmdale, California, and will fly for the first time in 2021.
Image credit: Lockheed Martin

technical focus, therefore, is on developing scientifically valid tools and survey techniques to create the necessary database of community response to sonic boom noise. Once the international community has established a sonic boom level acceptable to the public, ARMD research will focus on enabling vehicle designs that achieve the acceptable level, as well as on technologies required to address other environmental and efficiency barriers to development and production of viable supersonic transports.

Since commercial over land supersonic flight is currently prohibited, ARMD's strategy for the near term (2015-2025) is to focus on enabling establishment of a standard for allowable sonic boom noise levels. Because international routes comprise a major share of the potential market for supersonic service, ARMD will work with the international standards community to define sonic boom levels based on scientifically valid data on community response to low noise supersonic overflight. In parallel, ARMD research will collect fundamental data on the characteristics of low noise waveforms in real atmosphere and develop low-boom design tools and models for extrapolating community response to fleet impacts as well as landing and takeoff analysis tools.

ARMD research supporting the mid-term (2025-2035) Outcome objectives will focus on technologies enabling the first and second embodiments of a new generation of supersonic transports, with emphasis on acceptable community and en route noise and high-altitude emissions, as well as air traffic management technologies and procedures for efficient supersonic and airport terminal operations.

Research objectives beyond 2035 will focus on technologies enabling supersonic transports that are competitive in the airline market, with emphasis on high efficiency and light weight for improved economics, as well as air traffic management technologies for efficient supersonic airline operations.

Table 3 presents the targeted capability metrics for supersonic air vehicles.

Table 3. Targeted Supersonic Transport Capability Metrics

VEHICLE CAPABILITIES	VEHICLE GENERATION	
	MID TERM 2025-2035	FAR TERM BEYOND 2035
Operating Economics	Business aircraft economics	Airline economics
Cruise Speed	Mach 1.6 to 1.8	Mach 1.3 to 1.6 overland, higher over water
Range	4,000 n.mi.	4,000 to 5,500 n.mi.
Passengers	6 to 90	100 to 200
Sonic Boom Noise	70 to 75 PLdB	65 to 70 PLdB
Airport Noise	Airport noise: ICAO Ch. 14, with margin	Airport noise: 15 EPNdB below Ch. 14
Cruise NO_x Emissions	<10 grams per kg fuel+	<5 grams per kg fuel (plus reduced particulates and H2O vapor)

Research Themes

The Research Themes described in Table 4, below, support the Outcomes associated with Strategic Thrust 2.

Table 4. Outcomes and Research Themes for Strategic Thrust 2

STRATEGIC THRUST 2: INNOVATION IN COMMERCIAL SUPERSONIC AIRCRAFT			
	2015	2025	2035
Outcomes	Supersonic Overland Certification Standard Based on Acceptable Sonic Boom Noise	Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	Increased Mission Utility and Commercial Market Growth of Supersonic Transport Fleet
Research Themes	**Elimination of Environmental Barriers to Commercial Supersonic Aircraft** Understanding and measuring community response to supersonic en route noise, minimizing the airport community noise impact of supersonic aircraft, and reducing or eliminating the impact of high-altitude emissions. **Integrated Design and Efficiency** Low boom design for certification; integrated design for efficiency, performance, and weight reduction; airframe and propulsion technology for improved efficiency, performance, and weight; and sonic boom mitigation technology. **Modeling, Simulation, and Test Capability** Integrated, physics-based models for aircraft design and analysis and quiet wind tunnel and acoustic test facilities. **Efficient Supersonic Flight Operations** Flight systems and cockpit displays for minimized impact of en route supersonic noise, operations for supersonic en route noise impact mitigation, airspace integration for maximum supersonic operational efficiency.		

Major Outcome Risks Addressed by Planned Research

Critical research will generate knowledge and develop technologies capable of supporting the elimination of the 1973 prohibition against over land supersonic flight through the reduction of sonic boom noise to a publicly acceptable level.

NASA is exploring the potential of this concept aircraft called Single-aisle Turboelectric Aircraft with an Aft Boundary-Layer propulsor, or STARC-ABL, which uses electrically powered propulsion technologies. Image credit: NASA

Strategic Thrust 3

Ultra-Efficient Subsonic Transport

The vision for Strategic Thrust 3 is to realize revolutionary improvements in economics and environmental performance for subsonic transports with opportunities to transition to alternative propulsion and energy. It is developed using the community's vision based on priorities identified during dialogue and through strategic analyses. It includes the Outcomes the aviation community can expect from implementing the results of this ARMD research.

Community's Vision

The aviation community expects that long-haul subsonic transports will provide the bulk of global and domestic air transportation through at least the 2050s. Sustainable growth to meet the demand for air transportation during these decades calls for safe, economical, energy-efficient, and quiet community-friendly transport aircraft with the payload, speed, and range performance demanded by the market.

Realizing this vision requires the aviation community accelerate performance improvements in drag, weight, and propulsion. Moreover, these improvements also must include safely reducing environmental impacts with goals of meeting specific levels of reduction in energy consumption, emissions of NO_x, and noise. These goals support reductions in carbon emissions expressed in an IATA resolution that calls for a 1.5 percent average annual fuel efficiency improvement between 2010 and 2020, carbon neutral growth from 2020 onward, and a reduction of 50 percent in net emissions by 2050 compared to 2005 levels.[8] These goals also support meeting and exceeding projected noise and NOx standards recommended by ICAO.[9]

The air traffic efficiency sought under Strategic Thrust 1 and the vehicle efficiencies sought in this Strategic Thrust will greatly reduce the impact of aviation on climate change. However, these efforts alone will not achieve the community's goal of enabling aviation growth while reducing net emissions 50 percent by 2050 compared to 2005 levels. As shown in a position paper prepared by the global aviation industry, and illustrated in Figure 3,[10] the community expects this 50 percent reduction goal to be achieved through a combination of more efficient operations, improved vehicle fuel efficiency, increased electrification of

8 International Air Transport Association. IATA Resolution on the Implementation of the Aviation "CNG2020 Strategy." June 2013.

9 International Civil Aviation Organization. "Developments in Civil Aviation and the Environment," ICAO Working Paper A38-WP/25. July 18, 2013.

10 Air Transport Action Group. Aviation Benefits Beyond Borders. "Environmental Efficiency: Climate Action." http://aviationbenefits.org/environmental-efficiency/our-climate-plan/.

aircraft and, in the longer term, new propulsion concepts and alternative sustainable jet fuels to incentivize emission reductions.

Therefore, research to improve airspace efficiency will be complemented by continued research into advanced airframe technologies as well as focused research on transformational propulsion capabilities – such as electrified aircraft propulsion – coupled with more efficient gas turbine engines capable of operating on alternative sustainable jet fuels and enhanced propulsion-airframe integration. Opportunities will be sought to transition these capabilities to operations in short-haul and regional markets as early as possible.

Figure 3, from the website of the commercial aviation industry Air Transport Action Group (ATAG), illustrates the community view of how carbon neutrality will be achieved through a combination of technology innovation, operational improvements, infrastructure efficiencies, and economic measures to incentivize emission reductions. NASA's key role in achieving the goals shown in Figure 3 will be important to maintain U.S. leadership in aviation and provide opportunities to open new markets such as electrified aircraft propulsion to U.S. industry.

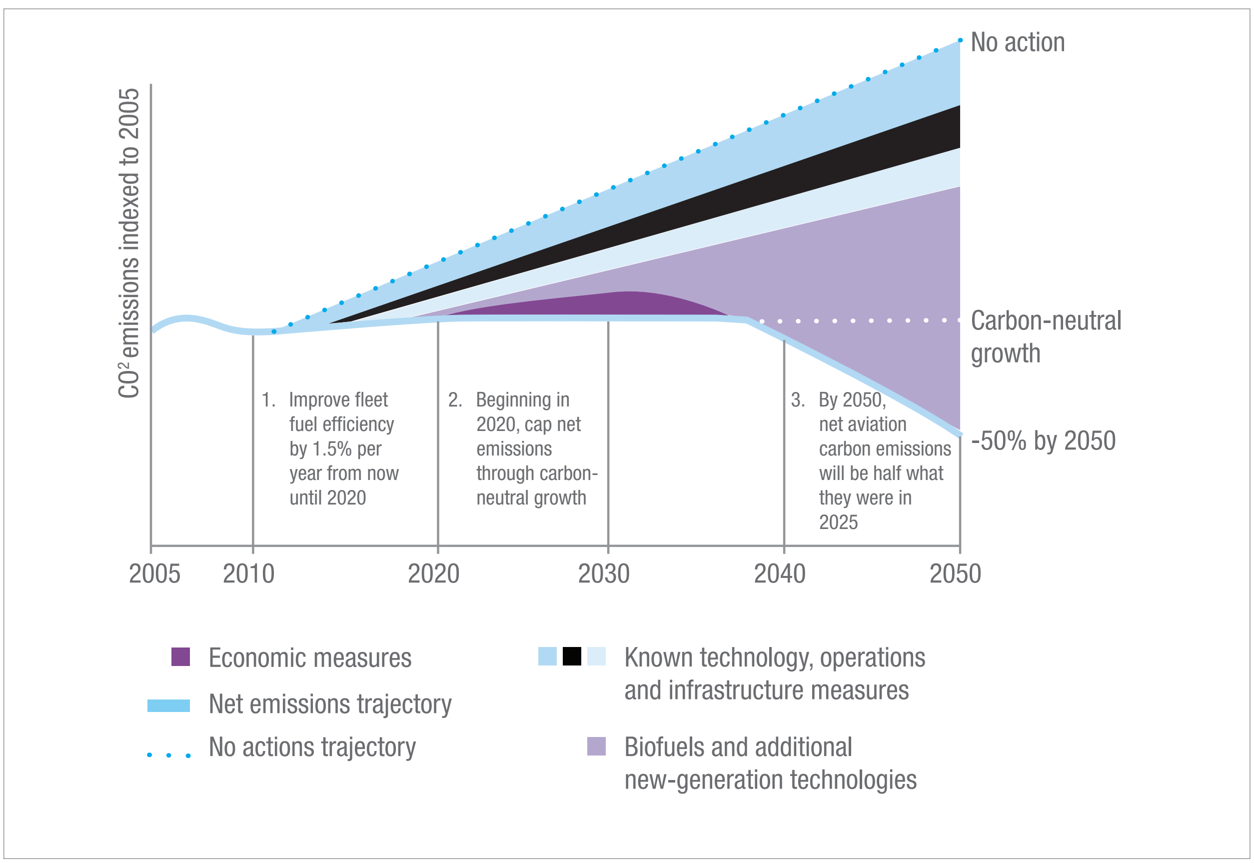


Figure 3. Aeronautics Community Vision for Achieving Carbon Neutrality

Outcomes:

1. 2015-2025: Aircraft meet efficiency, economic, and environmental demands of airlines and the public, and are on a defined path to fleet-level carbon neutral growth.

2. 2025-2035: Aircraft meet economic demands of airlines and the public with revolutionary improvements in community noise and energy efficiency to achieve fleet-level carbon neutral growth relative to 2005. Initial applications of advanced airframe technologies emerge in conjunction with new propulsion architectures such as electrified aircraft propulsion.

3. Beyond 2035: Aircraft meet economic demands of airlines and the public with transforming capabilities in community noise and energy efficiency enabling a 50 percent reduction in fleet-level carbon output relative to 2005.

ARMD's Role

ARMD's overarching strategy is to remove barriers and address high-risk technical challenges in lockstep with the community's vision and their progress toward that vision. ARMD will work with industry to mature promising technologies to meet near-term economic and environmental needs, enabling community Outcome 1, while developing promising technologies that will enable new aircraft products that meet or exceed mid- and far-term metrics, enabling community Outcomes 2 and 3.

ARMD's approach to enabling community Outcomes is to work with the aviation community to accelerate development of advanced technologies in the near term while pioneering revolutionary technologies and vehicle concepts. Together with the aviation community, ARMD will explore advanced vehicle concepts and enabling technologies capable of achieving these improvements. Conceptual designs responding to specific levels of performance provide an avenue to rapidly assess different technologies' impact on attributes of a vehicle design under various scenarios and constraints, as well as their dependencies on other technologies. The conceptual designs also enable comparisons of performance, technical risk, and other attributes of advanced vehicle concepts. In addition, the research will ensure that the safety implications of advanced technologies and concepts are identified and considered in the development process.

Innovative concepts, technologies, and methods with the highest potential impact will be prioritized for further development. ARMD will explore and develop these game-changing concepts, technologies and methods, and then verify their practicality via large-scale demonstrations to facilitate technology transfer into commercial products.

In addition, ARMD will continue to develop and validate enabling tools, methods, and processes (e.g., advanced computational methods, innovative materials and structures). The result is a base of evolving research and technology for the next generations of vehicles that will be developed and produced by industry. ARMD will continue partnering with industry and the FAA for research in specific areas for early transition to immediate near-term market opportunities. Additionally, ARMD will continue to support fundamental improvements in vehicle modeling, design, test, and evaluation, as well as advances in aerodynamics and aeromechanics, propulsion, and use of composites and other advanced materials.

Table 5 presents the targeted metrics for the projected subsonic transport vehicles relative to current performance. It shows target dates for demonstrating the readiness of technologies advanced enough to enable initial application in commercial aircraft.

Table 5. NASA Targeted Improvements in Subsonic Transport System-level Metrics

TECHNOLOGY BENEFITS	**TECHNOLOGY GENERATIONS (Technology Readiness Level = 5-6)**		
	Near term 2015-2025	Mid term 2025-2035	Far term Beyond 2035
Noise (cumulative below Stage 4)	22 - 32 dB	32 - 42 dB	42 - 52 dB
LTO NO_x Emissions (below CAEP 6)	70 - 75%	80%	>80%
Cruise NO_x Emissions (relative to 2005 best in class)	65 - 70%	80%	>80%
Aircraft Fuel/Energy Consumption (relative to 2005 best in class)	40 - 50%	50 - 60%	60 - 80%

Research Themes

The Research Themes described in Table 6, below, support the Outcomes associated with Strategic Thrust 3 for subsonic transport aircraft.

Table 6. Outcomes and Research Themes for Strategic Thrust 3

STRATEGIC THRUST 3: ULTRA-EFFICIENT SUBSONIC TRANSPORTS			
	2015	2025	2035
Outcomes	Aircraft meet economic and environmental demands of airlines and the public, and are on a defined path to fleet-level carbon neutral growth	Aircraft meet economic demands of airlines and the public with revolutionary improvements in community noise and energy efficiency to achieve fleet-level carbon neutral growth relative to 2005	Aircraft meet economic demands of airlines and the public with transforming capabilities in community noise and energy efficiency enabling a 50 percent reduction in fleet-level carbon output relative to 2005
Research Themes	**Ultra-efficient Airframes** Research and development of technologies to enable new airframe systems with high levels of aerodynamic performance, lower structural weight, and innovative approaches to noise reduction. **Ultra-efficient Propulsion** Research and development of technologies to enable new propulsion systems with high levels of thermal, transmission, and propulsive efficiency, reduced harmful emissions, and innovative approaches to noise reduction and opportunities to transition to alternative energy sources. **Ultra-efficient Vehicle System Integration** Research and development of innovative approaches and technologies to reduce perceived noise and aircraft energy consumption through highly coupled, synergistic vehicle system integration including but not limited to propulsion-airframe integration. **Modeling, Simulation, and Test Capability** Research and development of computational, experimental, and analytical tools and methods to improve vehicle mission capability in less time with reduced uncertainty and cost.		

Major Outcome Risks Addressed by Planned Research

Planned ARMD research for subsonic transport vehicles addresses two major risks to achieving the desired Outcomes for Strategic Thrust 3:

- Research dramatically reduces technical and financial risk to industry to introduce new, advanced technology into products. Without research, technology infusion into future products would be slow, resulting in the industry being unable to advance at the pace needed to achieve the community Outcomes.
- Without research and technology development, international competitors could gain an advantage over U.S. industry, especially if international regulations advance more rapidly than technology. Moreover, such regulations could be costly to U.S. airlines, resulting ultimately in increased costs to the flying public.

Another possible future aircraft shape that NASA is exploring is the "transonic truss-braced wing," a version of which may use electricity to contribute to propulsion.
Image credit: NASA/Boeing

Safe, quiet, and affordable vertical lift vehicles for carrying passengers or cargo are critical for a sustainable UAM system.
Image credit: NASA

Strategic Thrust 4:

Safe, Quiet, and Affordable Vertical Lift Air Vehicles

The vision for Strategic Thrust 4 is to realize extensive use of vertical lift vehicles for transportation and services including new missions and markets. It is developed using the community's vision based on priorities identified during dialogue and through strategic analyses. It includes the Outcomes the aviation community can expect from implementing the results of ARMD research.

Community's Vision

The aviation community expects a radical increase in new and cost-effective uses of aviation to provide travelers the flexibility to fly when and where they want in a fraction of the time it takes today. This flexibility is expected to greatly increase the demand for air service and significantly increase the number of flights. Transportation by vertical lift aircraft in particular will be fast and convenient relative to ground transportation. To reach widespread use, however, the flights must be safe and must operate with a significantly reduced environmental footprint and generate less noise compared to existing aircraft.

Public demand for increased mobility will be met in part by vertical lift air vehicles developed to operate over a wide range of configurations and missions. These configurations will provide unmatched access to urban transportation and services (e.g., air taxi, air metro, and personal air vehicles). They also will make unique missions and services (e.g., cargo delivery and emergency medical services) economical to pursue for a spectrum of markets. Many of the unique missions will require various levels of automation and autonomy for both air vehicles and airspace, and they also will require noise and emissions to be non-intrusive when operating in close proximity to people and property.

Outcomes:

1. 2015-2025: Increased capability of vertical lift configurations that promote economic benefits, reduce environmental impact, and improve accessibility for new and current markets.

2. 2025-2035: New vertical lift configurations and technologies introduced that enable new markets, increase mobility, improve accessibility, and reduce environmental impact.

3. Beyond 2035: Vertical lift vehicles of all sizes used for widespread transportation and services, improved mobility and accessibility, with economic benefits and low environmental impact.

ARMD's Role

ARMD's overarching strategy is to remove barriers and address high-risk technical challenges in lock-step with the community's vision and progress toward that vision. ARMD will work with industry to mature promising vertical lift technologies to meet near-term needs, enabling community Outcome 1, while developing promising technologies that will enable new vertical lift products that meet or exceed mid- and far-term metrics, allowing industry to achieve community Outcomes 2 and 3.

ARMD near-term (2015-2025) research for vertical lift vehicles aims at key capabilities and technologies that directly benefit vertical lift aircraft and enable markets for industry and government. These include validated tools for multi-discipline vehicle design, analysis, and optimization; modeling noise from both the vehicle and fleet operations; and conducting trade studies. This also includes research of technologies for improved ride quality, pilot workload reduction, power-transmission efficiency and reliability; lower drag for increased speed, range, and payload; and lower energy consumption.

Mid-term (2025-2035) research focuses on key technologies that will enable U.S. industry to expand the global vertical lift market while setting new standards in noise, safety, reliability, and performance. These include predicting noise and the human response to it; high-fidelity computational algorithms for full-configuration simulations; efficient alternative propulsion options; and on-board systems to protect occupants and enhance safe operations in icing conditions, degraded visual environments, and operations in confined or urban areas.

Beyond 2035, vertical lift research is aimed at capabilities and technologies that will eliminate barriers for quiet, safe, efficient, autonomous vehicles operating in both urban and isolated environments. These include efficient integration of lift and propulsion systems, technologies and methods for low-noise operations, and advanced experimental methods for rapid ground and flight test validation of innovative vehicle configurations.

Reducing noise and annoyance to the communities in proximity to vertical lift operations is a significant challenge for vehicle designers, mission managers, and operators. NASA research will identify and recommend low-noise design practices and operational methods to mitigate the noise impact on communities.

Research Themes for Strategic Thrust 4

The Research Themes described in Table 7, below, support the Outcomes associated with Strategic Thrust 4.

Table 7. Outcomes and Research Themes for Strategic Thrust 4

STRATEGIC THRUST 4: SAFE, QUIET, AND AFFORDABLE VERTICAL LIFT AIR VEHICLES			
	2015	2025	2035
Outcomes	Increased capability of vertical lift configurations	New vertical lift configurations and technologies introduced that enable new markets, increase mobility, improve accessibility, and reduce environmental impact	Vertical lift vehicles of all sizes used for widespread transportation and services, improved mobility and accessibility, with economic benefits and low environmental impact
Research Themes	**Clean and Efficient Propulsion** Research and development advancing the efficiency of propulsion systems and expanding integration and development of alternative propulsion systems for vertical lift configurations. **Efficient and Quiet Vehicles** Research and development of technologies and configurations that optimize performance and speed and minimize noise and cost. **Safety, Comfort, and Accessibility** Research and development of technologies and capabilities that improve passenger and public safety during operations and improve vehicle dynamic response, as well as operational concepts that improve access to transportation and services. **Modeling, Simulation, and Test Capability** Research and development of computational, experimental, and analytical tools and methods to allow rapid design, development, and validation of a broad range of innovative vertical lift air vehicles.		

Major Outcome Risks Addressed by Planned Research

- Research will be critical to reduce uncertainties associated with vertical lift vehicle safety and noise and develop standards for certification and operations.
- Research and technology development will be critical to the progress of advanced design capabilities and enable industry to develop and produce a broad range of innovative vertical lift air vehicles.

This visualization generated from NASA's Sherlock ATM Data Warehouse shows flights departing JFK International Airport at 6:00 a.m. ET; green tracks represent U.S. domestic flight and red tracks represent international flights.
Image credit: NASA

Strategic Thrust 5:
In-Time System-Wide Safety Assurance

The vision for Strategic Thrust 5 is the ability to predict, detect, and mitigate emerging safety risks throughout aviation systems and operations. It is developed using the community's vision based on priorities identified during dialogue and through strategic analyses. It includes the Outcomes the aviation community can expect from implementing the results of ARMD research.

Community's Vision

Decades of continuous efforts to reduce risk in commercial aviation have made it the safest mode of transportation. By addressing known hazards and responding to issues illuminated by analysis of incidents and accidents, commercial aviation has achieved exemplary safety records and inspired the confidence of the flying public. As aviation adopts new technologies to enhance the capacity, efficiency, and uses of the NAS, maintaining a safe system will require recognition and timely mitigation of emerging safety issues before they become hazards. A shift toward proactive risk mitigation will become critical to meet these needs.

This Strategic Thrust will deliver a progression of capabilities to ensure safe operations in more complex airspace by accelerating the proactive detection, prognosis, and resolution of emergent threats to system-wide safety. The result will be a safety net that utilizes system-wide data to provide alerting and mitigation strategies in real-time to address emerging risks.

Outcomes:

1. 2015-2025: Domain specific in-time safety monitoring and alerting tools will expand system awareness and provide decision support for limited simple operations. Developments in data mining and analysis, prognostics, real-time system assurance techniques, and safety risk modeling will support increased access to safety relevant data, expanded system awareness, and initial integration of analysis capabilities. Safety will be improved through initial real-time detection and alerting of hazards at the domain level and decision support for limited operations.

2. 2025-2035: Integrated predictive technologies with domain level application will enable NAS-wide availability of more fully integrated real-time detection and alerting capabilities for enhanced risk assessment and initial assured human and machine decision support, enabling selection of mitigating responses in increasingly complex operations.

3. Beyond 2035: Adaptive real-time safety threat management will enable NAS-wide safety assurance and will feature fully integrated threat detection and assessment capabilities that support trusted methods for dynamic, multi-agent planning, evaluation, and execution of in-time risk-mitigating response to hazardous events.

ARMD's Role

Strategic Thrust 5 focuses on research that incorporates secure sensor and networking technologies, along with innovative data analytics and decision support methods, to enable unprecedented insight into system operations, health, and safety. System-of-systems modeling, prognostic tools, and run-time system assurance technologies will enable real-time, system-wide safety assurance.

In the near term (2015-2025), ARMD research will focus on initial continuous real-time monitoring, real-time anomaly and precursor identification and alerting of known safety hazards, mitigation response capability for selected applications, and assured access and analysis of secure data.

Research for the mid term (2025-2035) will enable integrated system-wide continuous monitoring of safety margins and trustworthy decision support tools that manage uncertainty to enable in-time hazard mitigation.

Beyond 2035, ARMD research will focus on real-time intelligent safety monitoring through integrated threat detection, prediction, and decision support to enable dynamic human-automation hazard mitigation strategies.

Research Themes for Strategic Thrust 5

The Research Themes described in Table 8, below, support the Outcomes associated with Strategic Thrust 5.

Table 8. Outcomes and Research Themes for Strategic Thrust 5

STRATEGIC THRUST 5: IN-TIME SYSTEM-WIDE SAFETY ASSURANCE			
	2015	**2025**	**2035**
Outcomes	Domain Specific In-time Safety Monitoring and Alerting Tools	Integrated Predictive Domain Level Application	Adaptive Real-time Safety Management
Research Themes	**Continuous System-wide Safety Awareness (Monitor)** Technical approaches and required architecture to support comprehensive safety monitoring through acquisition, integration, and assurance of sensitive data from heterogeneous sources. **Safety Risk Identification and Evaluation (Assess)** Assured tools that improve the accuracy of real-time detection, diagnosis, and prediction of hazardous states and the impact of these states on system safety. **Coordinated Prevention, Mitigation, and Recovery (Mitigate)** Trusted methods for dynamic, multi-agent planning, evaluation, and execution of real-time risk mitigating response to hazardous events. **Experimentation, Demonstration, and Assessment** Experimentation, demonstration, benefits analysis, and transition of new In-Time System-Wide Safety Assurance technologies within all elements of the airspace.		

Major Outcome Risks Addressed by Planned Research

- Research, technology development, and implementation of validated tools and effective in-time monitoring will be critically dependent on access to sensitive data from all elements of the system. Trust and confidence within the community of processes and tools providing data protection are additional non-technical aspects enabling a successful Outcome.

An artist's conception of a UAM environment where air vehicles with a variety of missions and with or without pilots are able to interact safely and efficiently.
Image credit: NASA/Lillian Gipson

Strategic Thrust 6:

Assured Autonomy for Aviation Transformation

The vision for Strategic Thrust 6 is to safely implement autonomy[11] in aviation applications. It is developed using the community's vision based on priorities identified during dialogue and through strategic analyses. It includes the Outcomes the aviation community can expect from implementing the results of ARMD research.

This Strategic Thrust incorporates recommendations of the National Academies report, Autonomy Research for Civil Aviation.[12] The report established the concept of increasing autonomy and identified NASA's role as supporting basic and applied research in civil aviation technologies, including air traffic management technologies of interest to the FAA.

Community's Vision

The evolution of autonomous systems will transform aviation operations, providing improvements in safety, efficiency, and flexibility of operations to increase the capacity, robustness, and flexibility of the NAS. Additional benefits will be realized through new uses of the airspace, enabled by advances in autonomy such as advanced UAS operations and on-demand personal air transportation. The objective of Strategic Thrust 6 is to enable autonomous systems that employ highly intelligent machines to maximize the benefits of aviation to society.

Outcomes:

1. 2015-2025: Introduction of aviation systems with bounded autonomy, capable of carrying out function-level goals. This period will see the introduction of initial adaptive automation functions within airborne and ground-based systems, assured by limiting envelopes of applicability. Functions will include machine-based strategic control of systems, advisory support of humans in planning and decision-making, and prognostics-based safety. Some functions will improve design and manufacturing processes and increase machine-to-operator ratio. New capabilities enabled by use of autonomous systems will be introduced, especially for UAS applications.

2. 2025-2035: Introduction of aviation systems with flexible autonomy based on earned levels of trust and capable of carrying out mission-level goals. Advanced machine learning and adap-

11 Autonomy is defined as self-governance without external control.

12 National Research Council of the National Academies. "Autonomy Research for Civil Aviation: Toward a New Era of Flight." National Academies Press, 2014.

tation capabilities will be introduced and assured through advanced prognostic approaches. Goals for autonomous functions will be specified at a high level, and increased trust will facilitate widespread certification and implementation. For many systems, humans and machines will work as team peers to accomplish all goals. Autonomous systems, made up of interconnected autonomous functions, will increase in scale. Systems will learn and adapt through access to large quantities of data, enabling sophisticated world models of system states and the operating environment.

3. Beyond 2035: Introduction of distributed collaborative aviation systems with assured autonomy capable of carrying out policy-level goals. Aviation applications possible only through advanced autonomy will predominate. Society will gain high confidence in autonomous aviation systems, and large-scale autonomous systems will achieve goals specified at levels of system governance and sustainability. Goals will include system-level maintenance, healing, and protection. Systems will be interconnected and rely on high-resolution world models generated using massive distributed sensor networks. System elements will be distributed and collaborative, enabling unprecedented efficiency, agility, robustness, and resilience.

ARMD's Role

The focus of Strategic Thrust 6 is to provide game-changing benefits of autonomy for civil aviation through use of machine intelligence and machine connectivity. ARMD will leverage rapidly evolving developments in machine learning, robotics, and adaptive, cognitive computing architectures to enable high-impact autonomy applications. These efforts will be complemented by extensive research and development of methods and capabilities to validate and assure trusted performance of highly complex systems-of-systems with substantial adaptive characteristics. Special focus will be placed on assessing the ability of machine learning functions to adapt to emergent conditions. The research will employ sophisticated testbeds to understand key challenges and develop solutions for specific applications.

ARMD's primary role will be in development of concepts, architectures, and applications for autonomous aviation systems; and addressing critical autonomy barriers that require unique NASA contributions. ARMD will leverage initial technologies to insert autonomy into operational environments and then build on experience. ARMD will conduct research to develop and demonstrate radical breakthrough autonomy concepts, technologies, and mission products. Research will include development of mission products that leverage the widespread growth and rapid development cycles of UAS. ARMD will provide community coordination and leadership to achieve research advances, implement selected applications, and leverage large investments in non-aviation autonomy technologies by repurposing those technologies for aviation.

In the near term (2015-2025), ARMD research will focus on advanced prescribed automation and initial goal-directed and adaptive automation, initial world models and world views from local sensors and limited data exchange, and predominantly human-supervised functionality. Research will progress to higher levels of machine independence under carefully controlled conditions, with applications to aviation system components and small-scale systems, including UAS.

Research for the mid term (2025-2035) will focus on mission-level, goal-directed adaptive automation, large-scale detailed world views using advanced sensors and networks, human/machine teams with many levels of control depending on specific situations, and extensive machine-based learning applied to large-scale integrated systems.

Research for the far term (beyond 2035) will aim at extreme flexibility and adaptability for large-scale systems, with extreme levels of reliability and recovery from disturbances. Research topics include campaign-level, goal-directed adaptive automation embedded within all system elements, adaptive collaboration based on extensive shared world views, highly distributed large-scale collaborative systems that constitute integral parts of larger systems they support, and human/machine teams, with humans primarily specifying strategic goals.

Research Themes

The Research Themes described in Table 9, below, support the Outcomes associated with Strategic Thrust 6.

Table 9. Outcomes and Research Themes for Strategic Thrust 6

<table>
<tr><th colspan="4">STRATEGIC THRUST 6: ASSURED AUTONOMY FOR AVIATION TRANSFORMATION</th></tr>
<tr><th></th><th>2015</th><th>2025</th><th>2035</th></tr>
<tr><td>Outcomes</td><td>Introduction of aviation systems with bounded autonomy, capable of carrying out function-level goals</td><td>Introduction of aviation systems with flexible autonomy based on earned levels of trust, capable of carrying out mission-level goals</td><td>Introduction of distributed collaborative aviation systems with assured autonomy, capable of carrying out policy-level goals</td></tr>
<tr><td>Research Themes</td><td colspan="3">Technologies and Methods for Design of Complex Autonomous Systems
Methods and technologies for design of intelligent machine systems capable of operating and collaborating in complex environments.

Assurance, Verification, and Validation of Autonomous Systems
Methods for certification and assuring trustworthiness in the design and operation of autonomous systems.

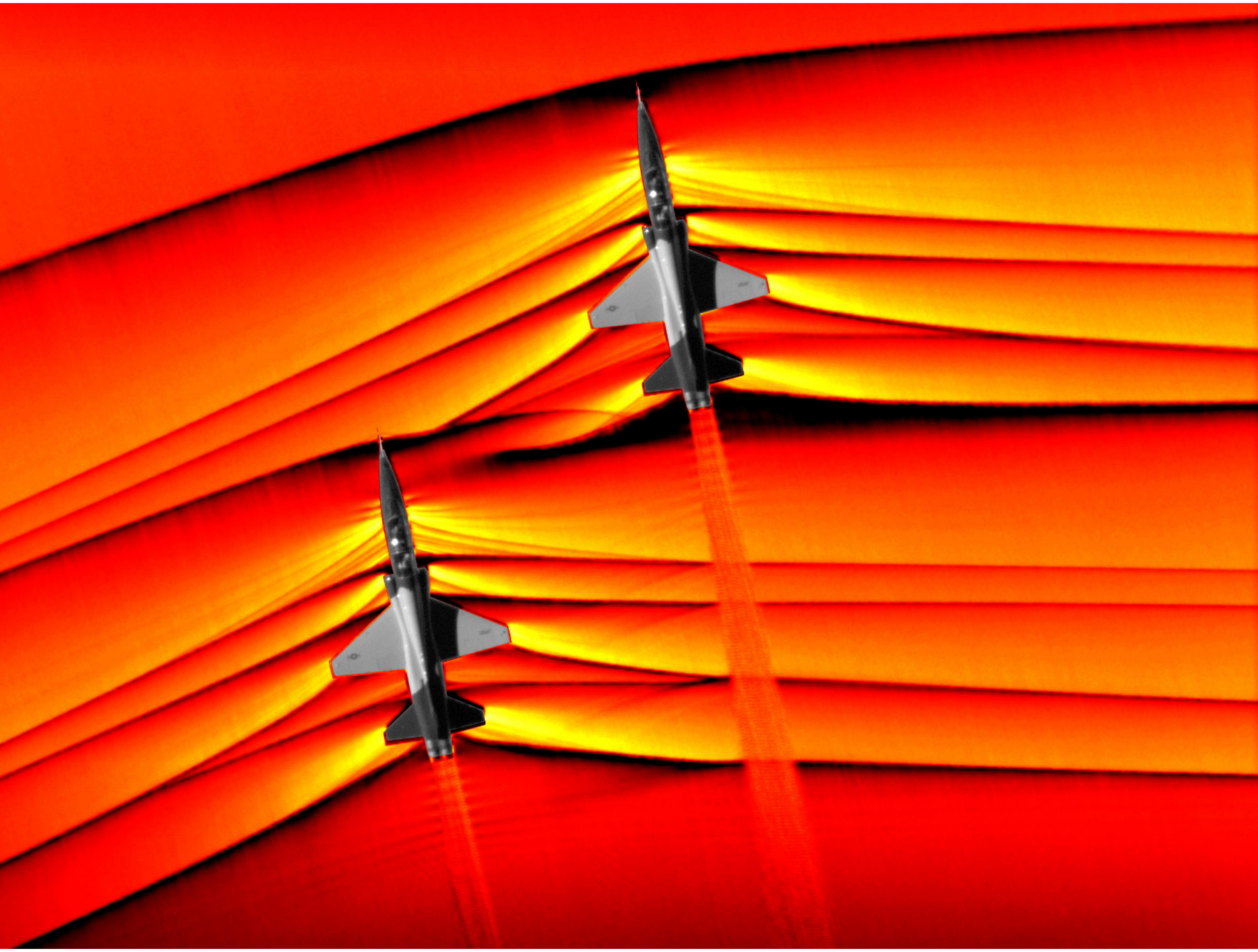
Human-Autonomy Teaming in Complex Aviation Systems
Optimal human-machine role assignments and teaming strategies for increasing machine autonomy and earned levels of trust.

Implementation and Integration of Autonomous Airspace and Vehicle Systems
Novel real-world autonomy applications and transition paths toward higher levels of autonomy.

Testing and Evaluation of Autonomous Systems
Metrics, models, simulation capabilities, and testbeds for assessment of autonomous systems in laboratory and operational settings.</td></tr>
</table>

Major Outcome Risks Addressed by Planned Research

- Relevancy of research will be critically dependent on maintaining awareness of unknown issues, risks, and opportunities through strategic partnerships.
- Without overcoming verification and validation challenges, technology infusion into future products would be slow, resulting in the industry being unable to advance at the pace needed to achieve the community Outcomes.
- Non-technical issues, such as legal liability, public acceptance, moral decision making, and transformation of human roles and tasks, could pose barriers to applications of UAS and other uses of machine intelligence.



Schlieren image of shock waves from two airplanes in supersonic flight. Image credit: NASA

Crosscutting Research & Testing

In addition to research that directly aligns with specific Strategic Thrusts, ARMD conducts foundational research on crosscutting ideas and technologies that provides critical support across multiple Strategic Thrusts. This research enables a broad range of aeronautics and aerospace applications and explores opportunities for technology convergence from disparate technology areas. Flight and ground capabilities for experimentation and feasibility demonstrations are additional elements that support the research for multiple Strategic Thrusts.

Crosscutting research falls mainly into two areas: (1) next-generation, physics-based modeling and design capabilities to enable realization of long-term vehicle and aviation system design concepts, and (2) enabling transformation of flight capabilities through innovations in discipline-oriented technologies such as new materials, measurement techniques, and flight and propulsion controls.

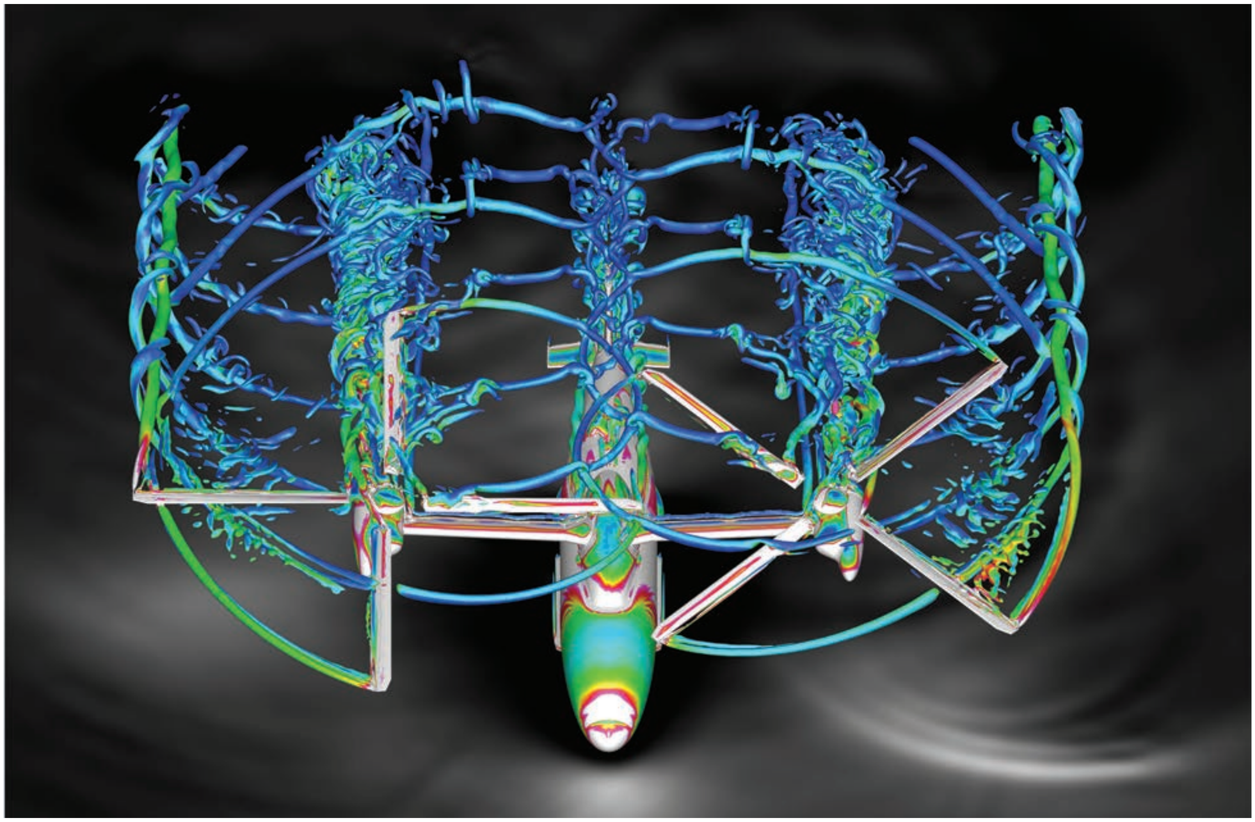
Research in revolutionary tools seeks to develop a multidisciplinary computational capability for modeling a broad range of phenomena of interest to aeronautics, including turbulent flow, transition, supersonic flow, reacting flow, acoustics, and other aspects of fluid physics, as well as development and validation of autonomous vehicle system control concepts enabling rapid progress from concept to flight. This research includes a range of capabilities, from system-level air vehicle design, analysis, and optimization tools, to high-fidelity computational fluid dynamics and structural and aeroelastic dynamics tools. Innovative numerical algorithms will take advantage of new computer architectures to make computational analysis faster and more efficient. Targeted validation experiments will develop databases for model assessment and validation, as well as provide insight for development of improved modeling ideas.

Transformational advances in discipline-oriented technology areas, such as materials, measurement techniques, and flight and propulsion controls, are required to enable advanced vehicle and propulsion system concepts for the future. These technologies range from new materials that enable improved capability to novel sensors and advanced actuators. Innovative measurement techniques, including optical techniques for both surface and off-body measurement, will improve diagnostic capability, as well as provide the advanced measurement capability needed for the validation experiments supporting development of tools and methods.

Fundamental research on reducing the barriers to reusable hypersonic systems provides one example of incorporating advancements across multiple disciplines to support an application. ARMD will conduct fundamental research to enable a broad spectrum of hypersonic systems and missions by advancing the core capabilities and critical technologies for hypersonic flight. The resulting technology advancements will be a benefit to national hypersonic programs both within NASA and in partnership with the DoD.

Analytical tools, test techniques, and fundamental capabilities will reduce the barriers to routine, reusable hypersonic flight. ARMD will create system-level design and analysis capabilities to enable more definitive systems analysis with quantified uncertainty, as well as developing and demonstrating key propulsion capabilities and technologies necessary to enable mode transition for combined-cycle hypersonic propulsion systems. ARMD will also address more foundational challenges associated with aerodynamic heating, boundary layer transition, and overall thermal management. Advances will continue in computational fluid dynamics for high enthalpy, chemically reacting flows. Research and development in high-temperature durable materials, dynamic seals, and sensor technologies will help to make reusable hypersonic vehicles a reality. Key to the mission will be engaging, invigorating, and training the next generation of engineers.

ARMD's flight and ground test capabilities, complemented by high-fidelity computational simulation, enable rapid experimentation and feasibility demonstration of advanced concepts ranging from individual experiments, to proof-of-concept tests, to demonstration of integrated concepts embodying converging technologies. Relevant assets include flight research and support aircraft, wind tunnels, propulsion, acoustic, materials, and structures laboratories and test facilities, flight research and air traffic management simulators, airspace operations laboratories, high-end computing laboratories, and test support infrastructure. These facilities and capabilities will continue to evolve in support of the research necessary to address the Strategic Thrusts.



This computer-generated high-fidelity visualization of side-by-side rotors on a vertical lift vehicle — the kind likely to be seen more frequently in a UAM environment — shows the complex 3-D vortex wake from the intermeshing rotors.
Image credit: NASA Ames/Patricia Ventura Diaz

NASA explores technologies that reduce aircraft noise and fuel use, get you gate-to-gate safely and on time, and transform aviation into an economic engine at all altitudes.
Image credit: NASA

Summary

The coming decades represent both a great opportunity and a great challenge for aviation to meet rapidly growing demand driven by global socioeconomic development. NASA's aeronautical research, carried out by ARMD, will play a leading part in enabling an efficient, flexible, scalable, and environmentally sustainable aviation system that will meet global needs for air transportation through 2035 and beyond. These needs are shaped by three Mega-Drivers: global growth in demand for high-speed; global climate change, sustainability, and energy use; and technology convergence.
Aviation serves a global marketplace, and it continues to be a technology-driven industry. Although the United States has long led the global aviation community, Europe now develops and markets commercial airliners at parity with the United States, while Brazil and Canada are delivering new narrow-body airliners and China is developing an indigenously designed commercial twinjet. Overall, Boeing projects that 83 percent of the sales volume for commercial aircraft from 2016 to 2036 will be outside North America, with Asia at 40 percent and Europe at 19 percent. [13] Moreover, international companies are leveraging new technologies to pioneer innovative aviation products; for example, DJI, a Chinese company, is reported to have a greater than 50 percent share of the U.S. market for small UAS.

Thus, in addition to serving the needs of domestic users of aviation and airspace, NASA will continue to play a vital role in maintaining competitiveness of the U.S. civil aviation industry by conducting research outside the economic and risk criteria that govern commercial investments. In this global environment, ARMD will continue to develop and apply new technologies and promote innovation to support six Strategic Thrusts:

- Safe, Efficient Growth in Global Operations
- Innovation in Commercial Supersonic Aircraft
- Ultra-Efficient Subsonic Transports
- Safe, Quiet, and Affordable Vertical Lift Air Vehicles
- In-Time System-Wide Safety Assurance
- Assured Autonomy for Aviation Transformation

ARMD's strategic planning emphasizes enabling the achievement of Outcomes expressed as societal or economic benefits within these Strategic Thrusts. Viewing the NAS as a complex system of systems and working closely with the aviation community, ARMD research will leverage new or non-traditional technologies and approaches, including alternative fuels and electric or hybrid propulsion, low-boom supersonic flight, automation and autonomy, and technology convergence to develop transformative solutions. The ultimate goal is to enable a safe, efficient, adaptive, scalable, and environmentally sustainable global aviation system to meet the challenges of the future.

Join the Conversation

This Strategic Implementation Plan is a living document through which NASA communicates with stakeholders and the research community. Feedback is welcome and encouraged and can be sent to *hq-armd-strategy@mail.nasa.gov.*

13 The Boeing Company. "Current Market Outlook 2016-2035." 2016.

Acronyms List

3-D	Three-dimensional
AAVP	Advanced Air Vehicles Program
AOSP	Airspace Operations and Safety Program
ARMD	Aeronautics Research Mission Directorate
ATAG	Air Transport Action Group
ATM	Air Traffic Management
BWB	Blended Wing Body
CAEP	Committee on Aviation Environmental Protection
CAST	Commercial Aviation Safety Team
CFD	Computational Fluid Dynamics
CNSi	Communications, Navigation, Surveillance, and Information
CO_2	Carbon Dioxide
dB	Decibel
DoD	Department of Defense
EU	European Union
eVTOL	Electric Vertical Takeoff and Landing
FAA	Federal Aviation Administration
IASP	Integrated Aviation Systems Program
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IFAR	International Forum for Aviation Research
LTO	Landing/Take-off
NACA	National Advisory Committee for Aeronautics
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System
NO_x	Nitrogen Oxides
SESAR	Single European Sky Air Traffic Management Research
TACP	Transformative Aeronautics Concepts Program
TBO	Trajectory Based Operations
UAM	Urban Air Mobility
UAS	Unmanned Aircraft System(s)
VTOL	Vertical Takeoff and Landing

National Aeronautics and Space Administration

Headquarters
300 E. Street, SW
Washington, DC 20546

www.nasa.gov

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