National Aeronautics and
Space Administration

Enabling America on the Space Frontier

The Evolution of NASA's Commercial Space Development Toolkit

Winter 2024

Contents

Dr. Alexander MacDonald
NASA Chief Economist

The growth in U.S. commercial space capabilities in the 21st century and their integration into an increasing array of NASA programs is the result of over five decades of effort by individuals and teams at NASA and in the private sector. While the story of commercial space is often depicted as a recent phenomenon dating back a decade or two at most, in fact NASA has utilized a variety of mechanisms to encourage commercial space capabilities dating back to its origins—and even before with one of its predecessor organizations, the National Advisory Committee for Aeronautics (NACA). When we understand NASA's role in commercial space development at a time-scale of decades, we can gain a fuller appreciation of the long-run importance of NASA to commercial space development and of the long-run importance of commercial space development to NASA.

This long history provides an opportunity to analyze and understand NASA's approach to commercial space development in a new way, by identifying the different high-level mechanisms that NASA has utilized to support commercial space development that are consistent over time, as well as the mechanisms that might be more recent or idiosyncratic to particular periods of time. In categorizing and identifying these mechanisms, and understanding the different contexts in which they have been used at different times, NASA employees and space policy stakeholders can gain a greater appreciation for the set of 'tools in the toolbox' that NASA has utilized to support commercial space development. In identify the 'tools in the toolbox' and describing their use, the hope is also that those interested in thinking about how NASA can help support commercial space development can refer to this document as a handbook to interrogate and guide new initiatives and alternative options.

From the perspective of NASA's Office of the Technology, Policy, and Strategy (OTPS) and the NASA Chief Economist, the array of mechanisms that contribute to commercial space development are much more varied and significant than those often discussed. Many are familiar with the important role played by NASA's Other Transaction Authority (OTA) and associated Space Act Agreements (SSAs), NASA's use of milestone-based firm-fixed price payments for commercial services, as well as the NASA Small Business and Innovative Research Program (SBIR). Often less discussed, however, and arguable equally important to the development of commercial space capabilities, are NASA's in-direct mechanisms of support, such as partnerships with academia and the education and development of the overall national aerospace workforce, or the mobility and external engagement of the NASA workforce that results in NASA skills and experience flowing into commercial companies, or even the simple encouragement of public narratives that include a vibrant and growing future in space that includes substantial commercial activity.

This handbook is meant to be utilized by anyone trying to understand how the current moment of growth in commercial space development came to be, and how we might continue to encourage this growth in the future. It is not meant to be a comprehensive history, nor a final account. It is hoped that this handbook will be updated and improved in the future as refinement in our understanding improves, as lessons are learned from the many current programmatic experiments in commercial space development, and hopefully as new mechanisms are developed and put into practice. All handbooks are partial and incomplete, as the true complexity of the field that they try to describe can never be condensed to a single document. If this handbook can serve either as a gateway to those new to field of commercial space development, or as a useful reference and idiosyncratic guidebook to some already in the field, then it will have done its job. To those utilizing their labors to encourage the long-run future of commercial space development in the U.S. and around the world, we hope that this handbook can serve as a productive companion.

Alex MacDonald

Executive Summary

Throughout NASA's history, the Agency has supported the development and growth of the U.S. commercial space sector via various mechanisms that have nurtured the technology, companies, people, and ideas driving an industry that today is a significant contributor to the American and global economies.

This report identifies 17 such mechanisms and qualitatively examines how they have been applied across four distinct periods in NASA's history:1915–1960, which covers NASA's predecessor, the National Advisory Committee on Aeronautics (NACA), and NASA's pre-Apollo years; 1961–1980, the Apollo era; 1981–2010, the Space Shuttle era; and 2011–present, the post-Shuttle commercial era. These eras are defined by dominant technologies, programs, or economic trends.

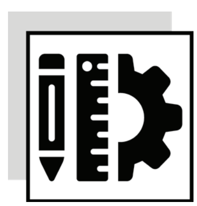
Not all 17 mechanisms were applied during each era; some are relatively recent conceptions, while others have been used throughout the history of NASA and NACA. Additionally, there is inevitably some overlap between the mechanisms; this overlap adds an element of subjectivity to the categorizations in this report. In most eras, and for most mechanisms, there are far more examples than can reasonably be summarized in a single document. Therefore, this report should not be considered an exhaustive review of every iteration of any given mechanism's implementation. Finally, with many of these mechanisms, such as contracts, commercial space capabilities sometimes resulted as a serendipitous by-product rather than a planned outcome.

The Mechanisms

The following are the 17 mechanisms employed since the NACA's creation in 1915:

Contracts and Partnership Agreements

Includes the various procurement and nonprocurement vehicles (e.g., Space Act Agreements) that NASA develops to achieve its missions across oth er mechanisms.



Research and Technology Development (R&TD)

Covers NASA-funded science and technology development work. NASA's civil servant workforce, academia, and industry, often in partnership with each other, have progressively advanced the state of the art and the practice of space technology, including regarding technology with commercial applications.

Dissemination of Research and Scientific Data

Includes technical papers and conferences that share NASA's R&TD results and science mission data with the public. Results of NASA-funded research by industry and academia are also widely shared.

Education and Workforce Development

Refers to NASA's longstanding support for science, technology, engineering, and math (STEM) education initiatives and partnerships with academic institutions and professional associations. (This mechanism does not include the professional development of the science and engineering workforce that results as a secondary benefit of funding university research.)

Workforce External Engagement and Mobility

Covers official and unofficial interactions between the nurtured, highly skilled, and knowledgeable cadre of NASA's workforce who engage with industry and often go on to work for—or establish—commercial space companies.

Technology Transfer

Includes direct sharing of NASA-developed technology with industry through collaboration and licensing arrangements.

Technical Support

Refers to NASA experts' direct support of commercial space activities, such as launch-vehicle development.

Enabling Infrastructure

Includes rocket engine test stands and satellite testing facilities located at NASA Centers; this infrastructure is made available to industry for programs that are commercially focused or have commercial potential.

Launch

Covers NASA-upplied launch services to commercial space companies on a cost reimbursement basis in the era before a viable commercial launch industry existed. Also includes more recent launch-related support and facilitation conducted by the Agency.

Direct In-Space Support

Typically refers to the use of NASA in-space infrastructure, assets, and astronauts to assist with commercial space activities.

Standards and Regulatory Framework Support

Encompasses NASA's role in developing interoperability standards and providing technical support to other agencies with regulatory oversight of the space industry.

Public Engagement

Encompasses efforts to familiarize the public at large with and involve them in space activities; includes everything from lectures and documentaries to citizen science projects and public prize competitions. These efforts help inspire people to pursue careers in and shine a spotlight on talent that can support the space sector.

Industry Engagement

Often occurs outside of formal contractual arrangements, sometimes referred to as nonprocurement business relationships, and usually between formal groups or entities within organizations. Typically entails working with companies to better understand mutual plans and interests.

Venture Capital Engagement

Involves partnering to various degrees with venture capital companies, in part because of their focus on early-stage technologies, to invest in technologies with the potential to support NASA goals. In one historical example, this engagement involved setting up a short-lived investment organization.

Market Stimulation Funding

Involves NASA's programs designed to stimulate the creation of commercial space products and services that can be used to support NASA missions.

Economic Analysis and Due Diligence Capabilities

Refers to criteria and tools NASA uses to assess the viability of companies to raise capital and provide commercial services to support NASA missions.

Narrative Encouragement

Refers to NASA's efforts to propagate public narratives in support of the commercial space sector.

Origins of NASA

NASA's origins trace back to 1915, decades before the dawn of the Space Age, with the formation of the NACA. The NACA had the objective of advancing U.S. capabilities in the emerging field of aviation, both military and commercial. The NACA was the largest of the government R&TD organizations that were merged in 1958 to create NASA, and many of the NACA's mechanisms for supporting the aviation sector were adapted for space activities.

The NACA was primarily focused on R&TD rather than on the procurement of capabilities to fulfill specific missions; industry developed capabilities for commercial or government use, based in part on the R&TD that the NACA conducted. The NACA also conducted research on rockets and atmospheric reentry vehicles that NASA, and in turn industry, would later build up to create space capabilities. The NACA worked closely with industry in R&TD efforts, often in collaborative, nonhierarchical arrangements. The NACA published technical papers and memoranda—albeit with limited distribution, to preserve industry's competitive edge—that ultimately promoted the aviation industry's growth and adoption of new solutions.

NASA's long history of providing technical and infrastructure support began with the NACA, which had assets, including expertise and wind tunnels, that were regularly leveraged by the aviation industry, often on a paid basis.

The NACA also engaged with the public through a speakers' bureau, composed of volunteers who spoke to members of clubs, religious centers, and other civic organizations, and through the Office of Public Information, which issued press releases to the aerospace industry. After NASA's creation, the Office of Public Information was greatly expanded to handle the huge public and media demand for information about U.S. space activities.

Apollo Era

From 1961 through 1980, what we refer to as the Apollo era, NASA's support for the commercial space sector (with the exception of satellite telecommunications) was to a large degree a by-product of the decade-long mobilization effort that ultimately landed astronauts on the Moon. NASA's budgets soared during the early part of this era, and contracts with industry to fulfill NASA's Apollo objectives moved the technology forward quickly, helping to establish some of the commercial industry's foundational capabilities. The Apollo program is even cited by some historians as a factor in the Silicon Valley–centered computing revolution that today is a major enabler and driver of commercial space activity. This digital revolution has enabled new space-based applications and created business cases that simply were not possible two decades ago.

The Apollo program, thanks in part to NASA's outreach efforts on multiple fronts, inspired countless people to devote their talents to space-related careers. Many went on to blaze trails in commercial space, as did many civil servants who cut their teeth on NASA programs during the 1960s and 1970s.

During the Apollo era, NASA committed significant resources to one area, with the express intent of nurturing a nascent commercial industry: satellite telecommunications. Throughout the 1960s and 1970s, NASA supported the sector with launch and ground station support services and invested internally and with commercially focused companies to advance satellite technology. NASA also supported the Federal Communications Commission in its satellite telecommunications regulatory role.

Space Shuttle Era

From 1981 to 2010, NASA made a significant push to advance the commercial space industry on several fronts. The Space Shuttle, which debuted in 1981, was designated by U.S. government policy as the launcher of choice for all U.S. payloads (including commercial communications satellites).

The Space Shuttle served in that capacity—launching more than 20 commercial satellites—until the 1986 Challenger disaster led to a new policy that barred commercial launches aboard the orbiter. Meanwhile, NASA backed several commercial space initiatives through investments and infrastructure. For example, the Agency created new contracting mechanisms, including Joint Endeavor Agreements and Space Act Agreements, to develop propulsion systems for the shuttle-launched payloads and for the transportation of commercial payloads aboard the orbiter to the International Space Station (ISS), which was assembled in orbit from 1998 to 2011.

During this era, NASA began experimenting with several innovative arrangements, including mechanisms designed to stimulate the commercial sector to coinvest in developing capabilities to meet Agency requirements. These mechanisms included cash-award initiatives modeled after the successful Ansari X-Prize competition, which led to the first successful privately crewed suborbital spaceflight. A more noteworthy example is the successful Commercial Orbital Transportation Services (COTS) program, which NASA and private companies coinvested in to develop commercially operated cargo delivery services to the ISS. This model was later used to develop commercial-crew transportation services to and from the ISS. The COTS program led NASA to enhance an increasingly important mechanism—economic analysis and due diligence capabilities—to help shape the program and assess the ability of the contenders to attract non-NASA investments.

Also during this era, NASA explored new models for obtaining scientific data from space. Among the higher-profile initiatives in this area was the effort to commercialize the Landsat program by underwriting the development and launch of land-imaging satellites whose data collection and sales were managed by a private company.

NASA also coinvested with R&TD companies on capabilities with game-changing potential, including the X-33 and X-34 spaceplanes, under the Reusable Launch Vehicle program, which aim to develop a fully reusable launch vehicle that ultimately could replace the partially reusable Space Shuttle.

This era also saw the introduction of new mechanisms of support, such as direct in-space support, and new kinds of enabling infrastructure, beginning with the Space Shuttle and later including the ISS. In 2005, Congress created the ISS National Laboratory to support non-NASA research aboard the orbiting platform, including for new materials with commercial potential.

Additionally, NASA experimented, albeit very briefly, with venture capital engagement through a partnership with Red Planet Capital, which invested in capabilities with the potential to support Agency goals.

In summary, the period spanning 1980–2010 was arguably the first in which NASA prioritized the development and expansion of a commercial space industry. While not all of the Agency's initiatives succeeded, many did, proving out new business models and helping to establish the foundation for the commercial sector as we know it today.

NASA Today Era

During the last era examined in this report, 2011–2024, NASA more fully embraced the commercial models proven during the previous period, with the goal of meeting core Agency requirements, including ISS cargo and crew transportation, lunar exploration, and infrastructure in low Earth orbit (LEO). NASA's willingness to rely more heavily on commercial products and services helped spur unprecedented levels of investment in ventures aimed not only at NASA but also other government agencies, both domestic and international, and the private sector.

As in previous eras, contracts and partnership agreements played a central role. NASA's Commercial Crew Program, modeled after the COTS program, began launching astronauts in 2020 and today is the only U.S. means of ferrying crews to and from the ISS. NASA also initiated the Commercial Lunar Payload Services program, which gives private companies substantial leeway in supporting the Agency's Artemis exploration objectives with robotic spacecraft and landers. NASA even embraced a commercial-like model to develop next-generation space suits and to develop the Human Landing System (HLS) to take astronaut crews to and from the lunar surface.

Additionally, NASA's Commercial LEO Destinations program supports private sector efforts to develop an ISS successor for the government and commercial organizations to use. This program is another example of NASA's efforts to transition a traditionally government-led activity to commercial providers that can serve private customers and meet NASA's requirements. Similarly, NASA began commercializing its space transportation requirements through initiatives such as the Launch Services Program and Venture-Class Acquisition of Dedicated and Rideshare.

Direct in-space support came into its own during this era, as the ISS became a platform not only for astronaut-assisted, commercially focused microgravity research but also for the deployment of privately owned CubeSats. This in-space support extended to commercial activities on the lunar surface, as NASA deployed its Lunar Reconnaissance Orbiter and other assets to help Intuitive Machines assess and address technical difficulties with its IM-1 commercial lander.

With the private sector's growing success in space activities, NASA made greater use of relatively new mechanisms, such as market stimulation funding, which proved itself in the COTS program, and economic analysis and due diligence capabilities, a mechanism that is necessary in evaluating the viability of companies and proposals. NASA also increasingly considered the equity of its efforts and expanded them to ensure benefits to and engagement of those who did not historically have significant access to the space sector.

The Bottom Line

Throughout NASA's history, the Agency has supported the development of the commercial space industry, helping to spawn industries such as satellite telecommunications, launch, and remote sensing. The last two to three decades have experienced a dramatic increase in this regard through new NASA-owned capabilities, such as space-based infrastructure, and the embrace of burgeoning commercial investment capabilities to support NASA's mission needs. NASA's use of commercial capabilities has evolved from being the exception to being the default arrangement for many missions, and the Agency continues to find creative ways and new mechanisms to further nurture this industry. The commercial space sector allows NASA to keep its focus on critical agency needs without a market and to continue pushing the boundaries of the space frontier.

NASA's use of commercial capabilities has evolved from being the exception to being the default arrangement for many missions, and the Agency continues to find creative ways and new mechanisms to further nurture this industry.

Introduction

The growth in U.S. commercial space capabilities in the 21st century and their integration into an increasing array of NASA programs is the result of over five decades of effort by individuals and teams at NASA and in the private sector. While commercial space is often depicted as being a recent phenomenon, beginning a decade or two ago at most, NASA has used a variety of mechanisms to encourage commercial space capabilities since it was established—and even before that, with one of its predecessor organizations, the National Advisory Committee for Aeronautics (NACA). Understanding NASA's role in commercial space development on a timescale of decades provides a fuller appreciation of the long-run importance of NASA to commercial space development and vice versa. This history provides an opportunity to analyze and understand NASA's approach to commercial space development in a new way, by identifying the high-level mechanisms that NASA has used consistently over its history to support commercial space development, as well as the mechanisms that NASA has used during particular periods. Through our categorization and identification of these mechanisms and discussion of the contexts in which they have been used, NASA employees and space policy stakeholders can gain a greater appreciation for the tools in the toolbox that NASA has used to support commercial space development. Because this report identifies the tools and describes their use, we hope that individuals interested in how NASA can support commercial space development will refer to this document to guide new initiatives and alternatives.

From the perspective of NASA's Office of Technology, Policy, and Strategy (OTPS) and NASA's chief economist, the tools—what this report calls mechanisms—that contribute to commercial space development are much more varied than those often discussed and are much more significant than typically assumed. Many people are familiar with the important role played by NASA's Other Transaction Authority (OTA) and associated Space Act Agreements (SSAs); NASA's use of milestone-based, firm-fixed price payments for commercial services; and NASA's Small Business Innovation Research (SBIR) program. Less discussed but arguably equally important are NASA's indirect mechanisms of

NASA has used a variety of mechanisms to encourage commercial space capabilities dating back to its origins.

support. These mechanisms include partnerships with academia; the education and development of the national aerospace workforce; NASA employees' mobility into industry and engagement with external audiences, both of which result in skills and experience flowing into companies; and even the public narratives of encouragement that point to a vibrant and evolving future in space featuring substantial commercial activity.

This report describes NASA's toolkit for commercial space development and is intended for use by anyone trying to understand how the current growth in commercial space development came to be and how to continue encouraging this growth. The document is not meant to be a comprehensive history, nor a final account of NASA's mechanisms. The hope is that the toolkit will be updated and improved as our understanding improves, lessons are learned from the many current programmatic experiments in commercial space development, and new mechanisms are developed and put into practice. All toolkits are incomplete because the complexity of the field they try to describe can never be condensed into a single document. This toolkit will be considered effective if it provides a gateway to those new to commercial space development or provides a useful reference and unique guidebook to those already in the field. For those working to encourage the long-run future of commercial space development in the United States and around the world, we hope this toolkit serve as a productive companion in their efforts.

Introduction to Commercial Space Development Mechanisms

There are many ways in which a government agency can support the development of the commercial space sector. The toolkit described in this document uses the concept of commercial space development mechanisms as a framework to simplify and categorize the many types of tools while also being specific enough to capture the nuances between the mechanisms' various implementations. Mechanisms beyond NASA's ability to implement, such as tax credits, are not considered. Furthermore, not every historical implementation of each mechanism or submechanism is covered.

Readers familiar with commercial space development at NASA will notice that SAAs and SBIR grants are not listed as mechanisms. That is because SAAs and SBIRs are specific examples or implementations of a given mechanism, as described in the mechanism definitions section below.

It is also important to remember that the core of implementing and enacting any commercial space development mechanism at NASA is the actions of individuals. Throughout NASA's history, including when the NACA operated, many key individuals have played pivotal roles in the commercial development of aviation and space. Many have been underrepresented in the annals of history. This report features short vignettes—titled NASA Champions of Industry—of many, though far from all, of the pioneers who left their mark on the history of commercial air and space development. Their lives and work echo in the present, improving the Agency and the aerospace industry.

Eras of Commercial Space Development at NASA

In this report, the mechanisms of commercial space development are assessed across four eras: the origins of NASA era (1915–1960), the Apollo era (1961–1980); the Shuttle era (1981–2010); and the NASA today era (2011–present).

The origins of NASA era included both the first few years after the creation of NASA in 1958, as well as the activities of NASA's predecessor organization, the NACA. Many of the core mechanisms that NASA has used to support commercial space development were first implemented by the NACA to support commercial aeronautics capabilities.

The Apollo era included the first human spaceflights on Mercury and Gemini; these flights created the foundational technical and operational knowledge for all subsequent human spaceflight vehicles, including commercial ones. These flights also motivated the first national commitment to land astronauts on the Moon, which resulted in unprecedented investments in industrial space capabilities. This era also included the early generations of commercial communications satellites, which NASA supported in several ways, and NASA's development and launch of the first civilian Earth observation satellites, activities that helped give rise to today's vibrant commercial remote-sensing industry.

The Shuttle era began with the first Space Shuttle launch and continued through the orbiter's 40 years of operation, which supported the development of commercial space capabilities in new ways. One example is the assembly of the International Space Station (ISS), which continues to serve as the core of economic development related to human spaceflight in low Earth orbit (LEO). Additionally, this era included the introduction of new commercial space development mechanisms, including engagement with venture capital (VC) and the provision of direct in-space support by NASA astronauts for companies and commercial applications.

The NASA today era began with the start of the Commercial Crew Program, which committed the Agency to launching its astronauts on commercially owned and operated vehicles. This era has also seen a dramatic expansion of the use of commercial capabilities to achieve a variety of NASA missions, including everything from acquiring Earth observation data to landing the next astronauts on the Moon through Artemis. This era includes arguably the most significant expansion of commercial space activity and the most extensive commitment by NASA to leverage these capabilities, but fundamentally new high-level commercial space development mechanisms have not been introduced during this period. Rather, there has been, and very likely will continue to be, an extensive expansion of the use of and innovative experimentation with the mechanisms that have been proven beneficial in the earlier eras.

Definitions of Commercial Space Development Mechanisms

The National Aeronautics and Space Act of 1958, which established NASA as a new agency of the federal government, charged the Agency with advancing the United States' industrial capabilities related to spaceflight. Although the Space Act did not explicitly mention commercial space applications, one of its core objectives for future

NASA activities was to improve “the usefulness, performance, speed, safety, and efficiency of aeronautical and space vehicles.” This objective has continuing commercial space implications.

The 1990 NASA Authorization Act amended the Space Act and added two important foundational responsibilities: (1) “seek and encourage to the maximum extent possible, the fullest commercial use of space” and (2) “encourage and provide for Federal Government use of commercially provided space services and hardware, consistent with the requirements of the Federal Government.”[1] NASA has employed a variety of strategies and mechanisms across its programs to fulfill these responsibilities.

The commercial space development mechanisms identified in the toolkit stem from an economic perspective that includes a recognition of the major factors of production that are involved (e.g., labor, capital, land, and industrial technology advances). NASA executes its missions through programs and projects, and attempting to categorize at a high-level the mechanisms is to some degree a subjective exercise. The goal here is to be sufficiently comprehensive to cover a majority of NASA’s commercial space-related efforts, with the expectation that this framework will be refined and improved over time.

This report describes and provided examples of the following mechanisms, which NASA uses to encourage commercial space development:

Contracts and Partnership Agreements

NASA contributes to commercial space development by extensively using and innovating procurement and nonprocurement agreements (e.g., firm-fixed-price contracts, grants, and unfunded SAAs) to achieve its missions. Since the earliest days of NASA, over 80% of all appropriated dollars received by NASA have been allocated to industry and academia, with most allocated by procurement contracts. Innovation within NASA’s procurement contracts has been at the core of supporting commercial space development. In addition, NASA enters into 600–800 nonprocurement partnership agreements with a wide variety of domestic and foreign entities each year under multiple partnering authorities, and these partnerships affect every other mechanism. NASA currently has approximately 2,600 active partnership agreements.

Research and Technology Development (R&TD)

NASA contributes to commercial space by funding R&TD for its workforce and partners. NASA-funded R&TD improves the state of the art of technologies, which the private sector often incorporates into products and further improves. NASA has often needed to develop new technologies through R&TD to achieve its goals, and these development efforts collaterally advance commercial capabilities. These efforts often include collaborative R&TD between NASA, industry, and academia.

Dissemination of Research and Scientific Data

NASA contributes to commercial space development through ensuring that R&TD results and scientific mission results are broadly disseminated. NASA and NACA technical publications have often served as foundational knowledge that, when externally disseminated, have facilitated the broad diffusion of technical knowledge that can then be incorporated into commercial products and applications. NASA also shares data from its science missions and requires its science grant recipients to share their resulting findings, allowing for foundational Earth science, planetary science, heliophysics, and astrophysics data to be used for commercial space development purposes.

Education and Workforce Development

NASA contributes to commercial space development by directly providing and supporting nationwide STEM education and workforce development opportunities. NASA partners with academic institutions, professional education associations, industry, and other government agencies to provide instructors with experiences that capitalize on the excitement of NASA's discoveries in order to spark student interest and involvement. This effort includes offering professional development experiences, lessons, and classroom materials; using emerging communications and education technologies; and providing research opportunities and hands-on science and engineering activities that draw on NASA's unique missions. Although workforce development also occurs via NASA's funding of university R&TD, this mechanism focuses on NASA's activities in which education and workforce development are the primary rationale and measure of success.

Workforce and External Engagement Mobility

NASA contributes to commercial space development through the external engagement and mobility of the NASA civil servant workforce. NASA's civil servant workforce includes some of the most experienced and capable space professionals in the world, and the experience and skills that employees develop at NASA often flow into the commercial sector through engaging with the space community, including in their personal activities, as well as when they leave NASA, including to support and found commercial space companies.

Technology Transfer

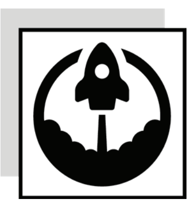
NASA contributes to commercial space development by transferring technologies it has developed to industry, including through direct technical assistance, tacit sharing of knowledge, and the licensing of patents. By transferring know-how and technology to industry, NASA allows companies to benefit from its technology investments.

Technical Support

NASA contributes to commercial space development by providing direct technical support to commercial space missions and development projects. NASA has provided its technical expertise to industry in the development of new commercial capabilities, including for operational commercial space missions.

Enabling Infrastructure

NASA contributes to commercial space development by providing access to and enabling use of NASA infrastructure, including buildings, launch pads, rocket testing facilities, and other capital-intensive physical sites. This access enables industry to access often-unique capabilities at a marginal cost.



Launch

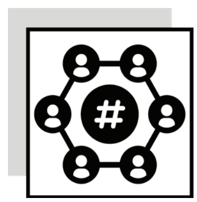
NASA has contributed to commercial space development by directly providing space access to companies. While prohibited from competing with the commercial launch industry since the 1980s, NASA can and does provide unique launch services that are not available commercially.

Direct in-Space Support

NASA contributes to commercial space development by directly providing in-space support for commercial space projects. This support has included the provision of communication capabilities for commercial missions and the technical assistance and support of NASA astronauts for commercial payloads on the Space Shuttle and the ISS.

Standards and Regulatory Framework Support

NASA contributes to commercial space development by setting technical standards that enable industry interoperability and by supporting regulatory frameworks that enable commercial use of space. NASA contributes to the development of common technical reference standards, including for various spacecraft interfaces. NASA also contributes to regulatory standards that support a sustainable space environment in which commercial space development can grow and that support norms for responsible behavior in space.



Public Engagement

NASA contributes to commercial space development by creating opportunities to engage the general public in space activities. These efforts include a wide range of activities, such as public lectures, documentaries, and citizen science events. Additionally, NASA allows commercial use of the NASA logo under certain conditions. Public engagement directly benefits commercial space development by publicizing shared achievements and benefits commercial space development indirectly by inspiring individuals to commit their talents to the space sector.

Industry Engagement

NASA contributes to commercial space development by engaging with space companies outside of projects and contracts so that the Agency better understands industry plans and interests, and vice versa. Industry engagement is distinct from formal, contractually defined efforts and includes requests for information, industry days, and industry representation on NASA's advisory committees.

Venture Capital Engagement

NASA contributes to commercial space development by engaging with VC firms to better understand the space investment landscape and to support space innovation programs and projects. NASA has undertaken a variety of VC engagement efforts, including inviting venture capitalists' input to program evaluation and working collaboratively in start-up accelerators to support technology developments of interest to NASA. While venture capitalists are not the primary private funders of space technology development and companies, NASA has engaged with them particularly because they are involved at the early stages of technology development.

Market Stimulation Funding

NASA contributes to commercial space development by providing funding to stimulate commercial space markets independent of NASA procurements. This funding encourages the emergence of new commercial space capabilities, including some that NASA has later gone on to purchase under contract.

Economic Analysis and Due Diligence Capabilities

NASA contributes to commercial space development by conducting economic analyses and due diligence of commercial space proposals. NASA's economic analyses have provided publicly available information related to commercial space investments and opportunities, and NASA's due diligence on commercial space proposals helps to ensure efficient use of taxpayer funds in support of viable commercial space businesses.

Narrative Encouragement

NASA contributes to commercial space development by creating and propagating public narratives that include a future of commercial space development. Narrative encouragement of a commercial space future happens through press releases and media engagements, internal publications and posts, and external consulting and advisement for films and other media for wide distribution.

Table 1 lists the mechanisms and indicates which eras the mechanisms have been used in.

Mechanism	Origins of NASA *1957–1960*	The Race to the Moon and the Expansion of NASA's Role in the Economy *1961–1980*	The Rise of Internationalism and Commercial Space Development at NASA *1981–2010*	Commercial Space Acceleration and The Future *2011–2024*
Contracts and Partnership Agreements	X	X	X	X
Research and Technology Development	X	X	X	X
Dissemination of Research and Scientific Data	X	X	X	X
Education and Workforce Development	X	X	X	X
Workforce External Engagement	X	X	X	X
Technology Transfer	X	X	X	X
Technical Support	X	X	X	X
Enabling Infrastructure	X	X	X	X
Launch		X	X	X
Direct In-Space Support		X	X	X
Standards and Regulatory Framework Support	X	X	X	X
Public Outreach	X	X	X	X
Industry Engagement	X	X	X	X
Venture Capital Engagement			X	X
Market Stimulatation Funding			X	X
Economic Analysis and Due Diligence			X	X
Narrative Encouragement		X	X	X

Table 1. Mechanisms and eras of use.

Law: The Frame of Every Mechanism

NASA's interactions with other entities are governed by various legal instruments. These legal instruments can be divided along several lines: procurement versus nonprocurement, reimbursable versus nonreimbursable, and funded versus unfunded.

NASA has explained that procurement contracts, "subject to the Federal Acquisition Regulations (FAR) and procurement statutes, are required when the principal purpose of the transaction is to acquire property or services for the direct benefit or use of the Federal Government."[2]

NASA partnerships include "a wide variety of relationships with various external entities (e.g., contractors, academia, the public, other stakeholders). a distinct type of non-procurement business relationship that does not involve the acquisition of goods and services for the direct benefit of the Agency."[3]

Table 2 summarizes major legal instruments that NASA has at its disposal. The table excludes legal instruments that are purely between noncommercial entities, such as Economy Act Agreements and Employee Training and Development Agreements. The table also excludes international agreements because the focus of this document is on development of the U.S. commercial space sector.

Name	Legal Code	Definition and Use	Compliance
Procurement Contract	31 U.S.C. § 6303	Required when the principal purpose of the activity is to acquire (by purchase, lease, or barter) property or services for the direct benefit or use of the U.S. government	Armed Services Procurement Act (10 U.S.C. 2302) and the Federal Acquisition Regulation (FAR)
Cooperative Agreement	31 U.S.C. § 6305	Assistance instrument (i.e., the work being performed by the recipient is primarily for its own purposes, which NASA is supporting with financial or other assistance) Required when the principal purpose of the relationship is to transfer a thing of value to a party to carry out a public purpose of support or stimulation	Not subject to the FAR; subject to 14 C.F.R. Part 1260, OMB Circular A-110, and NPR 5800.1: "Grant and Cooperative Agreement Handbook"
Grant	31 U.S.C. § 6304	Assistance instrument Required when the principal purpose of the relationship is to transfer a thing of value to a party to carry out a public purpose of support or stimulation Use is appropriate (compared to a cooperative agreement) when no substantial involvement is expected between NASA and the party carrying out the activity	Not subject to the FAR; subject to 14 CFR Part 1260, OMB Circular A-110, NPR 5800.1: "Grant and Cooperative Agreement Handbook"
Other Transaction Authority Agreement	51 U.S.C. § 20113(e)	Can be of 3 types: • Nonreimbursable (NASA and the partner fund their own collaborative activities); may be called another name, such as a Space Act Agreement, memorandum of understanding, or memorandum of agreement • Reimbursable (on a noninterference basis, the partner pays NASA to use NASA resources to advance interests, when providing such resources is not in competition with the commercial sector) • Funded (NASA pays a partner to accomplish a goal consistent with NASA's mission and available only if the objectives cannot be accomplished by using a contract, cooperative agreement, or grant)	Not subject to the FAR; subject to NPD 1050.1 on Delegation Authority and the Space Act Agreements Guide, NAII 1050.1
Cooperation With Federal Agencies and Others	51 U.S.C. § 20113(f)	Allows NASA to use the services, equipment, personnel, and facilities of federal and other agencies and cooperate with other public and private agencies and instrumentalities in the use of services, equipment, and facilities, with or without reimbursement	Authorized in the National Aeronautics and Space Act
Commercial Space Launch Act Agreement	51 USC § 50913	Gives NASA authority to provide property and services supporting launch or reentry efforts to state governments and the private sector Intended to facilitate: • Private sector operation of U.S. expendable launch vehicles • Acquisition by the private sector of launch or reentry property and services that are excess or otherwise not needed for public use	Must be provided on a noninterference basis Appropriate only if no equal commercial services are available on reasonable terms Requires only direct-cost recovery for launch property and services that are not provided by sale or similar transaction

Table 2. Relevant legal instruments.

Name	Legal Code	Definition and Use	Compliance
Commercial Space Competitive-ness Act Agreement	51 U.S.C. § 50504	Provides NASA discretionary authority to allow nonfederal entities to use its space-related facilities on a reimbursable basis if: • The facilities will be used to support commercial space activities • Such use is compatible with federal activities • Equivalent commercial services are not available on reasonable terms • Such use is consistent with public safety, national security, and international treaty obligations Provides for recovery on a direct-cost basis Payments received for use of facilities must be credited to the appropriation from which the cost of providing the facilities was paid	OCFO's NPR 9090.1 provides that it is NASA policy to use Space Act authority in lieu of CSCA authority for use of NASA space-related facilities by nonfederal entities
Cooperative Research and Development Agreement	15 U.S.C. § 3710(a)	Principal purpose is to transfer federally developed or controlled technology to state and local governments and to the private sector The collaborating party has the option of an exclusive license for a prenegotiated field of use for any invention developed under a Cooperative Research and Development Agreement (CRADA) The option for an exclusive license under an SAA is not permitted NASA may not provide any funding to the CRADA collaborating party	CRADA authority cannot be used to circumvent statutory and regulatory requirements of federal procurement laws (*Chem Services v. EPA*) Must be consistent with Executive Order 12591: "Facilitating Access to Science and Technology"
Property Loan	51 U.S.C. § 20113(e) OR 51 U.S.C. § 50913	Agreement used to loan personal property to non-NASA entities, generally for a specified period (temporary basis) and for specific purposes Loan may be accomplished under different authorities: • Other Transaction Authority (51 U.S.C. § 20113(e)): Loans optimally include charges for full cost; may charge fair and reasonable prices in light of clear and demonstrated NASA benefits, risks, and resources attributable to the activity • Commercial Space Launch Act (51 U.S.C. § 50913): For launch and reentry property that is excess or otherwise not needed for public use (direct costs)	Use of the loaned property is on a non-interference basis and the property must be available to NASA when required, and returned at the conclusion of the loan. Loan may not compete with the private sector Borrower is responsible for any damage to the property and must keep suitable records while property is in borrower's care, custody and control Subject to NPR 4200.1
Property Use Agreement	51 U.S.C. § 20113(e)	Legal instrument used to convey to a non-NASA entity for a specified period of time and for specific purposes the nonexclusive, nonpossessory use of land, buildings, and other structures (real property) that are not excess Based on NASA's OTA authority Does not convey a property interest in real property Proposed use must be consistent with NASA's mission Use is on a noninterference basis with NASA programs and activities	Use and associated services may not compete with private sector facilities and services NASA must receive fair value in money Payment with in-kind consideration requires a waiver consistent with 14 C.F.R. § 1204.504 Revenues received above operating costs, generally must be deposited in the Treasury's Miscellaneous Receipts account Subject to NPD 8800.14 and NPR 8800.15

Table 2. Relevant legal instruments.

Name	Legal Code	Definition and Use	Compliance
Real Property Lease	40 U.S.C. § 483	Legal instrument used to convey the exclusive use of land, buildings, and other structures (real property) that is not excess to a non-NASA entity for a specified period Payment is generally determined based on fair market value	Provision of associated services required for use of the land is appropriate; additional services cannot be provided in competition with the private sector Subject to NPD 8800.14 and NPR 8800.15 Revenues received above operating costs, generally must be deposited in the Treasury's Miscellaneous Receipts account
Enhanced Use Lease	51 U.S.C. § 20145	Permits NASA to lease real property to nonfederal entities at fair market value Also permits leases with federal entities; however, NASA policy does not give this permission (NASA Desk Guide for EUL of Real Property) Appropriate for use of underutilized, nonexcessed land, buildings, and other structures (real property) Funds (receipts) may be used for maintenance, capital revitalization and improvements to real property assets Net proceeds divided between the Center and NASA Headquarters Administration Pricing is based on fair market value Precludes in-kind consideration (payment) except for leases for the purpose of developing renewable energy production facilities Commercial alternatives are not required to be considered	Provision of associated services required for use of the land is appropriate; additional services cannot be in competition with the private sector Subject to the NASA Desk Guide for EUL of Real Property
Licenses for Intellectual Property	35 U.S.C. § 207	Agreement to transfer specific rights associated with federally owned inventions covered by a patent or patent application Scope can be defined as a "field of use" Licenses may be nonexclusive, partially exclusive, or exclusive Consistent with 37 C.F.R. Part 404, NASA must advertise requests for exclusive or partially exclusive licenses in the Federal Register and provide a 15-day response time; NASA minimally retains a government purpose license CRADAs require that NASA provide the cooperating party with the option of an exclusive license to government inventions; NASA retains a government Purpose license	License holder must commercialize the patentable invention or NASA can terminate the license Royalties generally are collected for licensed technologies Consistent with NPD 2092.1, NASA's policy is to share royalty payments with NASA inventors

Table 2. Relevant legal instruments.

Origins of NASA 1915–1960

Introduction

The Soviet Union's Sputnik I and Sputnik II launches prompted President Dwight D. Eisenhower and Congress to strengthen the United States' civil space efforts through the National Aeronautics and Space Act of 1958, which created NASA as a civilian agency. Eilene Galloway[4] deserves recognition as an indirect NASA Champion of Industry: her efforts to ensure NASA would be a civilian agency enabled NASA to engage more openly with outside partners, including companies.

NASA was not an entirely new organization, however. Rather, it was created by merging existing organizations, most notably the National Advisory Committee for Aeronautics (NACA). Other organizations included the California Institute of Technology's Jet Propulsion Laboratory (JPL), the Department of Defense's Advanced Research Projects Agency (ARPA), the U.S. Army Ballistic Missile Agency (ABMA), and the Naval Research Laboratory (NRL). Combined, these disparate components created an agency composed of Centers with distinct cultures[5] and characteristics that have contributed to a dynamic ecosystem driving innovation and creativity—an ecosystem that has supported the long-run development of commercial space capabilites.[6]

NASA was able to leverage an aeronautics industry that had been significantly advanced by the NACA—the single largest source of staff and infrastructure incorporated into NASA. The NACA was established by Congress after aviation became a significant factor in World War I.[7] The NACA was an advisory committee directly reporting to the president, just as the NASA administrator does today.[8] One of the NACA's most significant roles was to support the growth of the U.S. commercial aviation industry, and many of the mechanisms that NASA has used to support commercial space stem from that role.

In 1959, NASA published its long-range goals; this set of objectives, derived from the Space Act of 1958, have effectively defined the purpose of NASA ever since. These objectives include studying and exploring beyond the atmosphere, researching and developing aerospace vehicles, assessing solutions to aerospace technology problems, ensuring U.S. aerospace leadership, pursuing international cooperation on certain aerospace projects, and sharing relevant knowledge with the national security and intelligence communities.[9] Many of these objectives had been established by the NACA. NASA also introduced an important mechanism that the NACA did not employ: large procurement contracts for aerospace systems. The combination of the supply-side support mechanisms of the NACA and the demand-side, requirements-driven incentives of NASA is foundational to the core mechanisms that NASA has used to help advance commercial space development for more than half a century.

Contracts and Partnership Agreements

Contracts with industry were used to support NASA's unique needs, specifically in terms of human spaceflight systems and scientific robotic probes. The NACA, by contrast did not seek industry products or services related to commercial aviation development, nor did the NACA solicit contract proposals. To succeed with this new institutional approach, NASA adopted systems management practices from the Air Force air defense and ballistic missile programs during the 1950s, an approach that featured distinct roles for managers, scientists, and engineers from industry and the military.[10] Infused with significant sums of federal funding within just a few years, a contractor ecosystem quickly emerged to support NASA's new crewed spacecraft efforts. NASA ultimatedly contracted out up to 90% of its budget, a stark contrast to the much lower level at the NACA.[11] During NASA's early years, it contracted with companies to build and support systems owned and operated by the Agency.

R&TD

NASA and the NACA both played a driving role in advancing the state of the art of aerospace technology—in the NACA's case, through in-

NASA Champion of Industry

Dr. Abe Silverstein
Director of the Office Space Flight Development

Abe Silverstein. Credit: NASA/GRC.

Abe Silverstein had a seminal role in the history of NASA's contracts and procurement—one that ensured most of contracts would be performed by companies under significant government supervision. Silverstein was hired by the NACA in 1929 to manage the research portfolio at the Lewis Research Center, and later he became deputy director of the Center. He transferred to NASA in 1958 and soon led the Agency's Office of Space Flight Development. This office was charged with mission planning, spacecraft design and development, and in-flight research and operation, from robotic probes to Project Mercury and the Apollo Program. Silverstein leveraged his extensive NACA experience to manage a team that set the tone and established a foundation for how NASA engages with contractors on major agency programs. Silverstein became director of the Lewis Research Center in 1961 and retired from NASA in 1969.

house research; in NASA's case through in-house R&TD. The preamble of the National Aeronautics and Space Act of 1958 states that NASA's role is "to provide for research into problems of flight within and outside the earth's atmosphere, and for other purposes."[12] NASA was prepared to conduct this research because it incorporated all NACA assets and personnel as well as key programs from the Department of Defense. The NACA had primarily been a research organization from the beginning.[13] Its goal was to strengthen the overall state of American aviation technology, which was beginning to lag behind that of European countries after the outbreak of World War I. The Naval Appropriations Act of 1915 directed the NACA "to supervise and direct the scientific study of the problems of flight, with a view to their practical solution, and to determine the problems which should be experimentally attacked, and to discuss their solution and their application to practical problems."[14] The NACA was to conduct the research, and industry development was to follow.[15] The NACA's philosophy, essentially, was that strong research programs could support commercial development by enabling industrial innovation.

The launching of the first rocket at the NACA's Wallop's Island Facility on June 27, 1945. Credit: NASA on the Commons/Flickr.

During NASA's early years, one of the fundamental research questions regarded what the best approach to atmospheric reentry for a space vehicle was. The NACA also preformed research on this topic in the organization's later years, and the NACA's and NASA's combined work became the basis for spacecraft designs that commercial space companies employ today. The NACA's Pilotless Aircraft Research Division began conducting rocketry research in 1945 and developed "preliminary specifications" for a crewed capsule by the NACA's final year. These specifications were eventually used, at least in part, by the McDonnell Aircraft Corporation to construct the Mercury capsule.[16] The Pilotless Aircraft Research Division was led by Bob Gilruth, who remained in that role during its transformation into the Space Task Group at NASA. The Space Task Group was transferred to Houston in 1962 and went on to lead Project Mercury.[17]

Dissemination of Research and Scientific Data

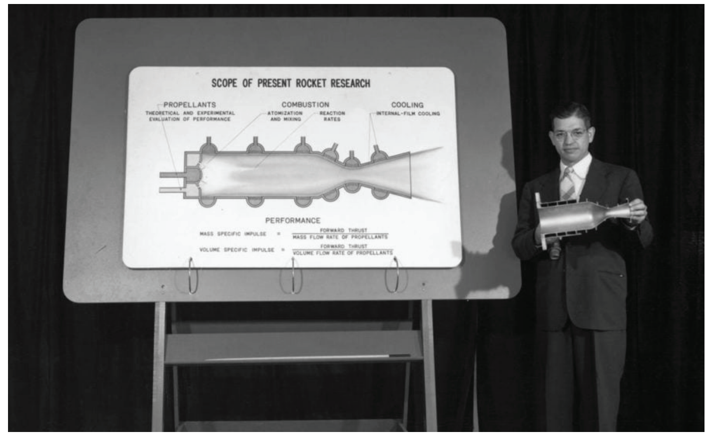
Disseminating the results of scientific research was a core mechanism used by the NACA. NASA has also used this mechanism, disseminating the results of development and thereby enabling the U.S. aerospace industry to advance its capabilities. From the start of this effort, there was a tension between the interest in companies having proprietary advantage and the interest in supporting broad U.S. capabilities and competition in the market. To retain good working relationships with industry while promoting competition and disseminating information when needed, the NACA adopted a policy on proprietary rights in 1949. The policy,

NASA Champion of Industry

H. Julian "Harvey" Allen
Director of the NASA Ames Research Center

Portrait of NASA Ames Engineer Harvey Allen explaining blunt nose principle. Credit: NASA/ARC.

H. Julian "Harvey" Allen's R&TD has had one of the most lasting impacts on the commercial development of space systems. Hired by the NACA in 1936, Allen was the mind behind "blunt bodies," the shape necessary to protect sensitive payloads from the heat of reentry following high-velocity spaceflight. Originally, this approach was classified, as it was a means to protect nuclear warheads launched on ballistic missiles. By the time Allen transitioned to NASA, this technology was used to support civilian missions, informing the design of reentry capsules and eventually the Space Shuttle orbiter.[18] Allen was responsible for defining the shape of future U.S. spacecraft, a shape ultimately adopted by spacecraft designers the world over.



Rocket research presentation at the NACA's 1947 Inspection. Credit: NASA GRC.

created by the NACA Executive Committee and Industry Consulting Committee, established that the NACA would withhold technical information, barring a special agreement, about models or components under active development, to "preserve the manufacturer's competitive position." Additionally, the policy stated that the NACA had to provide the manufacturer with a list of companies it would send testing results to and that any oral communication by NACA prior to report publication was subject to review.[19] The policy was designed to protect the competitive advantages of partner companies while incentivizing them to conduct aeronautics research with the NACA.[20] Companies came to admire the NACA for its discretion, but this discretion also constrained its freedom to stimulate competition through the sharing of information.[21] Publishing reports was one of the most important strategies that the NACA used to support U.S. aerospace interests. The NACA published its first technical report on rocketry in 1947.[22] That year, the NACA presented its research at the annual NACA Inspection, which included industry representatives. From then on, after researching a flight project, the NACA would release the resulting data in technical reports and memoranda, including an annual report called

NASA Champion of Industry

Pearl Young

NACA's First Female Professional

Pearl I. Young. Credit: NASA.

The improved readability and reputability of NACA reports was in no small part thanks to physicist and technical editor Pearl Young, who joined the NACA in 1922 as its first female professional. She initially worked in Langley's Instrument Research Division, where she noticed deficiencies in the writing quality of the NACA's technical reports. In response, Young created a better writing system for staff to follow, and in doing so she revolutionized the preparation of technical documents at the NACA. Many NACA engineers were originally annoyed at the extra time required to polish their reports before publication, but Young argued that it was better to produce superior documents than to publish information quickly. The NACA ultimately published more than 16,000 research reports, and these reports were considered "the industry standard for rigorous investigation and analysis," according to a NASA history article about Young.[25] Her improvements made it much easier for industry to understand and apply the technical information developed by the NACA and, later, by NASA.

Report to the President, which contained the NACA's best papers of the year.[23] These world-class reports informed aircraft manufacturers of the strengths and weaknesses in America's flight capabilities.[24] Disseminating the data to industry naturally fostered industry growth, as firms worked to develop new solutions. This era ultimately showed that industry often reaps the benefits of scientific data that the government freely and effectively shares.

Education and Workforce Development

NASA did not engage in specific mechanisms to promote education and workforce development in its early years, given the focus on Project Apollo. The Agency did discuss general congressional direction to strengthen American education, but most of NASA's education and workforce development efforts were through on-the-job training that increased employees' technical expertise. NASA's workforce culture centered on a constant state of learning, and this mindset produced a competitive R&TD envrionment that encouraged thinking creatively, taking risks, testing repeatedly, and learning rapidly from mistakes.[26] NASA also conducted training exchanges with other federal agencies, academia, and companies, a practice that continues today.

The NACA was known for its relationships with academia, and these relationships encouraged workforce development. For example, the NACA provided technical advice to universities, and this information was included in college programs that future NACA employees completed.[27]

Developmental opportunities were also facilitated when Congress passed the Government Employees Training Act of 1958, which gave federal agencies authority to conduct employee training.[28] Ultimately, encouraging and providing resources for NACA workforce development and education spurred external engagement and employee movement to industry positions.

Workforce External Engagement and Mobility

The early movement of the NACA workforce and then the NASA workforce in and out of industry helped seed new knowledge and experience related to the frontiers of private sector aerospace R&TD. The potential for higher salaries often prompted NACA employees to take their technical knowledge to industry.[29] For instance, Victor Ganzer worked for the NACA's Ames Aeronautical Laboratory (what became NASA's Ames Research Center in 1958) before transitioning to Boeing and then teaching at the University of Washington. While at Boeing, Ganzer applied the NACA's development of the swept-wing design[30] to Boeing's first operational jet, the B-47.[31] Overall, even during the mid-20th century when there was a popular sense of government jobs being 'jobs for life,' there was significant mobility of NACA and NASA employees, a phenomenon that has continued and grown to this day. Individuals who develop skills while working for the government can ultimately enrich the talent pool in industry and vise-versa when employment mobility occurs.

NASA Champiuon of Industry

Dorothy Simon

From NACA Employee to Corporate Manager

Dorothy Simon greets Dr. N. P. Moore of the Imperial College London during a September 1954 visit to the NACA. Simon had recently returned from her research sabbatical in England. Credit: NASA.

Dorothy Simon completed a doctorate in physical chemistry in 1945 and soon after developed synthetic fibers at Dupont. Next, she was hired by the Department of Energy's Oak Ridge National Laboratory, where she isolated a new calcium isotope. In 1949, she joined the NACA Lewis Flight Propulsion Laboratory's Fuels and Combustion Division, where she developed a method for measuring flame velocity; this method was later used by engine manufacturers. Simon was promoted to assistant chief of the Lewis Combustion Branch, and her papers on combustion garnered international acclaim. In 1955, Simon left the NACA to work in the Texas oil industry, and later she worked at the aerospace firm AVCO Corporation, serving as a technical advisor, head of the combustion group, and eventually the company's first vice president and director of research. In the 1960s, Simon contributed to the design of spacecraft heat shields. She died in 2016, leaving a legacy through her contributions to the field of combustion and her support of women in STEM.[32]

Technology Transfer

Technology transfer at NASA began during the NACA's operations and continues to this day, including through patents and licensing. NACA professionals participated in technology transfer through technical publications and interactions with industry counterparts, often at conferences.[33] A few examples of NACA research that benefited industry are Richard Whitcomb's conceptualization of a way to lower transonic drag on aircraft,[34] Dorothy Simon's method for measuring flame velocity,[35] Lewis A. Rodert's system for deicing plane wings,[36] and John Stack's development of the slotted-throat wind tunnel for testing aircraft.[37] The NACA did not have the well-established legal mechanisms for technology transfer that exist today, and it is unclear how the results in NACA technical reports were translated to industry innovation at scale, though there are many examples of individual reports that had a positive impact.[38] According to one historian, "It was part of the unwritten rules of this [NACA-industry] interaction that the government did not ask for credit or receive patents."[39] This practice allowed industry to take credit by simply remaining silent. Potentially lucrative discoveries made by industry, by contrast, were often protected through patents or were kept secret.[40] This tension between government and commercial researchers continued to frustrate NACA staff until NASA's creation.

Unlike the NACA, which conducted research to benefit military and industrial aviation, NASA "became its own principal customer,"[41] and its contracts with industry, especially in its early years, were primarily to benefit the development of NASA-owned capabilities. The National Aeronautics and Space Act of 1958 made technology transfer a NASA mandate and required that the Agency widely disseminate the results of its activities. The act also gave NASA the ability to patent inventions and retain the rights to all NASA inventions and intellectual property—provided the research was conducted with government funds and the rights were not waived by NASA's administrator.[42] NASA was a pioneer of technology transfer activities that later spread to the rest of the federal government and around the world.

Technical Support

In NASA's early years, it does not appear to provide much technical support to industry outside of its own development programs. However, the NACA had a long history of providing this type of support to industry, and companies would sometimes pay the NACA up front to conduct research on a particular flight issue[43] or glean technical expertise from NACA employees.[44] For example, in 1939, the NACA tested an airplane model for famed aviator and founder of the Hughes Aircraft Company, Howard Hughes. Paranoid that outsiders would profit from the research data, Hughes designed a model plane that was not the final plane he wanted tested but was similar enough that he could obtain the data he needed before the actual flight.[45] NACA staff also directly supported external researchers. For example, in 1938, liquid-fuel rocket pioneer Robert Goddard met with the NACA's first employee and executive secretary, John F. Victory, in Washington, DC. This meeting led to a productive relationship between Goddard and the NACA. For instance, the NACA's director of aeronautical research, George Lewis, personally provided information to Goddard regarding recently captured German planes that showed evidence of jet-assisted-takeoff attachments. Lewis subsequently supported Goddard in submitting to the Navy a workable design for a liquid-fuel jet-assisted-takeoff; this submission resulted in one of Goddard's largest contract.[46] The NACA demonstrated that technical support can effectively occur through informal interactions—such as at conferences—and benefits from resources that are devoted to creating opportunities for these interactions.

Enabling Infrastructure

NASA's infrastructure is one of its most enduring mechanisms for supporting commercial space development, and much of the infrastructure was established at the NACA and during NASA's early years. The NACA's three large research laboratories (what later became the Langley Research Center, the Ames Research Center, and the Glenn Research Center) and two small test facilities (what later became the Wallops Flight Facility and the Armstrong Flight Research Center) were the largest components incorporated into NASA in 1958. Other sites followed, including the Redstone Arsenal (in 1960, parts of this facility were renamed the Marshall Space Flight Center) and the JPL, among others. NASA used this infrastructure to support its early programs, most significantly Project Mercury.

Although NASA's space missions had almost complete priority in using Agency infrastructure during the early years, the NACA's infrastructure had long been leveraged by industry to advance its R&TD objectives. Wind tunnels were the main enabling infrastructure that the NACA provided to industry. Wind tunnels provide a valuable means of connecting aviation design theory to practice and were the main methodology for studying aeronautics; consequently, they were in high demand. They were also expensive. For these reasons, industry came to greatly rely on the NACA for wind tunnel testing.[47] The NACA provided industry access to NACA wind tunnels, especially after the Unitary Wind Tunnel Plan Act of 1949, which formalized this access to support the aircraft industry.[48] The gathered data allowed industry organizations to perfect airplane manufacturing, and the resulting innovations stimulated competition. In 1938, Robert Goddard even used Langley's high-speed wind tunnels for aerodynamic tests of 18-inch rocket casings.[49] In addition to sharing wind tunnels, the NACA and industry also occasionally shared and exchanged airplane parts and hardware on an unofficial basis.[50] The NACA's history of enabling industrial use and benefits from its infrastructure showed that long-term investments in large, expensive infrastructure that industry does not own supports commercial innovation.

Turning Vanes inside the Altitude Wind Tunnel. Credit: NASA.

Standards and Regulatory Framework Support

Both the NACA and NASA played important roles in recommending and establishing standards and regulatory frameworks for companies to use in subsequent decades.

The NACA helped promote and advance aviation standards, including proposing the licensing of pilots; recommending the creation of the Manufacturers Aircraft Association; proposing aircraft inspection; proposing that funds be given to the Weather Bureau to promote safe air navigation; and advising President Calvin Coolidge's Morrow Board, which led to the first federal legislation regulating civil aeronautics, in 1926.[51] The early standard-setting efforts, established through operational spaceflight and the growth of the early aviation industry, led to an enduring role that NASA fills to aid commercial space development.

In NASA's early years, it focused on executing its missions, and it set standards for the industry through these missions. One example is the Agency's policy involvement in U.S. satellite telecommunications development. Toward the end of the 1950s, policymakers faced the question of whether to help AT&T extend its national telecommunications monopoly into space. AT&T was prepared to invest $30 million to build what would become the first true telecommunications satellite and was looking to NASA for technology, launch, and operations support.[52] At the same time, Hughes Aircraft Company was actively seeking NASA funding for the company's proposed Syncom geostationary-orbiting communications satellite program, and these competing interests created a contentious policy issue. Keith Glennan, NASA's first administrator, influenced the Eisenhower administration's policy decision to let the private sector, represented by AT&T, take the lead in developing the industry, with NASA taking on a supporting role.[53] This policy was subsequently abandoned by the John F. Kennedy administration, which gave the Federal Communications Commission regulatory authority over the industry and directed NASA to pursue contracts to advance the technology that ultimately aided AT&T competitors Hughes and RCA. One could interpret the direction given to NASA as evidence of the Agency role in supporting market competition—a vital function for encouraging the growth of the industry.

Ultimately, the NACA promoted standards and regulations that advanced the U.S. aerospace industry, and NASA continued this role with mixed results in the following decades, as this report will show. Governmental standards and regulatory frameworks provide industry with guidance regarding acceptable, effective, safe, and organized operational practices.

Public Engagement

Public engagement can be effective in inspiring future generations to pursue specific careers and also conveying a geopolitical narrative about the state of American technology as a symbol of national power; this narrative can later translate into organizational funding. In the early years, the NACA and then NASA participated in public engagement to share the news of joint accomplishments with industry and to inspire future generations to pursue spaceflight-related careers.

The NACA, for example, informed the public of the organization's activities, including those involving industry through the speakers' bureau and the Office of Public Information, established in 1947 and led by Walter Bonney. The Office of Public Information published approximately 50 news releases for the aerospace community.[54] Additionally, NACA employees volunteered to participate in the speakers' bureau and spoke at external organizations to "sell NACA to the public."[55] Speakers' bureau members spoke to insurance groups, clubs, church groups, and other civic organizations throughout their careers.[56] Eventually, the speakers' bureau evolved into NASA Engages, which helps NASA in its efforts to inform and inspire the public and which draws upon the knowledge and experience of NASA's employees.[57]

In 1959, the NASA Mercury Program began and the Office of Public Information greatly expanded its workload to support press inquiries, update the public on NASA's activities, and support science education so people could better understand what NASA was doing.[58] In that year alone, the office published several hundred public new releases.[59]

In many ways, NASA's early years were defined by significant political, technical, and human drama, elements that enabled the Agency to inspire and engage the public and future aerospace professionals. However, in the first two years following NASA's founding, perhaps the most outwardly inspiring event related to public engagement was the selection of Project Mercury astronauts, a group of seven men officially introduced to the public in April 1959. The Mercury Seven epitomized the notion of having the "right stuff." The astronauts became larger than life, even heroic, wearing their silver space suits, climbing into dangerous machines, and hurtling through space at high speeds. These men became symbols for NASA and the nation overall.

The selection of Mercury astronauts and their subsequent legacies as American space heroes is inspirational, but it is also important to acknowledge NASA's painful exclusion of women and persons of color from the original astronaut core. Two years after the selection of the Mercury Seven, under a privately funded initiative 13 commercially rated female airline pilots passed the astronaut fitness tests required of their male counterparts.[60] Despite the Mercury 13 women's impressive aptitude, they were ultimately disqualified as astronaut candidates because of their sex. Similarly, African American U.S. Air Force pilot Ed Dwight, who was personally championed by President Kennedy to make the 1963 roster of NASA astronauts, was denied entrance to the NASA astronaut corp. More than 50 years later, it would be Blue Origin, not NASA, that flew Mercury 13 member Wally Funk and Ed Dwight to space. NASA did not welcome women or persons of color into the astronaut corps until 1978; this shift in practice was thanks in large part to the recruiting efforts of Nichelle Nichols, who played Lieutenant Uhura on Star Trek. While there is still more work to do in terms of diversity, the diversity of today's NASA astronaut corps communicates to millions that space is for everyone—whether they work for a space company or the federal government.

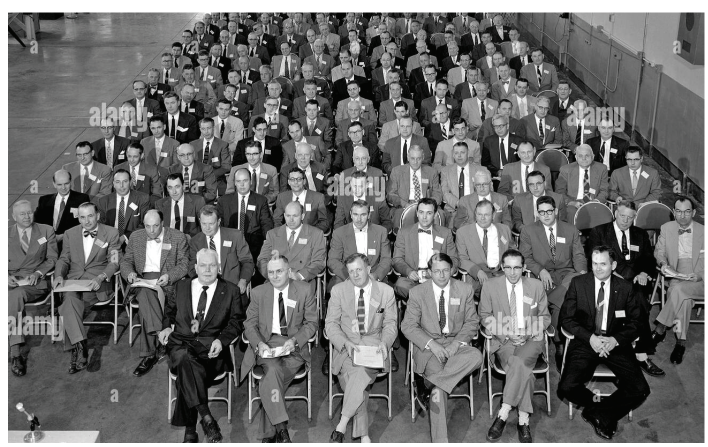
Industry Engagement

NASA relied heavily on industry during the Agency's early years, and the NACA pioneered several approaches to industry engagement that paved the way for the more collaborative relationship with commercial space companies that developed in the following decades. NACA's engagement with industry began slowly. The NACA initially resisted industry participation in the NACA's main committee, fearing that industry influence would turn the NACA into a "consulting service." World War II changed this perspective, and the NACA's industry relations began to strengthen when industry began visiting Langley during the war years to observe and assist in aircraft testing. In 1939, the first industry representative, George Mead, joined the NACA as the Executive Committee's vice chairman and as the Power Plants Committee's chairman, having retired from his role as vice president of the United Aircraft Corporation.[61] In 1945, the year the war ended, the NACA's Consulting Committee was established,[62] and in the years following the war, the NACA's interactions with industry continued at a heightened level.

The NACA also engaged with industry through yearly conferences and large "inspections" that detailed the various areas of the NACA's work, including rocketry. These events were designed to transmit research data to companies quickly[63] and were also open to members of Congress. In addition, NACA employees visited industry labs to deliver research data, and industry employees visited the NACA to likewise deliver data.[64]

The Industry Consulting Committee and members of the NACA Executive Committee at the Cleveland laboratory, September 26, 1945. Credit: NASA.

During NASA's first era, a prime example of engagement with industry was the establishment of the National Aeronautics and Space Council (NASC), required by the 1958 National Aeronautics and Space Act. The NASC initially reported to the president and then, starting in 1861, to the vice president and was directed to provide advice on interagency space activities, such as between NASA and the Department of Defense. Members included senior federal officials and, initially, three members of the private sector. Private sector participation was removed from the NASC in 1961 by the Kennedy Administration.[65] The NASC was



The NACA 1956 Inspection at Lewis Flight Propulsion Laboratory. Over 150 guests from industry, other NACA laboratories, and the media attended the event. Credit: NASA/GRC.

discontinued in 1973. In 1989, the George H. W. Bush administration established the National Space Council, which some people have viewed as a re-creation of the NASC[66] and which was discontinued in 1993 and then reinstituted in 2017. Today's National Space Council, under the Biden administration, is composed of a civilian executive secretary; a Users Advisory Group; and a Federal Advisory Committee with members from nonfederal offices, such as industry companies, academic institutions, and other organizations.[67] Internal to NASA is the NASA Advisory Council, whose membership includes people in industry.[68] In summary, during the NACA's operation and the early years of NASA, industry representatives were included in various Agency committees. This collaboration provided an opportunity for greater engagement and feedback from and to industry on government needs for commercial development.

Conclusion

The NACA's years of operation and the early years of NASA saw the development of many of the core mechanisms that NASA still uses to support commercial space development. Although there is often discussion of whether NASA should return to its NACA days, the truth is that NASA has never stopped doing the things that the NACA did in terms of sharing R&TD results with the public and industry, supporting industry through facilities and technical assistance, and setting and coordinating standards of value for the field. With the creation of NASA, a major mechanism was added to the NACA's support mechanisms: the mechanism of large procurements for new space systems. These procurements created the industrial foundation for the development of all space systems to come, including modern commercial space capabilities.

The NACA played a particularly large role in the growth of commercial aviation, in part because aviation was far easier to commercialize than space activities were, because of aviation's lower cost and evidently clear commercial applications. Though an aviation market existed in some form during the entirety of the NACA's existence, only in the last year of the NACA's operations did an artificial satellite orbit the Earth. Therefore, the NACA and NASA were started for similar reasons (to increase U.S. technical capability in aerospace), but the NACA had the benefit of beginning operations when a commercial market already existed and when barriers to development were lower. Barriers to the commercial development of space have always been higher than for aviation, but NASA, carrying on the tradition of the NACA, uses a wide variety of mechanisms to perpetually lower the barriers.

The early years of NASA and the preceding decades of the NACA established many of the core mechanisms that NASA still uses to support commercial space development.

The Race to the Moon and the Expansion of NASA's Role in the Economy 1961–1980

Introduction

Spurred by President Kennedy's Cold War challenge to land astronauts on the Moon by the end of the 1960s, NASA's budget soared during the early years of the decade, peaked in 1965 at $5.25 billion[69] ($69.19 billion in 2024 dollars[70]), and then fell back toward Earth through the first half of the 1970s. NASA also invested heavily in infrastructure, establishing the Kennedy Space Center in Florida and the Johnson Space Center in Texas, while substantially beefing up the Marshall Space Flight Center in Alabama. Coupled with a surge in U.S. Air Force spending on early rocket and satellite programs, NASA's Apollo-era budgets helped industry develop the foundational space capabilities that eventually unleashed in the commercial sector.

Apollo's impact went well beyond the space industry, but here too, there were direct benefits to the commercial space sector. For example, NASA's embrace of what at the time was a novel technology—the integrated circuit—helped launch Silicon Valley's ongoing revolution in computing technology, which continues to pay major dividends as a commercial space enabler.[71] Apollo's stunning success also inspired countless people to pursue careers in space, with many cutting their teeth on NASA programs before going on to blaze trails in the commercial sector.

Apollo was clearly the dominant NASA program from 1961 to 1980, but during this era NASA also began supporting, in earnest, space applications with commercial potential. For example, during the 1960s NASA directly supported the nascent satellite communications industry with launch services, infrastructure support, and development funding. This support is perhaps the earliest example of NASA efforts aimed specifically at fostering the commercial space sector. During the 1970s, NASA launched the first civilian satellite dedicated to land imaging—a precursor to the commercial remote sensing industry as we know it today.

Contracts and Partnership Agreements

Arguably, NASA's most impactful form of commercial space sector support during the Apollo era was contracts to develop capabilities that later were applied commercially. NASA's 1960s investments in launch vehicles, for example, helped lay the technological foundation for a commercial launch industry that emerged in subsequent decades.

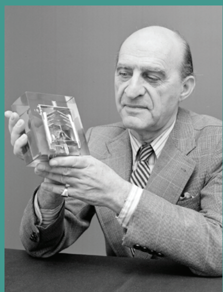
Commercial capabilities often were a by-product of NASA's exploration pursuits, but the Agency also made investments specifically intended to build up the nascent satellite telecommunications sector. The first communications satellite, Telstar, was developed and funded by the telecommunications monopoly AT&T, with NASA supplying only launch and in-space support. But after the change from the Eisenhower administration to the Kennedy administration, NASA began directly funding communications satellite development efforts by aspiring AT&T competitors, including Hughes Aircraft Company and RCA. In 1961, for example, NASA awarded Hughes a $4 million contract to develop the first-ever geostationary-orbiting communications satellites under a program called Syncom. The Syncom satellites were the forerunners of the first satellites operated by Intelsat, which began as an intergovernmental cooperative established by treaty and operates today as a fully privatized satellite communications company.[72]

Hughes went on to become a dominant supplier of commercial telecommunications satellites during a period of explosive industry growth in the 1990s and also founded the DirecTV venture, one of the world's most successful direct-to-home television broadcasting companies.

R&TD

Even as commercial manufacturing of telecommunications satellites gained footing during the Apollo era, NASA continued to push the technology envelope through collaborative R&TD programs, such as the Applications Technology Satellite (ATS) series, which developed and launched six satellites from 1966 to 1974. The ATS program was conceived as a follow-on to NASA's communications satellite development programs of the early 1960s. NASA and Hughes hoped to develop a more advanced version of the Syncom satellites, but the Agency broadened the technical scope amid congressional concerns over the use of taxpayer funds to benefit the Communications Satellite Corporation (COMSAT), the private company established in 1962 to operate U.S. communications satellites.[73] Nonetheless, ATS-6, launched in 1974, demonstrated a number of capabilities later adopted by the commercial sector, including a parabolic, 9-meter, steerable high-gain antenna and ion propulsion for orbital station keeping.[74] AST-6 is considered the first direct broadcast satellite.[75]

NASA Champions of Industry



Heinrich Kosmahl

Engineer at Lewis Research Center

Heinrich Kosmahl. Credit: NASA.

Heinrich Kosmahl's research contributed to one of the most enduring commercial space activities, greatly enhancing the efficiency of ground support costs. In 1966, NASA's Lewis Research Center created a small satellite communications program and tapped German-born physicist Heinrich Kosmahl, who had immigrated to the United States amid high Cold War tensions in 1956, to manage work on traveling wave tube amplifiers. In that capacity, Kosmahl developed a device that dramatically improved traveling wave tube amplifier performance while reducing costs. The device, which he patented in 1972, expanded the areas that satellites were able to cover and reduced the size of ground receiving equipment. The improved device has been a standard component in nearly every subsequent NASA and commercial communications satellite.[76]

Dissemination of Research and Scientific Data

Disseminating research and scientific data during the Apollo era contributed to industrial activities that ultimately blossomed into commercial space enterprises. In 1972, NASA launched the Earth Resources Technology Satellite-1 (ERTS-1), later known as Landsat 1, the first satellite explicitly designed to study Earth. Landsat-1 was the first in an ongoing series providing a continuous data record of Earth's changes over time. From the beginning, NASA was aware of Landsat's practical utility and funded numerous experiments to examine the data's applicability in areas including agriculture, water management, forestry, environmental management, and natural resource exploitation.[77] A frequent participant in these studies was Earth Satellite Corporation, a pioneer in the use of remote sensing data and now part of Maxar Corporation.[78] Landsat helped create a private sector market for satellite remote sensing data that today is served by commercial operators including Planet and Maxar.[79]

The Agency began publishing short, one-page summaries of new technologies, called NASA Tech Briefs, in the early 1960s. To broaden access to these popular reports, a monthly magazine of NASA Tech Briefs was published beginning in 1976.[80] In 1985, publication of the magazine was transferred to a private company, and the magazine has been privately run ever since.[81] NASA Tech Briefs were part of the Agency's charter, and the information in the publication is specifically for commercial use.

NASA Champions of Industry

Dr. Valerie Thomas
Director of the NASA Ames Research Center

Valerie Thomas. Credit: NASA.

Valerie Thomas began working for NASA's Goddard Space Flight Center in 1964, after graduating from Morgan State University in Baltimore as one of just two female physics majors in her class. At NASA, she taught herself everything she could about computer and computer programming; she cut her teeth on the data processing programs for NASA's Orbiting Geophysical Observatory satellites. Thomas later managed development of the Landsat image processing software that facilitated the programs that many applications use. In the process, she became NASA's go-to expert on the early digital tapes containing Landsat data, and she created the authoritative document for its scientific use. In the LACIE program, Thomas managed a team of about 50 people who developed a processing system capable of identifying wheat fields around the world in Landsat imagery. She went on to invent the Illusion Transmitter, a holographic image transmitter that works without the need for special glasses. After retiring from NASA in 1995, Thomas worked as a substitute teacher at a Baltimore-area high school. Her NASA honors include Goddard's Award of Merit, the highest award given by the Center, and the NASA Equal Opportunity Medal.[82]

Education and Workforce Development

Driven by the national goal of putting astronauts on the moon, NASA increased its University Program budget sixfold, from to $120 million ($1.58 billion in 2024 dollars), from 1962 to 1965. The funding went to nearly 200 institutions engaged in a variety of R&TD activities.[83] Arguably the most consequential of these activities was the Apollo Guidance Computer development effort led by the Massachusetts Institute of Technology (MIT) Instrumentation Laboratory, now known as the Draper Laboratory. MIT opted to use the newly invented integrated circuit for its system, selecting a design developed by a San Jose, California, start-up called Fairchild Semiconductor. NASA's selection of MIT's approach over a more conservative alternative proposed by IBM was a major factor in the rise of what we know today as Silicon Valley, ground zero of the still-unfolding computing revolution.[84] Among the numerous companies whose roots can be traced to Fairchild Semiconductor are Intel and Advanced Micro Devices.[85] Silicon Valley's technology, investment capital, and philosophy have been a leading enabler and driver behind the wave of entrepreneurial activity

NASA Lewis Research Center Educational Services Staff with a Spacemobile Vehicle in 1964. Credit: NASA.

that dramatically changed the space industrial landscape over the last decade and a half.

Another noteworthy educational outreach effort of the Apollo era was the Spacemobile program. The brainchild of astronomer I. M. Levitt of the Franklin Institute in Philadelphia, the Spacemobile was a traveling space-science education program in which lecturers, accompanied by space hardware models and demonstrations, paid visits in specially marked vehicles to high schools, colleges, and other institutions across the country. Levitt proposed the concept to NASA in 1961, and the Agency responded by awarding the Franklin Institute a one-year contract to manage the Spacemobile as a pilot program. The program, which proved popular, was managed by multiple entities over the years, including for several decades by the Oklahoma State University.[86]

Workforce External Engagement and Mobility

Throughout the Apollo era, as in the eras before and since, NASA's highly skilled engineers and scientists regularly delivered technical papers and lectures in forums, including conferences sponsored by professional membership organizations, such as the International Astronautical Federation and the American Institute of Aeronautics and Astronautics. The topics ranged from the highly technical, such as environmental impacts on magnetoplamadynamic thruster performance, to triumphal, such as the forward-looking "Extensions of Apollo" lecture that George Mueller, NASA's associate administrator for manned spaceflight, gave at the IAF Congress in October 1969.

NASA Champions of Industry

Margaret Hamilton
Computer Scientist

Margaret Hamilton during her time as lead Apollo flight software designer. Credit: NASA.[87]

Margaret Hamilton is a premier example of the external mobility of the NASA workforce. As a young computer scientist with MIT's Instrumentation Laboratory, Hamilton was making plans to attend graduate school when, in 1965, she heard about an opportunity to work on NASA's Apollo program and thought, "Wow, I've got to go there."[88] She applied and was hired. She was the lead Apollo flight software designer and was responsible for a stack of code that, on paper, stood taller than she did. A pioneer in software engineering and credited with popularizing the term, Hamilton left MIT in 1972 to form her own company, Higher Order Software, in 1976 and then another, Hamilton Technologies, in 1986.[89]

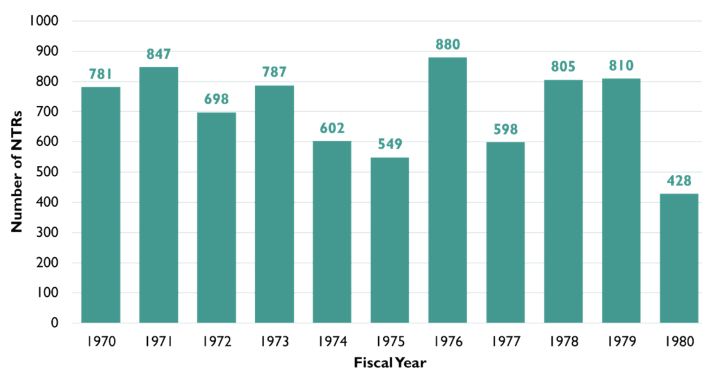
Many of NASA's civil servants went on to blaze trails in the commercial space sector. Among them is David W. Thompson, who worked on the Viking Mars lander program as a college student and then on the Space Shuttle program at NASA's Marshall Space Flight Center before moving on to cofound Orbital Sciences Corporation in 1982. Orbital's founding project was the Transfer Orbit

Stage, a commercial upper stage designed to carry payloads from the shuttle's cargo bay in LEO to higher orbits. Under Thompson's leadership, Orbital was one of the first companies to invest in what at the time were highly speculative commercial space ventures, including small satellite launch services, high-resolution remote sensing satellites, and an LEO constellation for data and messaging communications. Orbital also designed, built, and demonstrated a geostationary satellite servicing system as well as a commercial cargo delivery service to the ISS. Along the way, Orbital grew through acquiring other space companies before being acquired by Northrop Grumman in 2018.

Other notable examples include Donald "Deke" Slayton, one of the original Project Mercury astronauts, and Dr. Maxime Faget, who designed the Mercury capsule. Slayton, whose first and only spaceflight was in 1975 as part of the Apollo-Soyuz Test Project crew, left NASA in 1982 to become president and vice chairman of Space Services, a small payload launch services company that is credited with conducting the first privately funded space launch in 1982.[90] Faget, who as director of engineering and development at NASA's Manned Spaceflight Center in Houston made key contributions to the Gemini and Apollo programs, retired from NASA in 1981 and went on to found Space Industries, an early commercial space company. Space Industries developed the shuttle-borne Wake Shield Facility, which demonstrated production of semiconductor materials in space. The company had plans for a free-flying in-space manufacturing facility for industrial goods such as pharmaceuticals, but those plans were never realized.[91]

Technology Transfer

In 1962, NASA established the Industrial Applications Program, a formal mechanism to fulfill the mandate to share the Agency's research and technology with the public. By the early 1970s, public requests for NASA technology had soared from several thousand customers to more than 70,000 nonaerospace customers. The program, now known as the Technology Transfer Office, implemented and formalized changes in technology transfer that have benefitted a variety of sectors and inform how the rest of the federal government transfers its R&TD outcomes.[92] These efforts led to relatively stable outputs year after year.



New technologies developed at NASA, 1970–1980. Data provided by the NASA Technology Transfer Office. Data unavailable prior to 1970. New Technology Reports[93] include any invention, discovery, improvement, or innovation that was either conceived or first actually reduced to practice in the performance of NASA work.

Technical Support and Enabling Infrastructure

During the Apollo era, NASA provided technical and infrastructure support to the nascent commercial space industry in a number of ways. Under the agreement with AT&T on Telstar 1, for example, NASA was paid $6 million for launch, tracking, and telemetry services.[94] NASA provided similar services for Intelsat 1, also known as Early Bird, which the Agency launched for Intelsat in 1965.

In 1962, NASA's Lewis Research Center took full responsibility for the Centaur rocket upper stage development program, which earlier had been transferred to the Agency from the Department of Defense in accordance with the long-range U.S. space strategy in place at the time.[95] The program was plagued with problems, including test stand explosions and launch failures; Lewis was tapped for its expertise in high-energy liquid engine propulsion dating back to the NACA's days.[96] Working closely with Centaur designer and industrial prime contractor General Dynamics, NASA's experts helped perfect not only the Centaur but also the Atlas first-stage booster, an effort that included extensive testing at specially built facilities at Lewis's Plum Brook Station.[97]

In November 1963, the Atlas-Centaur carried out its first successful test flight, marking the first in-flight burn of a liquid hydrogen/liquid oxygen engine.[98] The Centaur has since flown more than 270 missions, government and commercial, on multiple launch vehicles. Of these payloads, some 75 were for commercial customers, the vast majority being geostationary orbiting communications satellite operators.[99] Centaur variants remain in use today on the United Launch Alliance's Atlas V and Vulcan rockets and are expected to continue flying for many years to come.

NASA's Apollo-era infrastructure continues to be used by the commercial space industry on a cost-reimbursable basis. Rocket test facilities at the Stennis Space Center, for example, are used by the launch companies Relativity Space Systems and Rocket Lab. At NASA's Kennedy Space Center in Florida, Launch Complex 39A, originally built for the Apollo Saturn V rocket, is currently leased by the commercial launch service provider SpaceX for Falcon 9 and Falcon Heavy launches.

Launch

During the 1960s and 1970s, NASA was the sole provider of access to space for commercial satellites. During this era, U.S. manufacturers of launch vehicles produced rockets only under contract to NASA or the Department of Defense.[100] Companies and foreign governments needing launch services contracted directly with NASA. The first-ever communications satellite, Telstar 1, was a public-private partnership in which AT&T/Bell Laboratories was responsible for building the satellite and NASA was responsible for the launch, telemetry, and tracking services. NASA launched the early generations of Intelsat satellites, first with Intelsat 1, starting in 1965.

In 1972, NASA began full-scale development of the Space Shuttle, which was to be the sole source of access to space for all U.S. satellites, government and commercial. Although the shuttle did not launch its first commercial satellites until 1982, NASA developed Space Shuttle pricing policies during the late 1970s that were designed in part to shift commercial satellite operators away from expendable rockets.

Direct In-Space Support

NASA's direct in-space support during the Apollo era is covered in earlier sections of this chapter and was limited to ground segment capabilities leveraged in support of telecommunications satellites.

Standards and Regulatory Framework Support

Although NASA is not a regulatory agency, federal regulators with purview over space activities have long relied on NASA's technical expertise to assist in the decision-making process. For example, the U.S. Communications Satellite Act of 1962 gave the Federal Communications Commission responsibility for approving, in consultation with NASA, the technical characteristics of communications satellites.

Public Engagement

NASA's public engagement efforts expanded dramatically along with the human spaceflight program that culminated with the Moon landings. NASA's innovations in this regard include allowing its first group of astronauts, popularly known as the Mercury Seven, to sign individual contracts to be profiled exclusively in Life magazine, a widely circulated publication.

In NASA's earliest years, the Agency followed the military's lead in keeping quiet about rocket launches until after the fact, but as the human spaceflight program ramped up, the Agency shifted gears, releasing details in advance. For example, before the Apollo 11 launch, NASA, through industry partner North American Rockwell Corporation, released the *Apollo Spacecraft News Reference*, which described the mission hardware and operations in detail. Additionally, NASA's public affairs team lobbied and obtained approval for live coverage of the event, which drew a worldwide television audience of an estimated 650 million people.[101] Thanks in part to NASA's public relations efforts, Apollo inspired countless people, who would go on to make their mark in commercial space. In 1976, NASA began regularly publishing Spinoff, a magazine dedicated to Agency technologies improving life on Earth. The inaugural issue cited the benefits of communications satellites and the progress of Intelsat, the international cooperative formed to provide satellite communications services on a global basis. The issue noted the ATS-6 satellite, built by Fairchild Industries, was performing flawlessly and delivering vital educational programming and medical services to remote corners of the globe.[102]

Industry Engagement

During the 1960s and 1970s, NASA worked closely with industry, operating as a customer; a market driver; and a provider of expertise, technology, infrastructure, and launch support. The Agency kept industry apprised of its programs, activities, and needs through conferences such as the NASA-Industry Program Plans Conference. The first such conference, held in July 1960, provided industry with an overview of NASA's organization and programs. NASA's growth and organizational changes during the next couple of years fueled industry calls for a second such conference, which was held in 1963 in Washington, DC. In opening remarks at the conference, Walter Lingle, NASA assistant administrator for management development, explained one reason for holding the conference:

"Industry has asked that we let them know more accurately what we are now planning for the future so that they can more intelligently invest in their own facilities, their own research and technology development programs, and develop their organization to make better-informed responses to our future requests for proposals."[103]

NASA also held a number of workshops geared toward industry. On March 17–19, 1970, for example, 51 representatives from almost 20 industry companies and government agencies attended the Manned Flight Awareness Workshop at the Marshall Space Flight Center, during which the participants discussed how to promote the safety of spaceflights and the reliability of hardware.[104]

Narrative Encouragement

During the Apollo era, NASA had not yet come to fully recognize the commercial space sector's potential to contribute to its own mission needs or to the economy in general, and the Agency has always been wary of statements that might be construed as a public endorsement of any company. Nevertheless, during this era the Agency provided narrative encouragement in subtle ways, both to the nascent satellite communications sector and, in the wake of President Richard Nixon's 1972 approval of the Space Shuttle, to enterprises that might benefit from the routine, low-cost access to space that the orbiter, as envisioned, was to provide.

In NASA's semi-annual reports to Congress during the early 1960s, the Agency touted the results of its communications satellite activities with its industrial partners, which were identified by name. The report for July 1–December 31, 1962, cited the August passage of the Communications Satellite Act of 1962 and called it "important for the eventual establishment of an operational communications satellite system."[105] The report for January 1–June 30, 1964, discussed the Agency's activities in the context of the announcement by COMSAT, the company in effect created by the 1962 law of plans to proceed with a geosynchronous satellite system and to offer stock for sale. NASA's report characterized the announcement as a substantial advance "toward a worldwide satellite communications network."[106]

Following the approval of the Space Shuttle, NASA frequently touted the benefits of routine, low-cost space access, stating that access would open a variety of new applications in addition to supporting proven ones, such as satellite telecommunications. A film produced by NASA later in the decade said the Space Shuttle would usher in a new era of commercial space use and "vast new areas of development in space," including power reflectors, solar power generation, and even satellites for mail transmission.[107]

In 1979, NASA published the results of the 1977 *Ames Summer Study on Space Settlements and Industrialization Using Nonterrestrial Materials*. The study laid out some of the technical requirements for future space settlement and industrialization, including regenerative life support systems, habitats, manufacturing, resource identification, and logistics hardware. This highly technical paper envisioned a future involving large-scale industrialization in space, providing early narrative support for a vision of an expanding space economy fueled primarily by commercial activities.[108]

Conclusion

NASA came into its own during the 1960s and 1970s, captivating the world with the Moon landings and expanding humanity's frontier to the outer planets. NASA advanced industry's capabilities during this era primarily through massive investments to execute its own programs, which it publicized through sophisticated outreach campaigns that encouraged countless people to pursue space careers. These activities set the stage for the rise of the commercial space industry, which the Agency further fostered with technical support and targeted investments in areas such as satellite communications and remote sensing. Although the commercial space support mechanisms were limited in this era, by the end of the 1970s the Agency clearly was beginning to recognize the commercial space industry's potential.

Apollo was clearly the dominant NASA program from 1961 to 1980, but during this era NASA also began supporting, in earnest, space applications with commercial potential.

The Rise of Commercial Space Development at NASA 1981–2010

Introduction

The Space Shuttle era, spanning from 1981 to 2010, included the Space Shuttle's operational lifetime and the initial development of the ISS. This period was also consequential for the future of commercial spaceflight development, with industry using government space infrastructure, the Space Shuttle serving as companies' access point to space, presidential administrations pushing for space commercialization, and space acquisition and partnership approaches expanding. Ultimately, this period represents a major shift toward using more commercial space development partnerships. In NASA's attempts to spur the commercial development of space, the Agency experienced instances of success and instances of failure and missteps. Despite the setbacks, this period was one of learning and laid the foundation for today's commercial space sector.

The first Space Shuttle launch, on April 12, 1981. Astronauts John Young and Robert Crippen piloted the orbiter, named Columbia. The Space Shuttle enabled commercial access to space during its first few years and later enabled NASA-industry partnership payloads that were part of the Centers for Commercial Space Development. Credit: NASA.

Contracts and Partnership Agreements

Contracts and arrangements between NASA and industry began to flourish during the Space Shuttle era because of the Shuttle and ISS programs combined with a political atmosphere designed to support commercial space development. NASA used Joint Endeavor Agreements (JEAs) and SAAs to work with industry. Specifically, agreements were established regarding the development of upper stage propulsion systems for Space Shuttle payloads,[109] launch services provided by the commercial sector,[110] and transportation of commercial payloads to the ISS via the Space Shuttle.[111]

A photo of an incomplete ISS, taken by a shuttle Discovery astronaut on August 20, 2005. The ISS enables companies to undertake research in space. Credit: NASA.

JEAs served as a means of increasing the ability of industry to conduct space-related research and become aware of NASA enablers, such as infrastructure and facilities to support this research.[112] Under JEAs, industry was allowed to access NASA facilities; in exchange, NASA was allowed to use the data from the research.[113] JEAs also allowed industry payload space aboard the Shuttle, with the intended outcome of encouraging companies to conduct research in space to benefit the American economy.[114] According to NASA's 1987 budget estimates, NASA had formed 65 SAAs with industry by that year.[115]

Also during this era, NASA implemented new kinds of contracts and partnership agreements inspired by renewed public enthusiasm in and the birth of a new kind of entrepreneurial activity in space. By the time Anousheh Ansari, the founder of the XPRIZE Foundation, became the first female space tourist in 2006, the $10 million Ansari XPRIZE for Suborbital Spaceflight (1996–2004) had already led to the first crewed private spaceflight: Scaled Composite's SpaceShipOne. This stunning success led to NASA leveraging similar mechanisms. A 2003 NASA space architecture study assisted by XPRIZE led to the creation of NASA's Centennial Challenges[116] in 2005. In 2006, the Lunar Lander Challenge, managed by the XPRIZE Foundation on behalf of NASA, investigated innovative technologies to enable the 2004 Vision for Space Exploration's[117] lunar robotic exploration goal. NASA Prizes and Challenges were a key thread in this era's movement from the public as audience to the public as participant in NASA missions, science, and technology development. The Prizes and Challenges were so important that, following the astronaut glove challenges of 2007 and 2009, which seeded the space company Flagsuit LLC,

Rockwell International was engaged in a Joint Endeavor Agreement (JEA) with NASA's Office of Commercial Programs in the field of floating zone crystal growth and purification research. The March 1987 agreement provided for microgravity experiments to be performed in the company's Microgravity Laboratory, the FEA. This photo documents an overall scene of the operations devoted to the fluids experiment apparatus (FEA) aboard Atlantis for NASA's May 1989 STS-30 mission. Astronaut Mary L. Cleave, mission specialist, is seen with the computer which was instrumental in the carrying out of a variety of materials science experiments. An 8 mm camcorder which documented details inside the apparatus is visible at bottom of the frame. Credit: NASA.

Office of Management Budget identified NASA as a catalyst in the office's decision to authorize other federal agencies to leverage prizes and challenges.[118]

There was also a move toward performance-based contracts during this period, particularly at the turn of the century.[119] When the first Commercial Resupply Services (CRS) contract was signed in 2008, NASA had a deep understanding of evaluating performance, but the CRS helped NASA better understand the value of not overly prescribing the

NASA Administrator Michael Griffin, far left, met with CEO of SpaceX Elon Musk, far right, on April 20, 2005, at NASA Headquarters in Washington, DC. Looking on in the background are SpaceX Vice President for Strategic Relations Larry Williams, NASA astronaut Marsha Ivins, and NASA Director of Strategic Investments Christopher Shank. Credit: NASA/Renee Bouchard.

nature of performance in contracting relationships. The commercial space transportation systems built through CRS and the Commercial Orbital Transportation Services (COTS) program paved the way for the Commercial Crew Program. COTS innovated the trend of using performance-based contracts by awarding unfunded SAAs to companies that did not win funded contracts. This practice broadened NASA's ability to support commercial space beyond the bounded and highly regulated procurement system.

R&TD

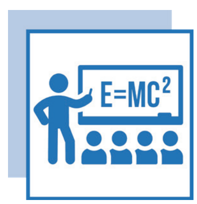
Between 1981 and 2010, NASA engaged in various commercial R&TD programs, including the NASA SBIR program and X-33 collaboration with Lockheed Martin. The SBIR program was founded in 1982 because of the Small Business Innovation Development Act. The program was designed to support the potential

Concept art in 1996 of the X-33 Reusable Launch Vehicle, Venture Star, developed and built by NASA and Lockheed Martin. The X-33 program was cancelled in 2001. Credit: NASA.

commercialization of technologies created by small businesses via federally funded R&TD, thereby enabling the agency to achieve objectives using highly specialized small businesses. In 1985, the NASA SBIR program was put under the authority of the Office of Commercial Programs (OCP). Additionally, in 1992 the Small Business Technology Transfer program was founded, and it likewise provided a method of funding small businesses' research on and development of technology that NASA could use.

Another significant instance of R&TD involving NASA and industry was the unprecedented arrangement between NASA and Lockheed Martin to partner starting in 1996 to construct the X-33 suborbital but reusable space plane. According to historian Roger Launius, this government-industry partnership used "expeditious acquisition procedures, streamlined bureaucracy, [and] limited oversight" to revolutionize the way that NASA and industry did business. The project's equal partnership between industry and NASA was an "enormously important lesson for future human spaceflight initiatives in the 21st century."[120] Because of the technical complexity of the project, it was cancelled in 2001, by which time engineers proved that composites could be a viable material for fuel tanks in a single stage to orbit reusable launch vehicle.

NASA's return to the Moon during the Space Shuttle era strongly connected technology development with commercial objectives while providing complementary benefits to science. In the first mission involved in the return to the Moon, NASA collaborated with the Department of Defense. The mission, called Clementine, demonstrated the potential for low-cost spacecraft development and operations and led to the discovery in 1996 of water ice on the Moon.[121] Shortly after Clementine, the first Discovery-class mission to the Moon, Lunar Prospector, was announced. Both missions' science team leaders were proponents of commercial activity on the Moon.



Dissemination of Research and Scientific Data

From 1981 to 2010, NASA disseminated scientific data to directly and indirectly support commercial space development. The attempted privatization of the Landsat program and its scientific data in the 1980s also serves as a cautionary tale for commercializing space technologies without an established market. At the same time, NASA's use of the internet to publicly disseminate Hubble Space Telescope images and scientific data indirectly assisted industry because the images and data were immensely popular and sparked renewed public interest in space.

Image taken in 2004 by Landsat 5 of the Mergui Archipelago in Burma (Myanmar). Credit: NASA.

The Landsat remote-sensing program began in the 1970s through a partnership between NASA and General Electric to develop an Earth-sensing satellite system. In 1984, the same year Landsat 5 launched, the Landsat Commercialization Act of 1984 directed that the program be privatized by the Earth Observation Satellite Company (EOSAT). EOSAT was put in charge of Landsat data management and dissemination and launched the next two Landsat satellites under government subsidies. Because of EOSAT's remote-sensing monopoly and commercial restrictions imposed by the 1984 act, data prices increased 600%, hindering the market and forcing many users to turn to the French version of Landsat in 1986.[122] The government instructed EOSAT to cease operation of Landsat 4 and 5 in 1989 because of the lack of a market. Congress restored the Landsat program by enacting the Land Remote Sensing Policy Act of 1992, which led to the government-owned Landsat 7 and eventually returned data rights to the government.[123] Today, the Landsat program is supported by NASA and operated by the U.S. Geological Survey with publicly accessible data. The program is also a case study of the risks of privatizing space systems that produce scientific data; in a monopoly environment, the data can become unaffordable to users.

NASA's use of the internet to publicly disseminate Hubble Space Telescope data during the late 1990s and early 2000s is a more successful example of NASA disseminating scientific data—even if the connections to commercial space development are less direct. From the 1980s to the 2010s, NASA made more data available to the public than ever before thanks in large part to the internet—a tool that completely changed how scientific data is disseminated, accessed, and even created. NASA selected the Space Telescope Science Institute in Maryland as the host of Hubble's data archive through the Data Archive and Distribution Service developed by Loral Corporation. Internationally, NASA

The Hubble Space Telescope in a picture taken by a Servicing Mission 4 crew member just after the Space Shuttle Atlantis *captured Hubble with the shuttle's robotic arm on May 13, 2009, beginning the mission to upgrade and repair the telescope. Credit: NASA.*

collaborated with Europeans and Canadians to set up a copy of the archive in Germany, assess new storage media for the archive, and develop new data interfaces using the internet.[124] In 1994, the Data Archive and Distribution Service system became operational. Also that year, the Space Telescope Science Institute used the internet to assist astronomers in using Hubble through the Project to Re-Engineer Space Telescope Observing (PRESTO) program. In 1995, the decision was made to make all Hubble Deep Field observations publicly available immediately after processing; previously, the data had been mainly proprietary to the principal investigators for the first year of the data's existence.[125] In 1996, the Space Telescope Science Institute implemented the Hubble Archive Re-Engineering Project to improve the data archiving process. Beginning in 1998, all Hubble data have been made available online.[126] By 1999, approximately 17 million people accessed Hubble images each month.[127] Because of NASA's use of the internet to share Hubble data, astronomers gained easier access to astronomy data from the telescope and Hubble images "became a staple of the internet."[128] Because Hubble images became popular and ubiquitous on the internet, they also served as a source of public engagement.

The dissemination of scientific data from 1981 to 2010 reveals that there are risks in privatizing space systems that provide scientific data if no market for buying the data exists, as was the case with Landsat. However, in the case of publishing Hubble data on the internet, we see that when NASA uses revolutionary means to disseminate data, the public can benefit from the data.

The Moon Mineralogy Mapper imaging spectrometer, an instrument on India's Chandrayaan-1, during development at NASA's JPL. Credit: NASA/JPL-Caltech.

The NASA-developed Moon Mineralogy Mapper (M3) imaging spectrometer was a payload aboard the Indian Chandrayaan-1 lunar mission, which launched October 22, 2008. The M3 instrument was designed to take compositional measurements of the lunar surface and transmit the data to Earth. The M3 began collecting data November 18, 2008. Communication from Chandrayaan-1 was lost in August 2009, but by then 1,542 downlinked datasets from the mission had been acquired, providing coverage of 95% of the lunar surface. The data was later made publicly available in NASA's Planetary Data System database.[129] The M3 is significant because it was the first instrument to provide a mineralogical map of the lunar surface and the M3 found water molecules in the lunar poles.[130] Today, there is high interest in using and extracting lunar resources, particularly water because its hydrogen molecules can be used for rocket propulsion. Consequently, the data collected and transmitted from this NASA instrument may be useful to companies in their quest to one day profit from lunar resources.

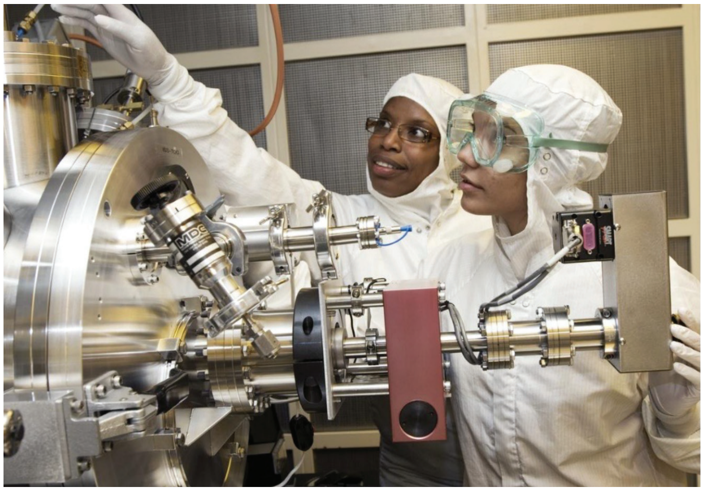


Photo from the 2005 NASA–Lewis' Educational and Research Collaborative Internship Program, LERCIP High School Student at worksite at Glenn Research Center. Credit: NASA.

Education and Workforce Development

During the Space Shuttle era, it became clear that if NASA funded opportunities for education and workforce development, more individuals would want to work at NASA. NASA had numerous programs in place from 1981 and 2010 to support education and workforce development. These programs included the NASA Student Intern Program, which was established in the early 1980s; the Centers for Commercial Development in Space, which was initiated in 1985 and included NASA and industry partnerships with academia; and the National Space Grant College and Fellowship Program, which was founded in 1989.

As an example of the fruits of NASA's labors regarding education and workforce development, in FY 2009 NASA tracked trends regarding college students who participated in NASA programs and found that 41% of participants who engaged in NASA programs as undergraduates went on to pursue advanced degrees. Additionally, of the 811 students who reported employment data after participating in NASA's higher education programs, 57% worked for NASA, aerospace contractors, and other NASA-related institutions, an increase of 6 percentage points from the previous year. An additional 13% entered other STEM fields.[131]

NASA has always been considered a national educational resource. As more students became interested in STEM fields because of NASA, NASA's sense of responsibility increased. Consequently, the NASA-Industry Education Initiative gathered representatives from NASA and 26 of its major contractors in 1991[132] to address the nation's education goals.

During this era, NASA-funded educational programs not only provided career inspiration but also produced physical outputs. For example, in 2004, students and faculty in the Minority University Research and Education Program produced 980 professional publications. Additionally, program participants gave 1,100 presentations and were awarded 11 patents.[133]

NASA also excelled in providing professional development for educators. For instance, in FY 2001, NASA held more than 400 workshops to train over 8,600 teachers in Earth science.[134] On a grander scale, in 2005, NASA's Higher Education Program provided professional development opportunities to 18,000 faculty members and more than 70,000 students.[135] NASA provided many additional professional development opportunities for educators during this period.

Beginning in 2000, NASA embarked on an expansive education and public engagement

1974 Apollo–Soyuz Test Project portrait of Donald "Deke" Slayton. Credit: NASA.

program for its science missions. By the end of FY 2000, all NASA science missions had a funded education and public outreach component with a designated lead. The education and public outreach programs were established in over 25 states, and exhibits were set up in museums, planetariums, libraries, and other locations in 44 states.[136] These efforts helped support the development of the space workforce that commercial space organizations draw on today.

Workforce External Engagement and Mobility

During the Space Shuttle era, employees who left NASA for industry took with them knowledge that aided their careers in industry, particularly at space industry start-ups. Former NASA astronaut Deke Slayton and other NASA employees were part of this trend

There are many examples of successful workforce mobility during this period. Mercury Seven astronaut Deke Slayton retired from NASA in 1982 to become president and vice chairman of Space Services. On September 9, 1982, Space Services launched what was arguably the first privately funded rocket in the world,[137] the Conestoga, from Matagorda Island, Texas. Slayton led the launch team and worked with other former NASA employees, such as Lee Scherer, former director of the Kennedy Space Center, and numerous subcontractors and advisors until the Conestoga's final flight in 1995. Unfortunately, a series of technical setbacks culminated in a launch failure and destruction of a partially-NASA-funded mission, COMET.[138] Despite the demise of the Conestoga, Slayton later became the head of the Space Services Division at EER Systems Corporation when the corporation bought the company Space Services. He later became chairman of Space America and director of Columbia Astronautics.

As another example of workforce mobility, former NASA civil servant Robbie Schingler and former NASA contractors Will Marshall and Chris Boshuizen founded Planet in 2010. Other NASA employee-founded companies established during this era include Planetary Resources (2009) and Golden Spike (2010), both of which folded after a few years. Planetary Resources was cofounded by Eric Anderson, who had been a NASA Academy summer intern in 1995. During his internship, he began thinking about commercial space tourism; he later pivoted to asteroid mining.[139] Golden Spike was founded by Alan Stern, a former NASA Science Mission Directorate associate administrator, and Gerry Griffin, the director of the Johnson Space Center in 2010.

NASA employees also found significant success outside of the space sector. Andrew Viterbi of JPL partnered with six other people to found the telecom giant Qualcomm, whose market capitalization is nearly $200 billion today. Viterbi's connection to NASA directly benefitted NASA missions when Qualcomm partnered with JPL to develop and test the Mars helicopter's chipset, enabling humanity's first powered flight on another planet.[140]

As in every era, not all space start-ups were successful during the Space Shuttle era. However, this era did experience a surge of dynamism in the commercial space ecosystem, spurred in part by the mobility of the NASA workforce.

Technology Transfer

The Space Shuttle era, supported by creative legislation in the U.S., is often considered the start of an innovation boom, with an increasing number of technologies transferred from government to the commercial sector. Examples include a thermalplastic coating that was designed to be resistant to the effects of UV radiation and that could therefore protect outdoor paint,[145] foam that was originally used to cushion Space Shuttle astronauts and was later sold as pillows and mattresses by Tempur-Pedic,[146] and scratch-resistant lenses originally developed to protect aircraft systems at the Glenn Research Center and were later used in commercial sunglasses.[147] These examples are just a few in a large pool of Agency-documented technology

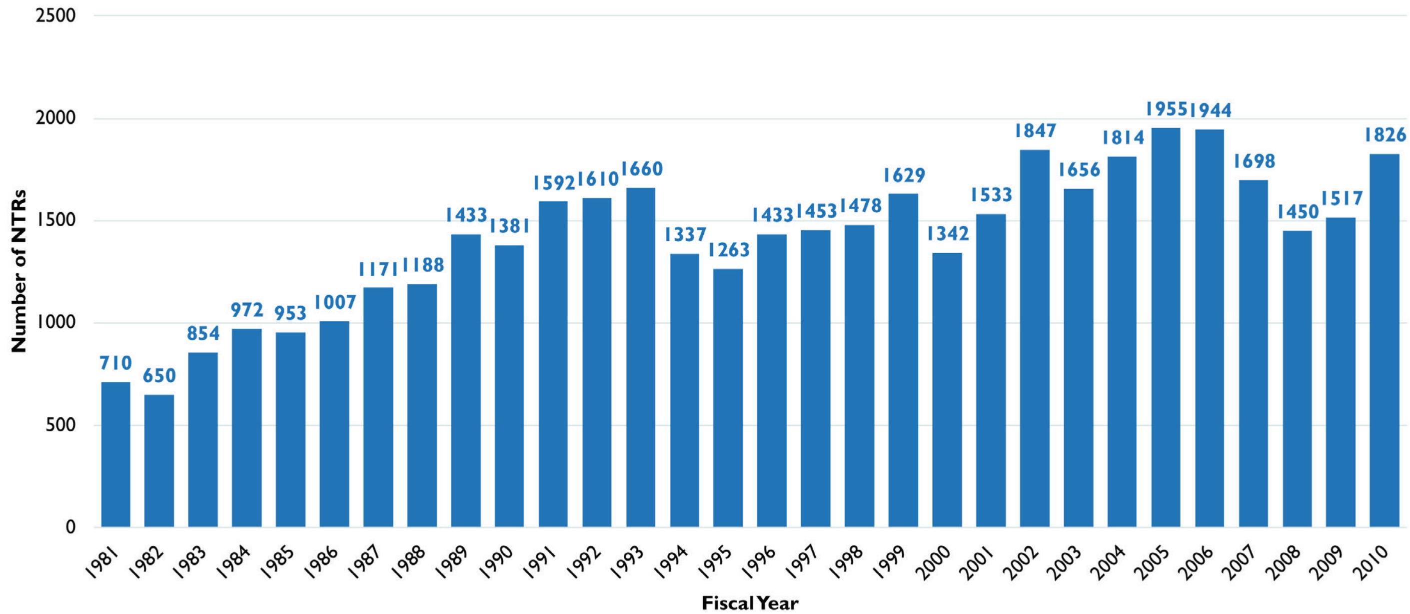
NASA Champions of Industry

Joseph Fuller, Jr.

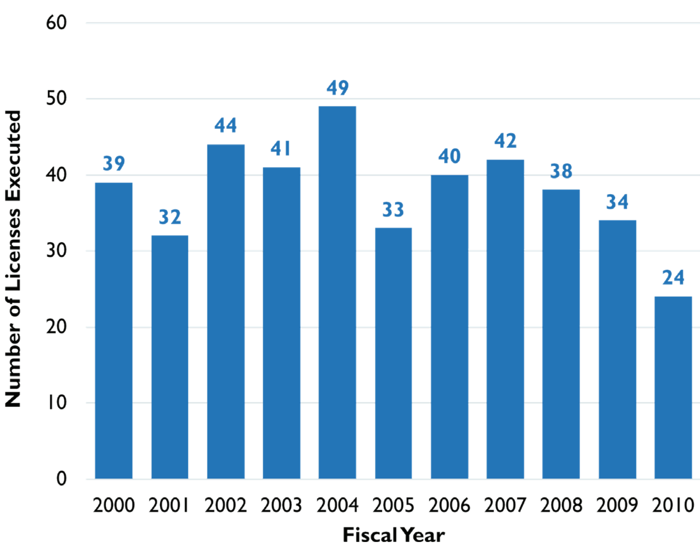
Director of the NASA Ames Research Center

Joe Fuller, former CEO of Futron. Credit: Futron/Avascent.

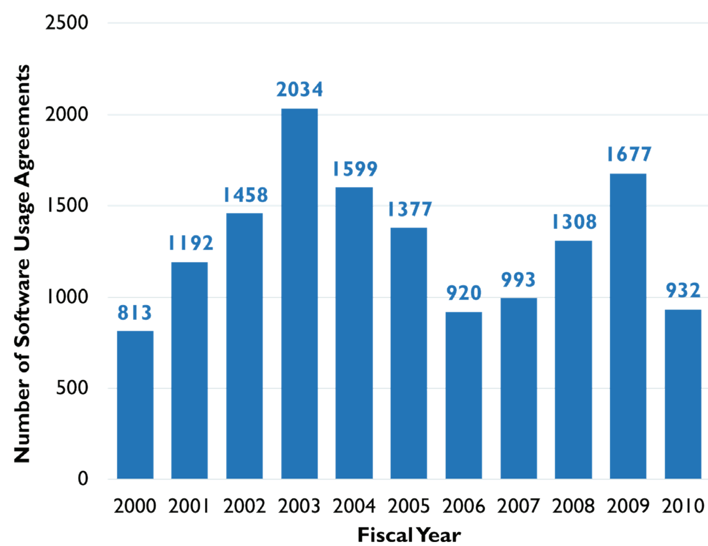
Joseph Fuller Jr. was an aerospace systems engineer, project manager, and senior executive at NASA for 20 years[141] before he founded and became the CEO of the Futron Corporation in 1986.[142] Futron specialized in conducting market research for space and telecommunications organizations, and there is no doubt that Fuller's NASA career assisted the company. While at NASA, Fuller received the NASA Exceptional Service Medal and gained experience in "the design, development, and operations of both human-piloted and robotic spacecraft." While managing Futron, Fuller served on the National Oceanic and Atmospheric Administration's Advisory Committee on Commercial Remote Sensing, was a member of NASA's Project Management (APPEL) Mission Operations Working Group, and served on the board of the Challenger Center for Science Education.[143] The space and telecommunications division of Futron was bought in 2014 by Avascent.[144] Clearly, Fuller's NASA experience helped bolster the aerospace industry via most of the mechanisms discussed in this report.



New technologies developed at NASA, 1981–2010. Data provided by the NASA Technology Transfer Office. The technologies include any inventions, discoveries, improvements, and innovations that were conceived of or first used in practice in the performance of NASA work.



Licenses executed in FY 2000 to FY 2010. Data provided by the NASA Technology Transfer Office. The licensing of NASA patents is one tool used to promote the use and commercialization of inventions. Data prior to 2000 is unavailable.



Software usage agreements established in FY 2000 to FY 2010. Data provided by the NASA Technology Transfer Office. Software Usage Agreements enable approved individuals and organizations to access NASA software. Data prior to 2000 is unavailable.

transfers. The NASA Spinoff magazine has been tracking the commercial application of NASA-funded technologies since 1976.[148]

Many laws that were enacted from 1981 to 2010 aided government technology transfer. This legislation includes the Stevenson-Wydler Technology Innovation Act of 1980, the Federal Technology Transfer Act of 1986, and the Technology Transfer Commercialization Act of 2000. The chart at the top of this page shows that the new technologies developed at NASA steadily increased from 1981 to 2010. This pattern continues today.

Technical Support

NASA-provided technical support can enable successful launches of commercial vehicles. NASA's technical support to industry from 1981 to 2010 primarily involved programs that enabled commercial launch markets, such as the Conestoga launch (as previously discussed), Orbital Science's Pegasus rocket, and the COTS program.

The founding of Orbital Sciences (now part of Northrop Grumman) in 1982 began a long period of innovative commercial space activities assisted in part by NASA technical support. In 1990, Orbital Sciences launched one of the contenders for the first privately developed launch vehicle, the Pegasus Rocket, beneath a NASA B-52 plane. Fast-forward to 1997, when Orbital Sciences launched the SeaWiFS

This image shows a Pegasus being carried to altitude by a NASA-obtained B-52 on April 5, 1990. An air-launched, three stage, all solid-propellant, three-axis stabilized vehicle, the Pegasus was designed to put a 400- to 1,000-pound payload into LEO. Credit: NASA on the Commons/Flickr.

mission, an ocean-sensing science mission via a partnership with NASA. In 2014, Orbital Sciences launched its first uncrewed cargo mission to the ISS aboard its Cygnus spacecraft, which was developed and tested as part of the NASA COTS program. With COTS, companies benefitted from NASA's technical support and well as NASA's funds.

Enabling Infrastructure

In terms of enabling access to NASA ground-based infrastructure, NASA released a Commercial Space Policy in October 1984 that advocated for coordinating with industry regarding the use of NASA facilities.[149] The OCP's Commercial Development Division negotiated agreements with aerospace organizations, including companies, to use NASA-developed technologies and facilities.[150] As another example, Rolls-Royce North America signed a NASA SAA in 2005 with the Stennis Space Center to test at the H1 Complex; this agreement is in effect until 2025.[151] NASA continues to allow infrastructure access to companies and assists industry in some of the more technically challenging and capital-intensive aspects of spaceflight ventures. The Space Station Processing Facility, built in 1992 to integrate elements of the ISS, was later used to support the Commercial Resupply companies' early development and launches to the ISS. The ISS may be one of the most important pieces of enabling infrastructure ever developed. Indeed, the ISS is the most important site off Earth for commercial space companies seeking to test their products in a controlled laboratory in a microgravity environment. Using the ISS helps companies learn everything from how to launch satellites in orbit to how flames behave, how to print metals, and even how to grow food in the microgravity environment.

NASA expanded use of its infrastructure as widely as it could in this era, and the Get Away Specials Program is a prime example. The program's implementation cut across several mechanisms. Conceived of in 1976, with the first flight in 1982, this program gave hundreds of interested external users, from industry professionals to students, the opportunity to propose and then observe small experiments conducted aboard the Shuttle. Jon Vellinger, an eighth-grade student in Lafayette, Indiana, entered his idea of studying the effects of microgravity on chicken eggs into a competition run by NASA and the National Science Teachers Association. In 1985, after Vellinger's freshman year of college, NASA paired him with Mark Deuser, an engineer from Kentucky Fried Chicken, to create a flight-ready egg incubator to be tested on the Shuttle.[152] This collaboration led the two to found Techshot, a space biotech company, in 1988. Techshot was acquired by Redwire in 2021.[153]

NASA also began contracting out elements of its infrastructure during this era. In 1995, Congress mandated that NASA privatize its microgravity flights, but no commercial providers existed at the time. In 2008, NASA contracted with Zero-G to provide microgravity services on aircraft; NASA addressed issues the inspector general raised about the partnership in 2010[154] and continues to work with Zero-G to this day. Additionally, beginning in 2010, NASA awarded a series of SBIR contracts to Paragon Space Development Corporation to develop better water reclamation systems for the ISS.[155] This and other examples highlight a major shift in how NASA engaged with the commercial space sector.

Launch

The Space Shuttle and COMET program are two primary examples during this era of how NASA enabled commercial applications' access to space, albeit for a short time.

The Space Shuttle debuted in 1981, and its first commercial satellites were Canada's Anik C3 and Satellite Business Systems-3, deployed in November 1982 on the STS-5 mission.[156] The Space Shuttle ultimately launched more than 20 commercial communications satellites. In essence, COMET was designed as a mechanism to deliver government or commercial microgravity payloads to space aboard a commercial Conestoga rocket. After a month in orbit—far longer than the Space Shuttle's mission maximum of 16 days—the microgravity payloads were parachuted to Earth. There was only one COMET mission, and this mission ended in failure when the Conestoga rocket carrying the COMET payload to space exploded 10 kilometers into the atmosphere.[157]

The Shuttle and COMET case studies demonstrate NASA's willingness to directly assist companies in accessing space in the late 20th century. A lesson learned from this era is that having dissimilar redundancies in launch vehicles allows companies to send commercial payloads to space aboard government vehicles even if one vehicle is out of commission because of an unexpected event.

NASA also supported commercial space and regional economic development during this era. For instance, the Virginia Commercial Space Flight Authority was created by the Virginia General Assembly in 1995, with support from NASA under the Commercial Space Launch Act and various agreements.[158]

Astronaut Charlie Walker operates McDonnell Douglas Astronautics Company's space continuous flow electrophoresis system (CFES) aboard Shuttle Discover for the STS-41D mission. Credit: NASA.

Direct In-Space Support

Government astronauts, especially those who are trained scientists and technologists, are valuable in-space assets regarding the assembly and operation of complex payloads. NASA provided direct in-space support from 1981 to 2010, primarily through astronaut time aboard the Space Shuttle and ISS to perform R&TD in microgravity.

The first commercial experiment sent aboard the Space Shuttle was the space continuous flow electrophoresis system developed by McDonnell Douglas Astronautics in 1984 for the STS-41D mission. Payload specialist Charlie Walker conducted the experiment. Tragically, the Challenger disaster occurred three missions later and prompted a policy that barred commercial payloads from flying aboard the Shuttle.[159] However, this change did not mark the end of in-space astronaut support for commercial payloads. With the establishment of the ISS as a national laboratory in the early 2000s, NASA provided the same type of in-space support that it does today.

In 1998, NASA released the Commercial Development Plan for the ISS. This report discussed the long-term plan to establish a foundation for space products and services in LEO, thereby stimulating the U.S. economy. In the short-term, the plan was meant to off-set the public cost of the Space Shuttle and the ISS via "commercial enterprise and open markets."[160] When the ISS was founded as a national laboratory in 2005, it created a broad set of applications for the LEO economy in research areas such as microgravity, protein crystallization, 3D printing, and materials. The ISS National Lab handles all non-exploration research conducted by government, commercial, and academic entities.[161] Through a contract with NASA, the ISS National Lab is operated by the Center for Advancement of Science in Space. The ISS National Lab functions to, in part, enable U.S. commercial space activity.[162] Two of the earliest commercial experiments that occurred through the ISS National Lab program were involved Astrogenix's research into developing a vaccine for salmonella and Guigne Space Systems' development of a materials processing chamber called the Space Dynamically Responding Ultrasonic Matrix System, which was launched to the ISS by the 2008 STS-126 mission.[163]

Standards and Regulatory Framework Support

Technical standards and regulatory frameworks ease the business-to-business and government-to-business interactions in space while also setting safety and sustainability standards. Between 1981 and 2010, NASA created

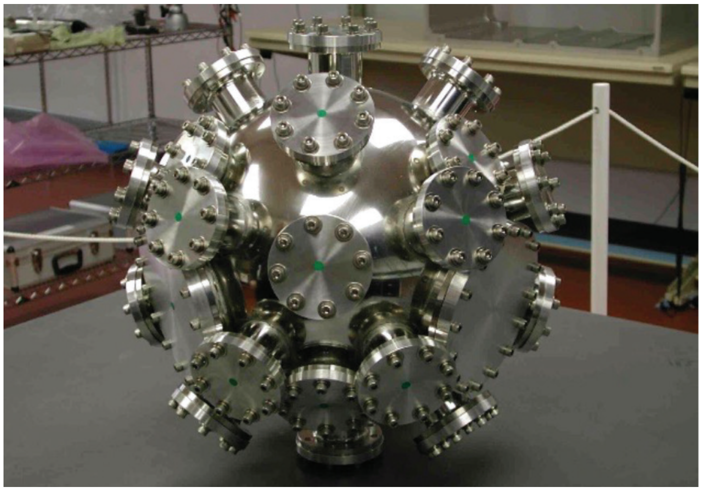


Image of the Space Dynamically Responding Ultrasonic Matrix System processing chamber.[164] *The system was developed by Guigne Space Systems to advance materials manufacturing through microgravity.*[165] *Credit: NASA.*

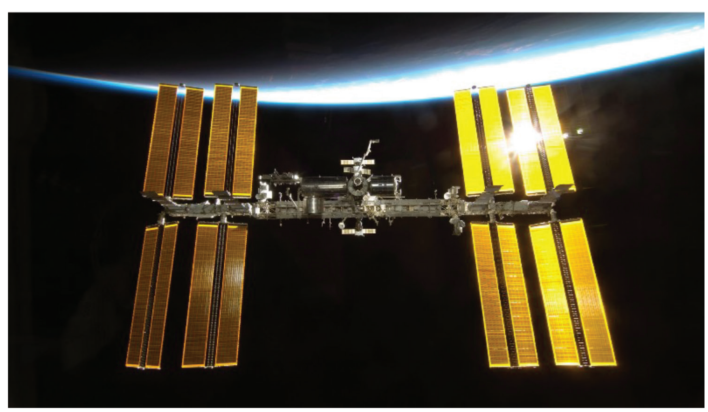
standards and regulatory frameworks that were used by the Agency and U.S. industry and also served as a driving force for international adoption of common frameworks. These standards and regulations include NASA technical standards, international interoperability standards, sustainability standards, and conjunction analysis standards.

An example of technical standards established during this era is NASA-STD-5001, Structural Design and Test Factors of Safety for Spaceflight Hardware. This standard was approved in 1996 after complaints from industry and NASA management that NASA technical practices and requirements were not uniform across Centers. NASA-STD-5001 was developed to help remedy this issue by introducing criteria to strengthen the commonality in hardware designs across projects, Centers, and contractors.[166]

With the creation of the ISS, NASA and its ISS partners found it necessary to create international operability standards for docking spacecraft. The result was the creation of the International Docking Standard in 2010. This standard outlines interface guidelines for users of two spacecraft, including companies, to apply to dock in space with greater ease.[167] This standard helped enable a future with multiple commercial vehicles from different companies seamlessly docking with the ISS in the same way that aircraft and boats can dock at any airport or seaport around the world.

Regarding sustainability standards and regulations, NASA-STD-6001, Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for Materials in Environments That Support Combustion, was established in 1998 to provide guidelines for evaluating, testing, and selecting materials in and around space vehicles to prevent combustion,[168] thereby enhancing safety on both government and commercial vehicles.

In 1995, NASA became the first space agency to issue guidelines for orbital debris mitigation; these guidelines inspired the U.S. government's orbital debris standard practices, which were



With a backdrop of Earth's horizon and the blackness of space, the ISS is featured in this image photographed by an STS-130 crew member as the space shuttle Endeavor and the station approach each other during rendezvous and docking activities. Docking occurred at 11:06 p.m. (CST) on February 9, 2010, delivering the Tranquility node and its cupola. Credit: NASA.

developed two years later. Similar guidelines were adopted in 2002 by the Inter-Agency Space Debris Coordination Committee, which was founded in 1993 and includes representation from 10 nations (including the United States) and the European Space Agency. In 2007, the United Nations Committee on the Peaceful Uses of Outer Space endorsed space debris mitigation guidelines based on the Inter-Agency Space Debris Coordination Committee's guidelines. Orbital debris mitigation policies remain relevant to space exploration today and to long-term use of Earth's orbit for commercial activity.[169]

NASA has also been instrumental in spacecraft conjunction analysis and has helped industry develop best practices to avoid devastating collision events. In 2005, NASA established the Conjunction Assessment Risk Analysis program to perform routine conjunction risk analysis of NASA's on-orbit satellites.[170] Today, the program provides external spacecraft owners and operators with source code and documentation for key conjunction risk assessment algorithms.[171] Additionally, the Office of the Chief Engineer's *2023 NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook* informs spacecraft owners and operators regarding how to safely conduct space operations to avoid spacecraft conjunctions.[172]

Public Engagement

Because of marketing experience, industry professionals and celebrities make valuable partners in communicating what space could look like in the future—including a future with prolific commercial activity. From 1981 to 2010, there were many instances of NASA using refined methods to engage the public. These activities were often made possible through industry partnerships. Examples of outreach include updates made to the Kennedy Space Center Visitors Complex, the Lunar Lander Challenge, NASA's partnership with the Lego Group, celebrity engagement with NASA, and use of NASA's website to communicate commercial space success stories. In 2010, NASA and Lego signed an SAA to inspire students toward engage in STEM activities. Today, NASA-themed Lego products are still being sold, to the benefit of both Lego and NASA.

The popular attractions at the Kennedy Space Center Visitors Complex is a prime example of successful public engagement made possible through public-private partnerships. Private funding and visitor fees allowed the Center's aging

In 2007, NASA, Kennedy Space Center, and Florida government dignitaries helped at the opening of the newest attraction at the Kennedy Space Center Visitor Complex: the Shuttle Launch Experience. Holding the ribbon for the opening are, left to right, Visitor Complex chief operating officer Dan LeBlanc, Florida lieutenant governor Jeff Kottkamp, former astronauts John Young and Bob Crippen, Center director Bill Parsons, Center director of external relations Lisa Malone, and former astronaut Buzz Aldrin. The attraction includes a simulated launch containing the sights, sounds, and sensations of launching into space. Credit: NASA/George Shelton.

On January 30, 1997, director and producer Robert Zemeckis and other Warner Bros. crew members oversaw the filming of scenes for the movie Contact at the Kennedy Space Center's Launch Complex 39 Press Site. The screenplay for Contact was based on the best-selling novel by astronomer Carl Sagan. The cast included Jodie Foster, Matthew McConaughey, John Hurt, James Woods, Tom Skerritt, David Morse, William Fichtner, Rob Lowe, and Angela Bassett. Described by Warner Bros. as a science fiction drama, Contact fictionally depicted humankind's first encounter with evidence of extraterrestrial life. Credit: NASA.

Actress Nichelle Nichols, known for her role as communications officer Lieutenant Uhura aboard the USS Enterprise in the Star Trek television series, displays her Lego astronaut ring while visiting the Build the Future activity, at which students used Lego bricks and other elements to create visions of the future in space. The activity was held inside a tent that was set up at the launch viewing area of the Kennedy Space Center in Cape Canaveral, Florida, on November 1, 2010. NASA and the Lego Group signed an SAA to spark children's interest in STEM. Photo Credit: NASA/Bill Ingalls.

"hardware museum" to be revamped from 1995 to 2007, resulting in the updated facilities and amenities we see today, including restaurants, shops, and newer exhibits.[173] Currently, the Kennedy Space Center Visitors Complex is operated for NASA by Delaware North Companies. International space centers and museums that have adopted similar interactive public engagement approaches include the European Space Research and Technology Centre's Space Expo in the Netherlands, the Tsukuba Space Center in Japan, and the Cité de l'Éspace in France.

From 1981 to 2010, engagement with a plethora of popular public space intellectuals and celebrities helped NASA form partnerships with industry. One example was *Star Trek* actor James Doohan, who narrated a film about the Space Shuttle in 1981. His costar Nichelle Nichols, who inspired women and minorities to apply to become astronauts in the 1970s, continued to partner with NASA during this period to inspire interest in space. Another example is Carl Sagan, who worked as a JPL visiting scientist for some of the Mariner, Viking, and Voyager missions. He inspired people to become space enthusiasts with his famed book and television show *Cosmos* (1980–1981), and his book *Contact* was later made into a blockbuster Hollywood film.

The advent and use of the internet during this era was a major boon for communicating NASA-sponsored research that enabled commercial development. For example, in the late 1990s and 2000, NASA had a website called the NASA Commercial Technology Network, which spotlighted success stories of NASA-industry technology transfers and commercialization.

The image below shows a screenshot from 1997 of the website, which lists topics such as 3D medical scans, radiation-tolerant technology, and air quality monitoring technology.


NASA Commercial Technology Network
www.nctn.hq.nasa.gov

Getting Started • What's New • Search • Service Directory •

Success Stories

The successful transfer and commercialization of NASA-sponsored research and technology occurs in many ways--information dissemination, technical assistance, technology licensing, cooperative R&D; and other forms of collaboration and partnership. The following stories illustrate technology transfer and commercialization methods, and highlight the benefits of NASA technology to U.S. enterprises, U.S. economic growth and competitiveness, and quality of life.

- NASA Software Clearly Displays Breast Tumor Scans in 3-D
- Radiation Tolerant Technology Poised to Revolutionize SpaceElectronics
- NASA "Space Suits" Help Brothers with Rare Genetic Defect
- NASA Boosts Commercialization of Dual-Use Technologies
- Space Research Provides Earthshaking Revelations
- Mars Rover "Sojourner" Hot Wheels Toy
- Commercialization of NASA Filter To Aid Pilots/Drivers
- Space Shuttle Leak Detector Goes Commercial
- New Wind Indicator Enhances Aviation Safety
- NASA LICENSES AIR QUALITY MONITORING TECHNOLOGY
- Space Station Technology Will Bring Expert Medical Care to RemoteAreas on Earth
- NASA-MSU Center Signs First Agreement with Montana Company

For More Stories...

At Home with NASA Technology -- this web presentation from NASA's Marshall Space Flight Center provides a down-to-Earth look at how NASA technology has been applied in numerous areas of everyday life.

Aerospace Technology Innovation -- a bi-monthly publication from NASA's Office of Aeronautics and Space Transportation Technology featuring stories on technology transfer and commercialization activities and accomplishments.

NASA TechTracS -- provides access to Success Stories highlighting the successful transfer and commercialization of NASA technology.

Service Directory -- the web sites affiliated with and sponsored by the NASA Commercial Technology Program present information on numerous Success Stories and Spinoffs.

Space Technology Hall of Fame -- established by the United States Space Foundation, in cooperation with NASA, in 1988 to honor aerospace spinoffs and their innovators.

Spinoff -- an annual NASA publication featuring the successful commercial and industrial application of NASA technology. Browse the current edition or search the Spinoff database to sample products and processes derived from NASA technology since 1976.

Search our Network -- use the key words "success story" or "spinoffs" to uncover stories posted on the web sites of NASA Commercial Technology Network.

U.S. Competitive Advantage -- a quarterly newsletter of the NASA Regional Technology Transfer Centers, highlighting successful technology transfer and commercialization projects with U.S. industry.

NASA SBIR/STTR Success Stories -- the NASA SBIR/STTR site provides an extensive collection of profiles describing the accomplishments of innovative firms funded by NASA's SBIR/STTR program.

Index: Select a Page Go

NASA Official: Jonathan Root, Commercial Technology Division
Curator: Production Team

National Aeronautics and Space Administration

DISCLAIMERS

Screenshot taken by Internet Archives' Wayback Machine of NASA's NCTN website on December 11, 1997. See: https://web.archive.org/web/19971211044025/http://nctn.hq.nasa.gov/success/index.html.

Industry Engagement

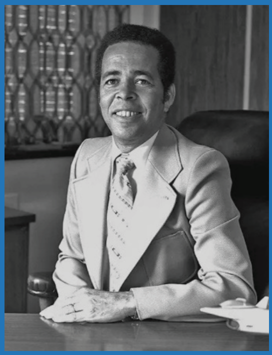
NASA was active in industry engagement between 1981 and 2010 through establishing initiatives such as the Space Commercialization Task Force and the OCP. NASA established the Space Commercialization Task Force in 1983, and it was chaired in part by representatives from industry. The task force was asked to develop a NASA space commercialization policy based on the group's findings. The task force recommended expanding commercial space activities and suggested that government, industry, and academia partner to create this policy.[174] The NASA Commercial Space Policy of 1984 was released to encourage commercial activity in space by providing industry access to NASA facilities and by involving industry in NASA's R&TD, patent rights discussions, and outreach programs.[175]

In 1984, NASA administrator James Beggs created the OCP.[176] The purpose of the OCP was to "negotiate and coordinate the bilateral/multilateral agreements with aerospace and non-aerospace companies that sought access to NASA-developed technologies and facilities."[177] The first associate administrator of this office was Isaac T. Gillam IV.[178] OCP began the Commercial Use of Space Program, which sought to increase industry awareness of opportunities and investments in space, even outside the realm of NASA funding. The program attempted to create new markets for the Space Shuttle[179] and NASA space services, in part through the Centers for Commercial Space Development. Ultimately, through commercial task forces and designated commercial offices, NASA was able to provide direct avenues of engagement with industry. NASA also played a coordinating role with regional development organizations to stimulate commercial space. Diana Hoyt deserves recognition for her efforts to coordinate partnerships and commercial space development across the country.

Additionally, NASA hosted workshops and other events to provide opportunities for NASA and industry employees to collaborate and exchange information. For example, Technology Interchange Meetings were a common means for NASA to discuss and work through technical problems and concepts with industry. Of the various Technology Interchange Meetings that were held between 1981 and 2010, those with publicly accessible proceedings were on topics such as lunar infrastructure,[180] in-space resource utilization,[181] and technology life cycle analysis.[182]

As industry companies developed launch vehicles and cargo delivery systems, the ISS Transportation Integration Office worked closely with the companies to ensure safe transport to and from the orbiting laboratory. NASA's ability to conduct new scientific investigations for the ISS Program, led by Mike Suffredini (above), significantly increased because of the rockets and spacecraft built by SpaceX and Orbital SciencesCorporation.[183] Credit: NASA/ Bill Ingalls.

NASA Champions of Industry



Isaac T. Gillam IV
Director of Dryden Flight Research Center

Isaac T. Gillam IV. Credit: NASA.

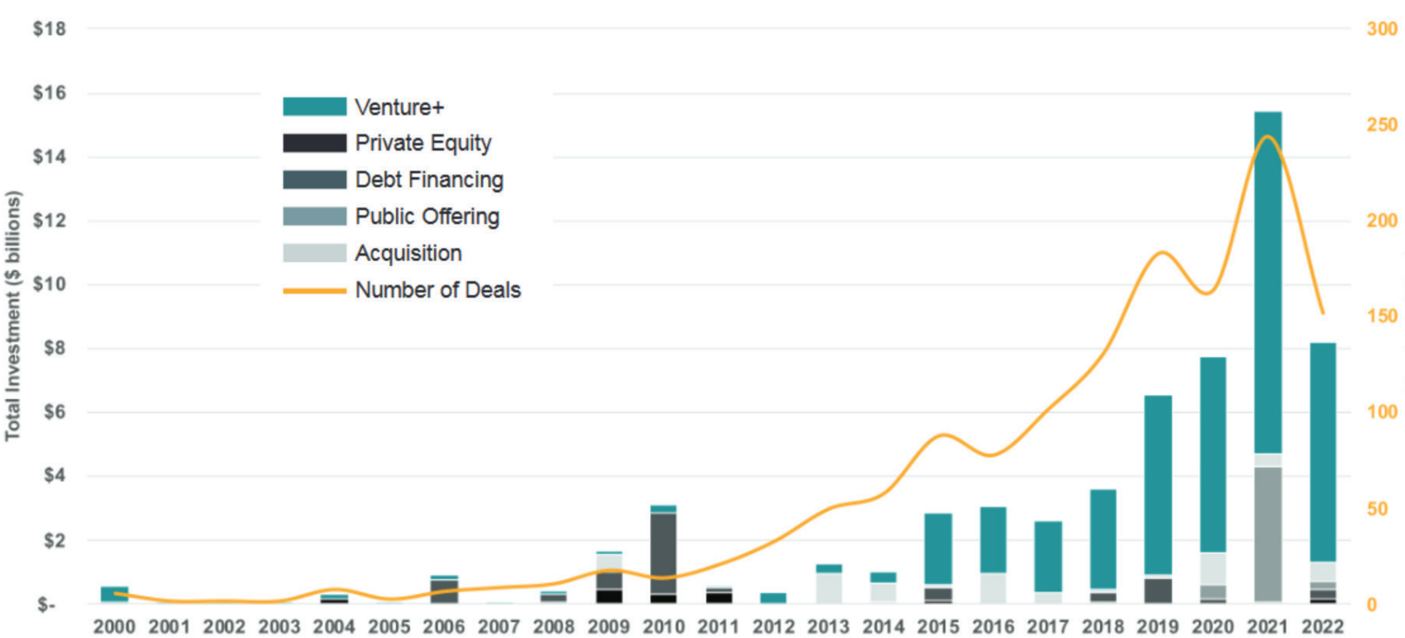
Upon joining NASA in 1963, Isaac T. Gillam IV worked as a resource management specialist. He was appointed to be the assistant program manager for the Delta Launch Vehicle Program in 1966 and to be the manager for the Delta program in 1968. Gillam later served as the program manager for Small Launch Vehicles and International Projects, director of Shuttle Operations at the Dryden Flight Research Facility (today called the Armstrong Flight Research Center), deputy director of Dryden, and acting director of Dryden. In 1978, he was appointed to lead the OCP, and he remained in that position until his retirement in 1987.[184] During his tenure leading the OCP, Gillam oversaw the establishment of the OCP Commercial Use of Space Program. Other of Gillam's contributions to commercial space development include assisting with developing NASA policy regarding Space Shuttle pricing, using the Shuttle for deploying communications satellites, establishing NASA-industry agreements regarding expendable launch vehicles, and making headway on NASA partnerships with nonaerospace companies. After the Challenger disaster in 1986 and the subsequent lack of shuttle space access, Gillam and OCP continued to promote commercial space development by increasing the number of centers in the Centers for Commercial Development of Space (CCDS) program and devoting resources to developing space flight hardware and their manufacturing processes.[185]

Government-Backed Venture Capital

During the Space Shuttle era, NASA experimented with a new commercial space development mechanism—government-backed VC—when the Agency partnered in 2006 with the strategic investment firm Red Planet Capital. The purpose of the partnership was to use VC and NASA funds to attract industry to engage in developing innovative commercial capabilities with NASA. Red Planet Capital invested in an antigravity treadmill company called AlterG before being shut down in 2007 because the firm failed to attract significant non-NASA capital and the Office of Management and Budget "gave guidance that government-run venture funds would not receive funding in subsequent budget years." Further, the George W. Bush administration was concerned that "government-sponsored venture capital projects might displace private funding."[186] Although this experiment has not yet led to other VC experiments, government-backed VC is a concept that NASA continues to study and consider. Though NASA did not succeed in this experience of engaging in government-backed VC, the Agency continued to engage with VC beyond the venture-backed companies in programs such as the SBIR.

Market Stimulation Funding

NASA's COTS program was one of the most significant strategies that NASA used to stimulate the commercial space market from 1981 to 2010. COTS was established in 2006 to fund the development of commercial space vehicles that could later deliver government payloads to the ISS. COTS represented a break from

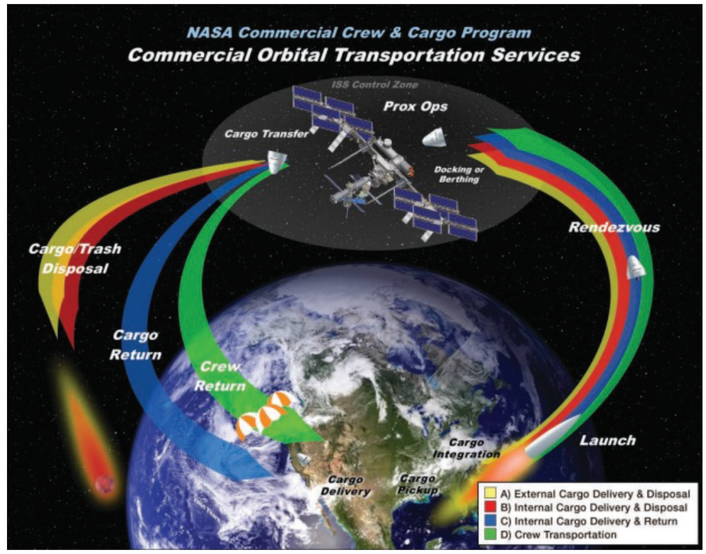


Private investment deals involving space companies, 2000–2022. The graph shows the number of private investment deals that involved space companies from 2000 to 2022. The results of NASA's consistent early efforts to engage venture capitalists and start-ups finally began to pick up momentum beginning in the 2010s. Credit: BryceTech.

the traditional way that NASA did business with companies: With COTS, NASA acted as an advisor and requirements setter but did not own or operate the spacecraft. The purpose of COTS was to "facilitate U.S. private industry development of reliable, cost-effective access to low Earth orbit" to "create a market environment in which commercial space transportation services are available to government and private sector customers."[187] In other words, COTS was designed to stimulate the commercial space market while ensuring low-cost but reliable U.S. access to space. The COTS program concluded in 2013 with demonstration flights completed by contracted companies SpaceX and Orbital Sciences. Today's commercial crew and resupply programs for the ISS are legacies of COTS.

NASA also used another new mechanism during this era to stimulate commercial space development: funded SAAs to coinvest and share risk. Via SAAs, industry companies were afforded the opportunity to partner with NASA according to their capabilities. Additionally, performance-based contracts, which were NASA's preferred NASA contracting technique in 1998[188] and were used in the COTS program, forcing industry to accept more risk. These contracts ultimately led to the establishment of effective products revolutionizing the space economy today.

Another market stimulation experiment worth mentioning is the CCDS program, which was established in 1985 and continued until the early 2000s. NASA began the CCDS with the goal of stimulating industry interest and investment in space technologies. Program centers were located at universities and research institutions and collaborated with NASA Centers and

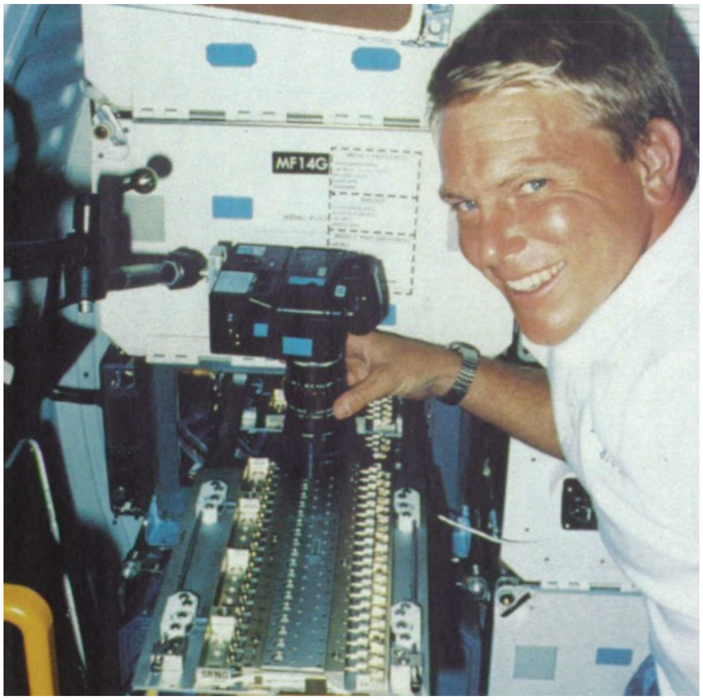


The COTS program focused on involving the private sector in crew and cargo delivery to LEO. NASA offered four options for being involved, to allow companies to optimize their unique services and capabilities.[189] *Credit: NASA.*

commercial partners on research topics such as materials processing, space power, remote sensing, and space propulsion.[190] Around 1991, the CCDS program was hindered by the cost and the lack of industry involvement, which was concerning given that industry was expected to provide the majority of CCDS funding.[191] Following a congressionally mandated investigation of the program in 1993, NASA announced it would phase out support for six of its 17 CCDS centers, based on recommendations from an independent committee, in order to better focus the remaining centers on "relevant commercial technologies and stronger industrial partnerships."[192] The last NASA budget estimate that mentioned the CCDS program was for 2003.[193]

Economic Analysis and Due Diligence Capabilities

During this era, NASA engaged in various economic analysis and due



Astronaut George "Pinky" Nelson activated and monitored protein crystal experiments, sponsored by NASA and the Center for Macromolecular Crystallography, aboard Discovery on STS-26 in September 1988. Credit: NASA.

diligence activities. For example, NASA engaged with a financial expert to obtain input regarding the COTS program, and the activity was successful in supporting the development of the program. An early example of more rigorous economic analysis is NASA's decision to seek the advice of a Silicon Valley financial expert when formulating COTS. Specifically, in the early 2000s, NASA chose to work with venture capitalist, former physicist, and White House Fellow Alan Marty, who provided strategic insight, including the recommendation to select contractors that could attract investment rather than selecting contractors solely because of their technical capabilities. This prudent advice helped COTS to enable the growth of the commercial launch market.[194]

Narrative Encouragement

Narrative encouragement does not have to be expensive and can reach thousands of people, as NASA's public news releases, strategic plans, and space resource report has shown. Via official press releases and other public documents, NASA communicates with a unified voice, and often that voice has supported commercial development. Communications in 1981 to 2010 included this narrative encouragement of the commercial development of space. Select press releases are described below.

December 20, 2011: "NASA Announces Plans for Human Exploration of Deep Space, Fosters Commercial Spaceflight, and Makes Major Discoveries in 2011." This press release described the Agency's efforts to accelerate commercial space development, particularly space transportation system concepts via $269.3 million in SAAs with companies. As the justification for this commercial support, NASA alluded to ending its reliance on the Russian government to transport U.S. astronauts to the ISS.

October 24, 2007: "NASA Offers $2 Million Lunar Lander Competition Prize." This NASA press release described the purpose of the X PRIZE Cup, which was to award funds to a group that could "accelerate technology development leading to a commercial vehicle" that was able to transport humans between lunar orbit and the lunar surface.

October 4, 2004: "NASA Congratulates SpaceShipOne's X Prize Win." In this press release, NASA administrator Sean O'Keefe congratulated the SpaceShipOne team on the third successful flight of a private human spacecraft. "The spirit of determination and innovation demonstrated today show that America is excited about a new century of exploration and discovery."[195]

August 17, 1999: "NASA to Host Conference Exploring Commercial Interest in Space Station Living Quarters." In this NASA press release, Daniel C. Tam, the special assistant to the NASA administrator for commercialization, described the Agency as "dedicated to the commercial use of space and fostering private enterprise on the new frontier." To achieve this aim, Tam announced that the Agency wanted to "explore potential commercial interest" in a government-industry partnership to build an ISS crew module. Tam also stated that the conference invitation was "one way for us [NASA] to actively pursue the ideas that businesses may have for using a living area in space for profit-driven motives" and that industry might "do a better job than government" in this venture.[196]

In addition to press releases, NASA provided narrative encouragement for the commercial development of space by describing relevant goals in strategic plans. For example, NASA's 1998 strategic plan states that the Agency should "encourage the fullest commercial use of space,"[197] and the 2000 strategic plan includes the Agency goals to "enable and promote commercial research in space" and "enable the commercial development of space."[198]

Further, in the 1990s, NASA released four volumes of a space resources report that provided narrative encouragement, including for companies that later became interested in mining space resources. Volume 1 described scenarios for advanced NASA missions; volume 2 described energy, power, and transport policy issues; volume 3 described technical and policy concerns regarding materials that support space operations; and volume 4 described social concerns about large-scale space activities. The volumes did not officially represent NASA policy; rather, the report was meant to "offer substantiation" for future human exploration of other worlds.[199]

NASA's narrative encouragement regarding the commercial development of space during this era may have given industry the confidence to partner with NASA and may have encouraged the development of the commercial space companies operating today.

Conclusion

The period between 1981 to 2010 was arguably the first period which prioritized NASA support to commercial space development. This was seen through the Space Shuttle, CCDS, COTS, the ISS and numerous other programs that acknowledged that NASA-industry partnerships would be necessary to execute a sustainable but cost-effective human presence in the solar system in an age where NASA's budget was no longer priority appropriation. However, this period also revealed failures in NASA support of commercial space development such as the demise of CCDS, the commercialization of Landsat, the COMET program, and the X-33 program, resulting either from lack of market or cost. Though NASA experienced failures, the Agency initiated many commercial partnerships between 1981-2010, and a sizeable number of these partnerships would continue or adapt to enable today's space exploration activities with more successfully.

Commercial Space Acceleration and the Future 2011–2024

Introduction

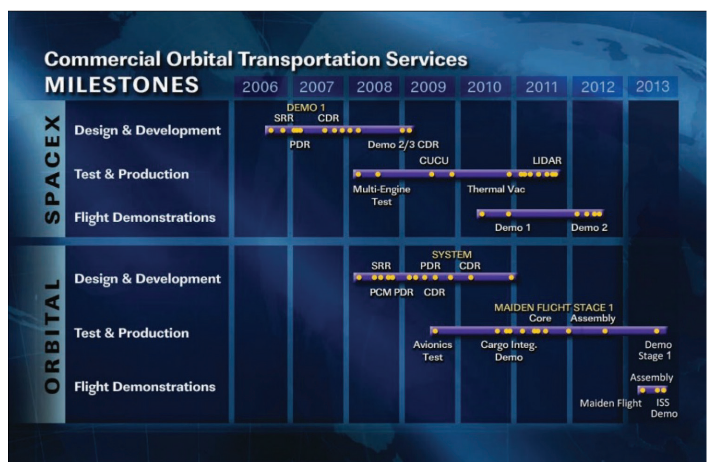
The NASA today era is one in which NASA has extensively supported commercial space development. By expanding the use of SAAs and building on past successes in seeding companies, in this era NASA has become one of the nation's foremost sources of support for commercial space development. At least in part because of NASA's efforts, private investment in the space sector has skyrocketed in this period. NASA has expanded opportunities in increasingly commercially oriented programs, all while broadening the social benefits that come with support of commercial space development.

During this era, NASA has for the first time turned to the commercial sector to own and operate the vehicles on which NASA flies its astronauts to the ISS. The previous era's effort to seed new launch companies has paid off, as the nation has been able to recapture most of the global launch market. At the same time, the creation of a new technology-focused organization, the Space Technology Mission Directorate (STMD), has created new opportunities for NASA to support commercial space development in everything from suborbital human spaceflight to on-orbit assembly and in-space manufacturing. Small satellite capabilities—including the CubeSat standard popularized by the combined efforts of Stanford University, California Polytechnic University, and NASA's Ames Research Center—have become the foundation for a new generation of space start-ups. New, smaller launch vehicles have taken this new generation of space commerce to orbit in large part thanks to the Launch Services Program's Venture-Class Acquisition of Dedicated and Rideshare (VADR) program. More new programs, covering more domains and environments than ever before, are just starting. Examples include Commercial Lunar Payload Services (CLPS), Commercial LEO Destinations, Human Landing Systems, commercial development of NASA space suits, and Lunar Terrain Vehicles. The post-Shuttle era of NASA-supported commercial space development has seen a level of technical development comparable to the Apollo era's Space Race. During the current era, companies have begun to launch cargo and crew to the ISS; have successfully landed a robotic craft on the Moon, and have built the next generation of space stations, and companies will certainly achieve more before the decade is out.

Contracts and Partnership Agreements

During this era, the COTS program's successful delivery of NASA mission value and commercial success for participating companies led to the rapid growth in the development of contract vehicles, which increasingly are commercially oriented. The agreements that were established as part of COTS include SAAs and service contracts for the delivery of core parts of NASA's missions in human spaceflight and exploration. Following the end of the COTS program, the CRS program contracted SpaceX and Orbital Sciences to deliver cargo to the ISS beginning in 2012. Following the end of the CRS, the Commercial Crew Program (CCP) took privately owned and operated missions one step further by sending NASA astronauts to space. CCP culminated on May 30, 2020, with the first crewed launch: the SpaceX Demo-2 successfully flew NASA astronauts Bob Behnken and Doug Hurley into space aboard a SpaceX Falcon 9 rocket. As of early April 2024, there have been eight other crewed CCP missions.[200] As with COTS, unfunded SAAs have allowed NASA to continue engaging with and supporting companies that did not win funded contracts. In fact, this strategy was so successful that Rob Meyerson, chief executive officer of Blue Origin at the time, said that "working with NASA accelerated our BE-3 development by over a year in preparation for flight testing."[201] The success of this new model led to several other similar programs that further pushed for commercial leadership in the design and deployment of new products and services. As a result, Axiom[202] and several other companies are competing to develop orbital platforms today.

NASA established a wide-ranging series of commercial engagements following the early successes of COTS. A notable early example is the Collaboration for Commercial Space Capabilities initiative. The initiative mainly focused on developing relationships with NASA Centers and industry through unfunded SAAs. These agreements enabled NASA to share thousands of technical documents, test facilities, and other physical infrastructure with industry and enabled technical interchanges that were beneficial to both NASA and the companies. The first public call for proposals was in 2014.



Milestones achieved in COTS program projects. NASA implemented the use of performance-based, fixed-price milestones to invest in its COTS business partners. Funding was issued only after the completion of predefined objectives, and any cost overruns were the financial responsibility of the company, not the government. This illustration shows actual completion dates.[203] Credit: NASA.

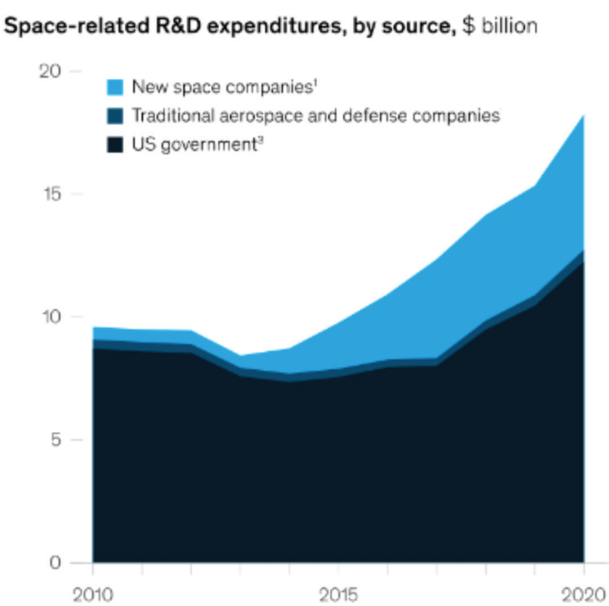
NASA's efforts to support commercial development have expanded beyond LEO to stimulate new lunar activities and to enable future exploration. Support for the latter objectives has come through the CLPS program. As CRS and CCP did, CLPS purchases services from private companies to deliver payloads. Unlike in CRS and CCP, companies in the CLPS program have much more autonomy in development and execution, partly because there is no risk to life. As of April 2024, two of the 13 planned CLPS missions have launched, although only one has made a successful soft-landing (in February 2024). After many trials and tribulations fitting for the namesake of the Intuitive Machines (IM-1) Odysseus spacecraft, it made the first American soft-landing on the lunar surface since 1972. The failed CLPS Astrobotic Peregrine Mission One sparked criticism, particularly among Indigenous communities because one payload carried human remains to be left on the Moon, which the Navajo Nation and other Indigenous communities consider to be sacred. The president of the Navajo Nation stated that placing the remains on the Moon would be an act of desecration and disrespectful of Indigenous communities' beliefs. This ethical concern has led to NASA and the U.S. government having broadened ethical oversight responsibilities for private contracted payloads, in accordance with the Moon to Mars program's tenet regarding responsible use.

NASA's use of commercial services in exploration ties commercial development to NASA's missions. Contract models have expanded to cover nearly all efforts in the Earth-Moon system, through agreements such as the Flight Opportunities Program, the Commercial Low Earth Orbit Destinations program, the Human Landing System contract, the Axiom AxEMU space suit contract, Deep Space Logistics' services for Gateway, and more. The Communications Services Program has followed the same model as COTS, using SAAs with multiple companies to drive design maturity, followed by commercial services contracts. As of Q4 2024, CSP is about to start awarding service contracts. Today, service contracts have become the mainstay of many new NASA missions, greatly expanding opportunities for commercial space development.

R&TD

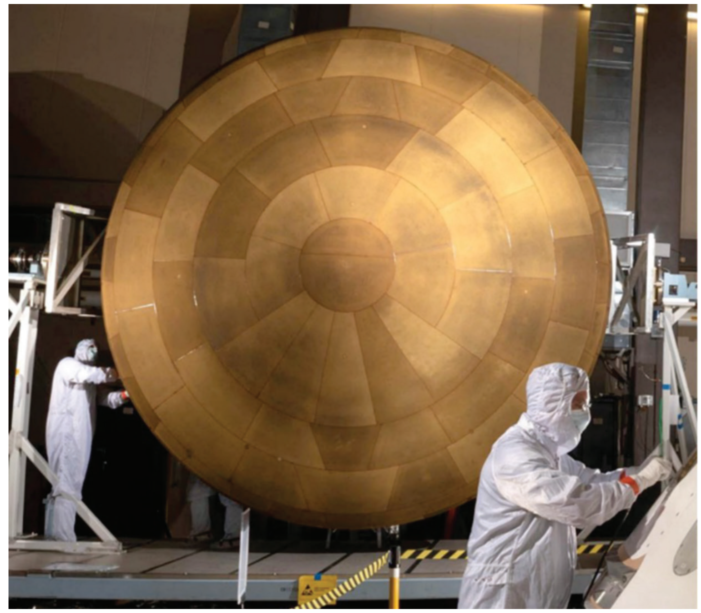
NASA's role in space R&TD remains crucial. NASA is the largest space R&TD performer and funder and delivers capability multipliers to the entire space sector, including low-cost innovative approaches for conducting space missions. These approaches include using small, low-cost satellite R&TD and low-cost robotic lunar lander designs to foster the development of commercial markets while supporting Agency goals. These efforts, combined with lower launch costs, create a substantial reduction in the barrier to entering space engineering and science. Consequently, even high school students can build and launch satellites.[204] The annual report titled "State-of-the-Art of Small Spacecraft Technology" provides insight into the latest publicly available small satellite technology developments.[205]

Until this era, private sector R&TD in space was virtually nonexistent. When the first "new space" company achieved unicorn status (i.e., a new company valued at over $1 billion), Space Exploration Technologies (SpaceX), it was clear that there was money to be made even in what was once considered the least profitable segment of the space sector: launch. SpaceX also took the lead in a cohort of companies developing constellations of thousands of satellites to provide global internet coverage and applying extensive use of assembly-line practices to satellite manufacturing. Additionally, dozens of companies have sprung up and developed new technologies, many entirely original and some entirely privately funded. As Figure 8 shows, "new space" accounts for most private space R&TD funding and has come to contribute a sizeable portion to global space-related R&TD expenditures. NASA's ability to fund both intramural and extramural research, unlike most other Federal R&TD funding agencies, has benefited this trend and benefits from it.[206]



Although U.S. R&TD receives more funding from the private sector than from the government, private sector R&TD in space technology has grown only recently and primarily at start-ups.[207] *Credit: NASA.*

NASA R&TD efforts increasingly lead to the discovery of new technology that directly affects companies. For instance, the phenolic impregnated



This photograph shows the Mars 2020 PICA heat shield, which protected the Perseverance rover and its descent stage during the deep space cruise to Mars and the descent through the Martian atmosphere.The image was taken at Lockheed Martin Space in Denver, Colorado, where the PICA aeroshell was integrated. Credit: NASA.

carbon ablator (PICA), which protects spacecraft from the heat of reentry, was invented at the Ames Research Center in the 1990s, when the technology was transferred to Fiber Materials to supply NASA missions. In the 2000s and 2010s, multiple supply chain issues beset the company, and as these materials were critical to flagship missions, such as the Mars 2020 rover, NASA stepped in with focused R&TD projects to develop a domestic alternative and to provide direct support to Fiber Materials, such as by refurbishing its equipment.[208] This support has led to commercial use of PICA. For example, Varda Space Industries used PICA to return the company's first in-space manufactured products[209] (pharmaceuticals) and is still using the technology today.

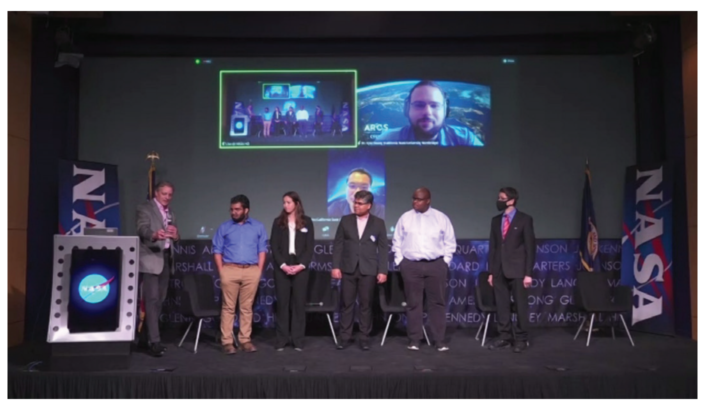
Dissemination of Research and Scientific Data

The present era, so heavily defined by the internet's proliferation, can be seen as a period of expansion, decentralization, opening of knowledge systems, and freer movement of information. In 2013[210] and 2022,[211] OSTP released memos instructing federal research agencies to distribute scientific data faster and to make access to it easier. Consequently, NASA's first software catalog was published in April 2014.[212] Less than a year after the 2022 memo, NASA updated its public access plan,[213] including by making several major changes. One of these changes specifies that software used to develop research results should be publicly released when the results are disseminated. The changes also enhance NASA's ability to disseminate and license the use of its technologies to industry. NASA has implemented other changes to make data more available. For example, the Science Mission Directorate's September 2022 Science Information Policy update[214] incorporates guidelines for openly sharing scientific data generated in all missions, included in solicitations, and generated via international partnerships. NASA's efforts over the decades to improve its dissemination of research and scientific data align with the National Aeronautics and Space Act of 1958's encouragement that NASA work to the greatest extent possible with other public organizations and with private organizations.

NASA is increasingly interested in the data collected by commercial platforms, so much so that NASA implemented the Commercial Satellite Dataset Acquisition program after completing a pilot project in 2017.[215] Beyond LEO, NASA's Lunar Crater Observation and Sensing Satellite mapped the locations and characteristics of lunar craters, water, and mineral deposits, building on the Lunar Prospector satellite's identification of large amounts of hydrogen.[216] These data have informed all subsequent commercial plans regarding the Moon, and NASA continues to develop more commercially useful missions.

Education and Workforce Development

The diversification of the NASA workforce and growth of the nation's aerospace workforce have been important focus areas for commercial space development. NASA currently runs numerous important programs to better collaborate with and enhance the experiences of historically marginalized communities, including minority-serving institutions (MSIs). This support is woven into some programs, while in other programs this support is the primary focus—examples of the latter include NASA's



Michael Seablom, left, of NASA's Earth Science Technology Office presents a trophy to the prize recipients of the first MSI Space Accelerator competition on June 2, 2022, at NASA Headquarters. Recipients in California who joined remotely are visible on the screen at the back of the stage. Credit: NASA.

NASA Champions of Industry

Satellite-Launching Students

NASA's PhoneSat, a four-by-four-inch CubeSat satellite, uses an Android smartphone as its motherboard. It was among the 29 satellites launched from Wallops Island, Virginia. Another miniature satellite, developed by high school students, was also on board. Credit: NASA. Credit: Dominic Hart/AP.

The hundreds of students around the country and world who have been launching satellites represent the future, soon-to-be champions of the commercial space age. NASA's PhoneSat, which leverages cell phone technology in an extremely compact package, represents the new CubeSat form factor and was quickly picked up by students to engage directly in the democratization of space. The first high schoolers who participated launched their satellite in 2013; the first grade school students launched theirs in 2016.

MSI Accelerator and Incubator programs,[217] which combine NASA-funded research, licensed technology, entrepreneurial support, and MSI-focused engagement. Workforce diversification, in the broadest sense, also ensures that students from across the country are inspired to join NASA. Similarly, more opportunities and avenues for engagement have encouraged more students to see themselves in the space sector.

NASA engages in a wide variety of creative approaches to promote workforce development and educational opportunities related to space. Data show that NASA's efforts are experience success. In 2012, for example, an encouraging 84% of elementary and secondary school students across the country expressed interest in STEM careers after participating in NASA's educational programs. Another example of NASA's efforts to encourage STEM careers is the Educational Launch of Nanosatellites program, which has attempted to launch approximately 150 CubeSats in 35 states and Puerto Rico.[218] Another 17 program missions are planned, including in three additional states.[219] NASA's goal is for students and instructors in all 50 states to launch CubeSats, as part the White House Maker Initiative in 2014.

Students at St. Thomas More Cathedral School in Arlington, Virginia, designed and built a miniature satellite that deployed from the ISS on May 16, 2016. Credit: NASA.

During the present era, NASA has expanded its internship programs and the Space Grant and Minority University Research and Education Projects (MUREPs) and has made more online course materials available to educators around the globe. Notably, the Office of STEM Engagement was created to better facilitate NASA internship programs and NASA educational and workforce development opportunities, as well as the Established Program to Stimulate Competitive Research[220] program, which facilitates relationships between U.S. states and territories that have reduced access to participation in federal R&TD.

From 2012 to the present, NASA has continued to support publications and presentations made possible through grants and internship opportunities. For example, in 2017, because of NASA grants and awards to students and institutions, 1,797 peer reviewed papers and technical presentations were produced. Of the awards sponsored by the Space Grant and MUREP, 52% were authored or coauthored by students.[221] In contrast, in FY 2019, 1,374 peer reviewed papers were produced,[222] and in FY 2020, 550 peer reviewed papers, 6 books, and 282 invited paper presentations were produced.[223] Both of these years, about half of the products were authored or coauthored by students.

Workforce External Engagement and Mobility

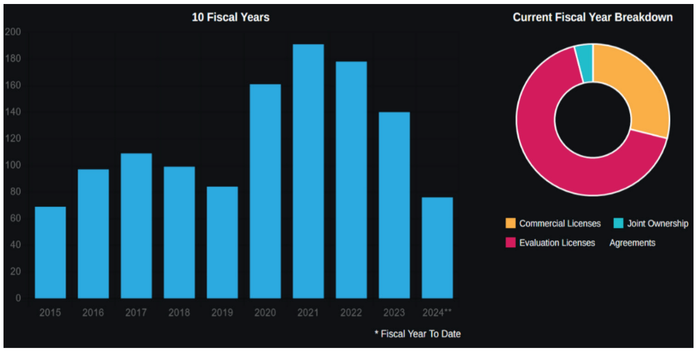
NASA's workforce became a major source of founders and employees for the emerging space start-up scene, which dramatically expanded in the 2010s and has continued to expand in the 2020s. The sheer number of companies and the overwhelming presence of the United States in this new market can in many ways be attributed to NASA.

Some of the most prominent space start-ups in this era involved NASA veterans and early-career professionals who left the Agency to take their experience into the private sector to build something new that they recognized was an opportunity to advance the sector. For example, the company Intuitive Machines was created by NASA veterans who had worked on the Johnson Space Center's Morpheus lander test-bed project. As another example, leadership for Axiom came directly from the ISS program. Capella Space's founders came from the Jet Propulsion Laboratory. Additionally, after Bill Gerstenmaier served as the Human Exploration and Operations Mission Directorate associate administrator, he became vice president of Build and Flight Reliability at SpaceX. Every space "unicorn" has former NASA team members.

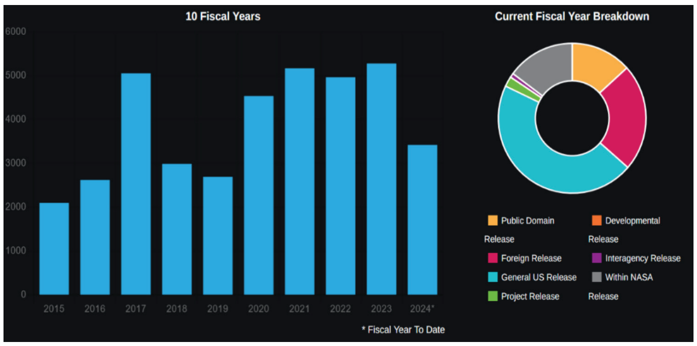
Technology Transfer

NASA's formal technology transfer activities during this era have included continuing the legislatively defined licensing of NASA technologies. For example, NASA's development of Toughened Uni-Piece Fibrous Reinforced Oxidation-Resistant Composite and Roll-Out Solar Arrays have become critical to the development of commercial space.

To increase the Agency's efforts, NASA significantly expanded the breadth and quality of its technology transfer activities. As an example, NASA developed software licensing agreements to accommodate different uses of information technologies, and these agreements have become as well defined as traditional mechanisms.

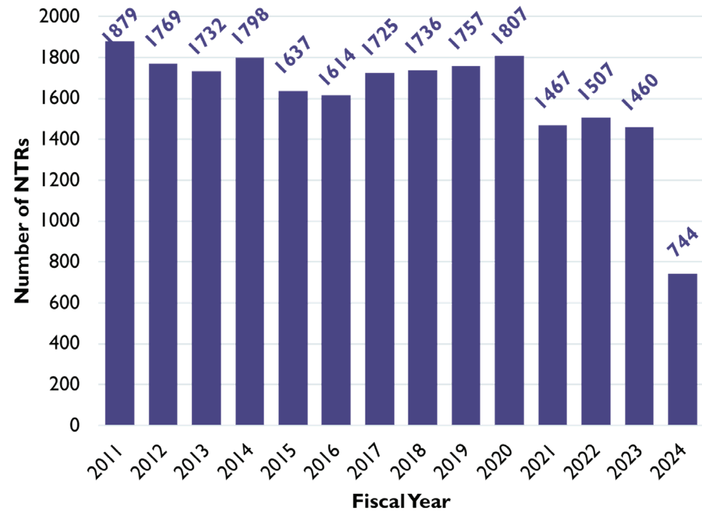


Number and types of licenses NASA issued, 2015–2024. Credit: NASA.

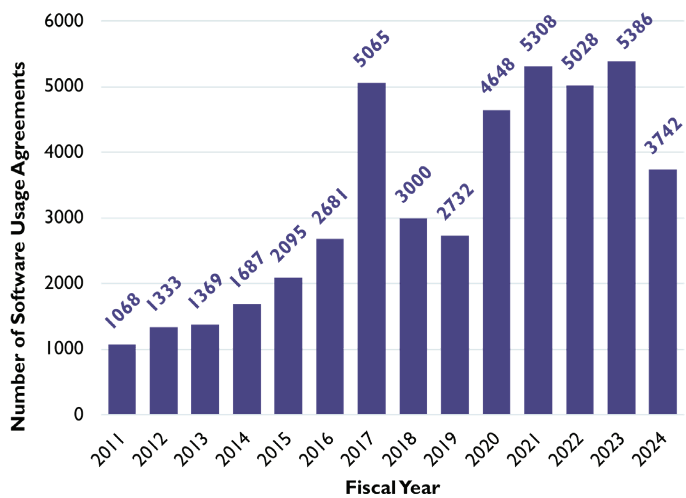


Number and types of software usage agreements NASA issued, 2015–2024. Credit: NASA.

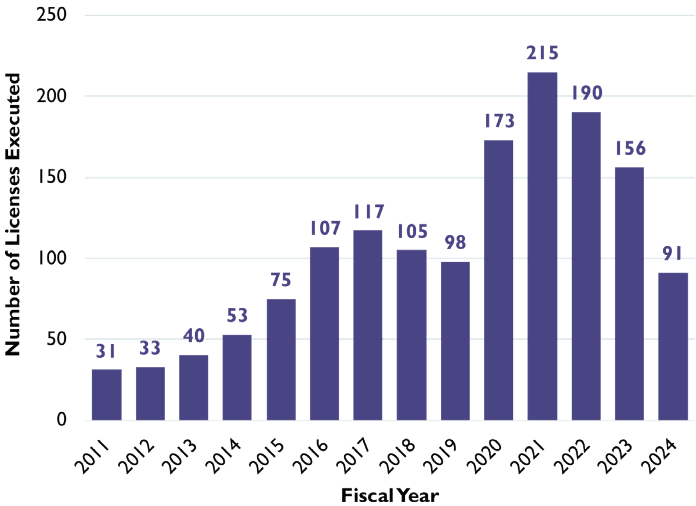
Technology transfer has also increasingly occurred through the transfer of tacit knowledge from one technical expert to another. This transfer was seen somewhat in the CCP with the transfer of human spaceflight knowledge; now, NASA's other commercially oriented programs are transferring knowledge across discipline areas via unfunded SAAs. NASA licenses have contributed to dozens of fields beyond aerospace, including shipping, medicine, construction, manufacturing, and home goods, among others.[224] The chart at top left shows the number and types of licenses NASA has issued since 2015, the chart below that shows the number and types of Software Usage Agreements NASA has issued since 2015, and the chart at top right shows the number of technologies developed at NASA since 2011.



New technologies developed at NASA, 2011–2024. Data provided by the NASA Technology Transfer Office. Data for 2024 was accurate as of May 2024. New Technology Reports include inventions, discovery, improvement, or innovation that was either conceived or first actually reduced to practice in the performance of NASA work. Source: NASA.



Number of Software Usage Agreements NASA Has Issued, 2011–2024. Data provided by the NASA Technology Transfer Office. Data for 2024 was accurate as of May 2024. Software Usage Agreements enable approved individuals and organizations to access NASA software. Source: NASA.



Number Licenses NASA Issued, 2011–2024 Data provided by the NASA Technology Transfer Office. Data for 2024 was accurate as of May 2024. Licensing of patents is one tool NASA uses to promote the use and commercialization of inventions. Source: NASA.

Technical Support

As commercial space capabilities have expanded and began to become operational, NASA technical experts have provided more and more direct support to industry through assisting with technical capabilities and providing technical knowledge. Direct technical support has been embedded in the many new contract vehicles that NASA has developed following COTS, including Commercial Crew Development (CCDev) and CLPS, among others. The flexibility of unfunded SAAs means that multiple technical support agreements can be entered into solely at NASA's discretion without dedicated funding, and the use of SAAs has expanded. Many of the use cases have focused on public benefits while leveraging and fueling commercial development.

One of the early examples of NASA supporting the nascent private lunar lander community was

NASA Champions of Industry

Minority University Research and Education Project (MUREP)

Students in the fall 2023 NASA MUREP Innovation and Tech Transfer Idea Competition pose in front of the Orion Mockup in the Space Vehicle Mockup Facility at the Johnson Space Center. Credit: NASA/James Blair.

NASA has always tried to bring as many along in its journey as it could, and while MUREP was established on the foundation of MSI-focused research funding and training programs,[225] the broadening of MUREP's opportunities represent a new phase in NASA's focus on equity in everything from research to commercial development. In recent years, NASA has developed multiple funded accelerators to assist MSIs in commercializing NASA technology. NASA has also held pitch competitions to fund research, training, educational programs, and more. The contributions of MSIs, traditionally disadvantaged by legacy education and procurement systems, have always been strong, and a whole-Agency approach to connecting MSIs' talent with space continues to deliver successes in terms of NASA's considerable untapped intellectual property.

the CATALYST program, which provided millions of dollars' worth of in-kind support to commercial lunar lander companies through a competitive selection process. The expansion of programs with collaborative technology development required contractual changes to include technical support and to balance NASA's use with protection of a company's ability to profitably market jointly developed technology. The 2020 Space Technology Announcement of Collaboration Opportunity[226] is one of many examples of opportunities companies have received to leverage NASA's technical support. NASA currently has approximately 2,600 partnership agreements, many providing a wide range of technical support to companies.

Enabling Infrastructure

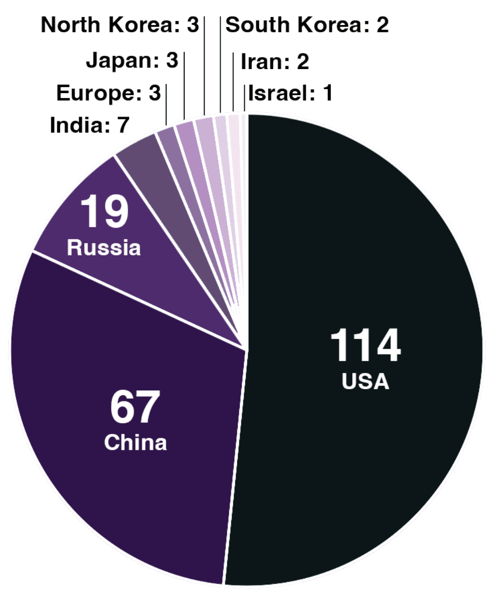
NASA infrastructure, from launch pads to the Deep Space Network, have been foundational in enabling major commercial space developments in this era. Although the capacity for infrastructure use by external users has been stretched to its limits, it has also catalyzed enhancements.

NASA has expanded how much of its property on Earth is made available to external users, notably its launch pads, equipment loans of NASA real property, and Enhanced Use Leasing of real property. Further, commercial access to and use of the ISS has expanded to include dedicated commercialization efforts, such as the In-Space Production Applications program, and deep space infrastructure is currently being developed. The Gateway space station, which is critical for Artemis lunar operations, will also enable a host of public and private sector activity in cislunar space and beyond.

On Earth, in LEO, and in cislunar space, the scale of commercial involvement in the development of new infrastructure represents a major evolution in how NASA deploys the mechanism of enabling infrastructure.

Launch

With the retirement of the Space Shuttle, NASA focused less on supporting commercial space actors with its own launch activities. During the current era, domestic commercial launches have once again become more frequent than launches by companies in any other country. This trend has been supported significantly by NASA's market stimulation activities in the 2000s and the continuing demand established through NASA contracts, such as CRS and CCP. As a result, NASA has been able to look further out to develop infrastructure not on Earth.



Share of global launches by provider nation or region in 2023 Companies in the United States had the largest share of launches in 2023.[227] *Credit: BryceTech.*

NASA's launch support has evolved from direct offerings on NASA launches, the practice in previous eras. In this era, NASA has begun to coordinate with multiple launch providers and assist partners in accessing launches. Beyond the CubeSat Launch Initiative, the Launch Services Program (established 1998) started the Venture-Class Acquisition of Dedicated and Rideshare program,[228] which selected its first launch provider in 2023 to stimulate the launch market with a pipeline of missions that could tolerate some additional risk. Additionally, NASA began supporting the launching of satellites from the ISS in 2013; offering rideshares to CubeSats on resupply missions via the ISS National Laboratory and commercial partners; and deploying the CubeSats from orbit on the Japanese Kibo module, first simply from the airlock and eventually via the Nanoracks CubeSat deployer. Since then, over 200 satellites have been deployed from the ISS. Beyond ISS, rideshares were offered on the Artemis I launch, during which several commercial space projects launched along with the Orion capsule around the Moon. NASA selected 10 CubeSat missions, including multiple commercial missions, to share in Orion's 2022 launch.[229]

Direct In-Space Support

NASA has supported commercial space development in space every single day of this era because of the continual operation of both the ISS and the ISS National Laboratory. Astronauts on board the ISS have helped launch commercial CubeSats from the ISS, have helped conduct commercial research experiments as part of the ISS National Laboratory's activities, and once again began hosting private astronauts—this time, ones launched on American rockets as part of private astronaut missions.

NASA's effort to nurture and integrate companies into its missions as part of the plan for a sustained lunar presence includes direct in-space support for commercial lunar activities. On February 22, 2024, the IM-1 lander became the first American-made spacecraft to land on the Moon since Apollo 17, in 1972. The IM-1 mission faced several technical challenges, from trajectory corrections to a rough landing to its end of mission a month later. NASA provided vital technical support to maximize the survivability and return on investment of IM-1; the support included Lunar Reconnaissance Orbiter's images of the lander and NASA's onboard instruments, which provided vital details of the lander's status and health. More of this kind of multifaceted direct in-space support should be expected as more companies make their way to the Moon, whether or not directly sponsored by NASA.

Standards and Regulatory Framework Support

As part of preparing for a more integrated international and commercially collaborative future, NASA has openly shared many critical designs that have enabled CubeSats and industry convergence on standards, including for human spacecraft docking and approach.

Formulated in 2010, the International Docking System Standard is an international standard for spacecraft docking adapters. The standard was created by the ISS Multilateral Coordination

Board on behalf of the ISS's partner organizations: NASA, Roscosmos, JAXA, the European Space Agency, and the Canadian Space Agency. This standard is a major example of how the early efforts of the NACA to develop aviation standards have evolved in the deeply interconnected global aerospace system, in which no standard can be developed unilaterally.

This photo shows Snoopy looking at his ride to space, which is currently stacked atop the Space Launch System rocket inside the Kennedy Space Center's Vehicle Assembly Building. Snoopy, the zero-gravity indicator for the Artemis I mission, was delivered to NASA's Kennedy Space Center on December 2, 2021. Credit: Kim Shiflett/NASA.

NASA also engages with domestic and international regulatory bodies, and this engagement often enables commercial activity. To assist in engaging with regulatory bodies, NASA created the lunar spectrum manager role. Specifically, the role was created "to facilitate more efficient pre-coordination of spectrum requirements amongst all public- and private-sector lunar activities."[230] This effort is crucial in enabling both the government and companies to operate in the lunar environment, and NASA's role is central in assisting other government agencies, Earth's spectrum regulators, and companies understand the regulation of new activities in new environments, such as the Moon.

Public Engagement

NASA has constantly expanded the ways it interacts with the public at large. NASA's constant engagement with the public serves large groups of people whose interest in space leads them to find opportunities to work in space, including commercial space. NASA first engaged the public to assist with science at the turn of the century. Early citizen science programs, including Clickworkers,[231] were used to conduct science tasks, such as identifying Martian craters and asteroids, and other activities that both engaged the public and helped NASA analyze the ever-growing amount of information and imagery that the new class of science missions was returning. Since the beginning of the 21st century, NASA has supported more than 600 public challenges, hackathons, and crowdsourcing projects.

NASA's public engagement has been accelerated in this era by the proliferation of social media platforms. NASA projects and programs are often some of the earliest government users of new platforms. Examples including early use of Twitter to share mission updates, which the Mars Phoenix lander did at the start of this era, and NASA's roll out in 2024 of a streaming platform (NASA+).

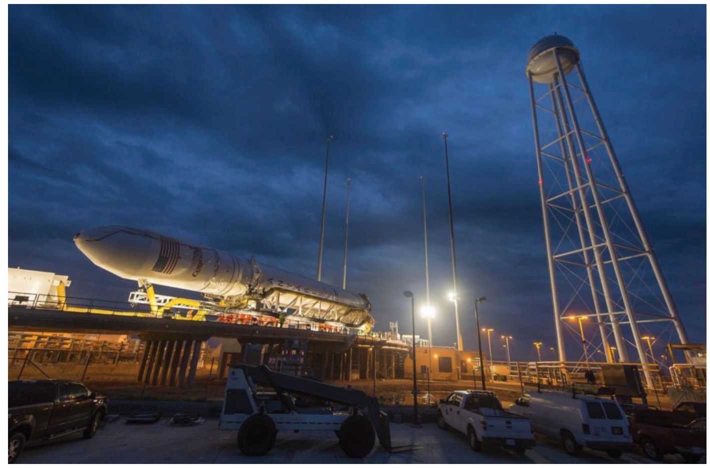
During this era, one of the most significant outreach innovations has been a simplified application for using the NASA logo—"the meatball'"—on commercial merchandise. Provided that applicants follow NASA's brand use guidelines, NASA's logo can be used for everything from luxury products to basic T-shirts, resulting in a proliferation of NASA's global outreach potential.

In the age of social media, space-related stories have taken on lives of their own, sometimes with NASA's encouragement, sometimes without. In one effective use of social media, NASA gave its Martian rovers personalities and portrayed them in social media posts as pining for home on Earth. These posts were viewed, reacted to, and reposted by millions of people. As another example of social media engagement, NASA mission employees who were on live video feeds began receiving nicknames, such as "Mohawk Guy" (real name: Bobak Ferdowsi). These sparks of NASA in the zeitgeist have fueled creators and inspired a new generation of entrepreneurs.

NASA's efforts at public engagement have received extensive critical acclaim. Since the first Webby award was given in 1998, NASA has won 37 Webbys and 53 People's Voice Awards.[232] The Agency also won an Emmy in 2019.[233] NASA has also received many science-focused communication awards.

Industry Engagement

Collectively, the founding of Orbital Science in 1982, Space X in 2002, Blue Origin in 2000, and Nanoracks in 2009 marked a turning point for NASA industry engagement, as these companies



Orbital Sciences developed the Antares launch vehicle as part of the company's COTS SAA. Originally named the Taurus II, the 131-foot rocket is capable of lifting over 11,000 pounds to LEO. This medium-class vehicle reflected the company's philosophy of relying on proven hardware components.[234] Credit: NASA/Brea Reeves.

became successful arguably because they were integrated into NASA projects. SpaceX and Orbital Science won NASA COTS contracts to build rockets that could transport cargo to the ISS in the 2010s, and Nanoracks became the first company during this period to deploy satellites from the ISS (in 2013). Blue Origin and SpaceX have since partnered with NASA and other organizations to deliver humans and cargo to the Moon for the Artemis endeavor.

As commercial space capabilities expanded, industry engagement became a more and more important part of the jobs of NASA senior managers and NASA Headquarters in particular. While requests for information and industry days have long been part of NASA's activities, these tools have become more and more frequently used in the present era as ways to receive input from industry and learning about what successful approaches, leading to better partnerships. A recent example of how industry engagement has broadened to strategic inputs for NASA decision-

NASA Champions of Industry

Steve Jurczyk
Acting Administrator of NASA

Steve Jurczyk, during an agency meeting at the 2019 Space Symposium meeting in Colorado Springs. Credit: NASA/Joel Kowsky.

Steve Jurczyk, a Virginia native, devoted 32 years of his life to NASA. He was the director of the Langley Research Center, the associate administrator of STMD, the associate administrator of NASA, the acting administrator of NASA, and the president and chief executive officer of Quantum Space before passing away at the age of 61 from pancreatic cancer. During his time at NASA, he oversaw nearly all STMD program that focused on fostering technology development, including commercial space stimulation programs, such as Tipping Point, which he championed in particular. In addition, as an associate administrator of NASA, he was the official for the original Human Landing Systems selection, which established a commercial service provider on the critical path to returning humans to the surface of the Moon. His experience was highly valued in the private sector, and he was a leader in incorporating commercial space development into multiple aspects of NASA's portfolio.

makers is the 2024 call for Space Technology Priorities.[235] This call demonstrates NASA's recognition of the intertwined nature of the Agency and commercial development.

NASA engages industry more broadly not than ever before, particularly for the development of new capability needs and regulatory frameworks. Since 2020, NASA's STMD has formulated and funded the Consortium for Space Mobility and ISAM Capabilities,[236] the Lunar Surface Innovation Consortium; and the Collaborative Network for Valuing Earth Information, among other groups, all of which foster industry engagement.

NASA also hosts a variety of workshops with industry and other government agencies, whether to share technical priorities and advances, assess overall strategic direction and alignment, or explore potential opportunities to collaborate. A recent example is the Apophis Workshop, conducted by the Agency's chief technologist. This listening workshop was held in February 2024[237] and was followed by a request for information from industry in August 2024 to solicit a non-NASA mission to the Apophis asteroid.

Market Stimulation Funding

During the current era, NASA's market stimulation capabilities have become more widely appreciated, thanks in large part to the success of the COTS program. As a result, funded and especially unfunded SAAs have been used more and more in STMD Tipping Point awards and Commercial LEO Destinations. Outside of programs, hundreds of funded and unfunded SAAs were signed to further stimulate the space market. A possible sign of the success of these efforts can be seen in the number of new investors in the space sector across investing organization types, as seen in Figure 15.

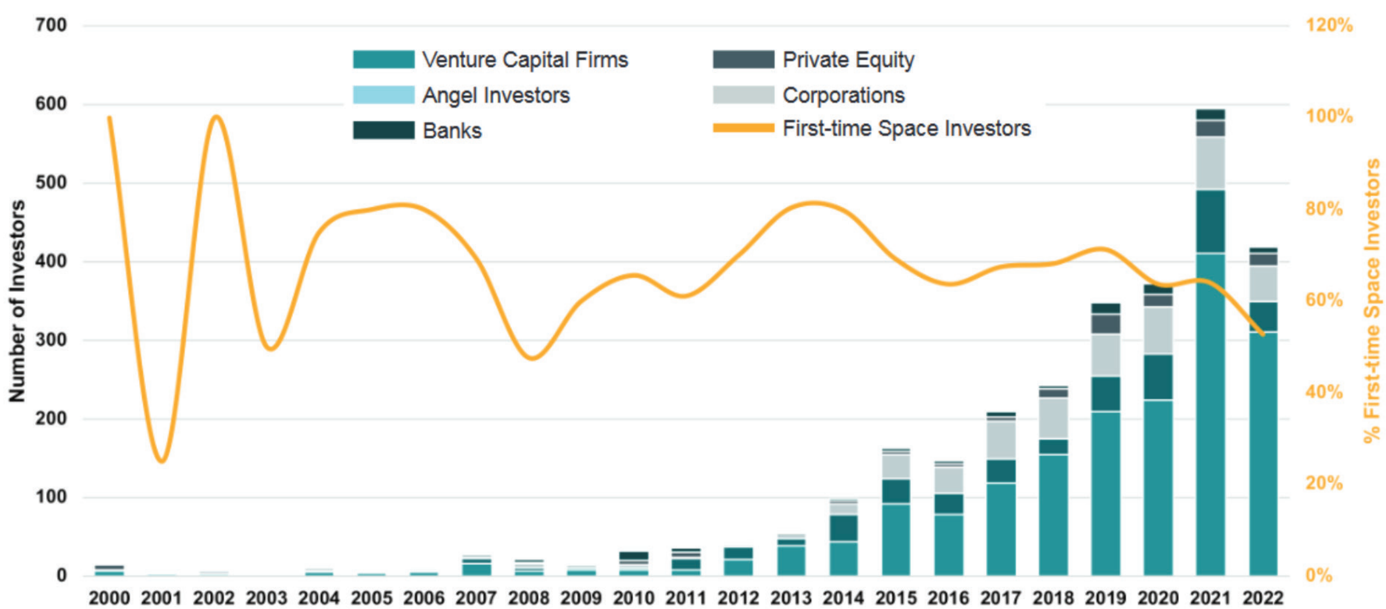
With the commercial launch capabilities created through the COTS market stimulation efforts and with the expanded use of SAAs for the Commercial Crew program, NASA has also finally embraced the long-promoted vision of commercial space stations. The adoption of this vision is evident in the establishment of the Commercial LEO Destinations Program and the use of funded SAAs to stimulate the emerging market for commercial LEO human spaceflight capabilities as part of the NASA LEO Microgravity Strategy.[238] These activities have allowed NASA to leverage seeded capabilities for the next frontier of commercial space development, from Earth's orbit to the Moon. In parallel, cross-cutting capabilities such as communications have experienced market stimulation through initiatives such as the Communication Services Program, as part of the Space Communications and Navigation's commercialization plan.

NASA has also stimulated the insurance market, which has been a broad enabler for commercial space activities. In addition to engaging in conversations and demand-signal efforts, NASA has begun requiring insurance for many partners, such as private astronaut mission providers.[239]

Economic Analysis and Due Diligence Capabilities

As more and more NASA programs have begun to rely on and engage with commercial space capabilities, NASA has increasingly needed to bring economic analysis and due diligence capabilities in-house.

During this era, market assessments have been completed for CATALYST, Tipping Point, and Next Step Broad Agency Announcements. The



Types of investors in the space sector, 2000–2022. This figure shows that, among other things, in most years from 2000 to 2022, the majority of space investors were first-time investors in the space sector.[240] *Credit: BryceTech.*

Emerging Space Office (2012-2016) funded economic studies, including the NexGen space study on commercial lunar landers. The Emerging Space Office also funded the original Start Up Space report;[241] funded studies such as Economic Development of Low Earth Orbit;[242] and, based on economic analyses, identified ZBLAN as a particularly valuable microgravity application.

Although economists have worked in and on contract with NASA for a long time, the proliferation of commercial space capabilities and NASA's increasing engagement with them resulted in the creation of a new chief economist position to directly support the NASA Office of the Administrator with economic analysis and advice related to the emerging commercial space economy.

Narrative Encouragement

As commercial space capabilities have been proven, NASA's commercial narrative has become more expansive. Reflected in NASA publications and public statements, this expanding narrative now includes support not just for an LEO economy but also a lunar economy. This increasingly economic tone to the space program has been heard in speech after speech by presidents and vice presidents across political parties, and new programs have been implemented to re-create the success of NASA's market stimulation.

One early example of this expanded narrative is NASA's report "Emerging Space: The Evolving Landscape of 21st Century American Spaceflight." The report was published in 2014, half a decade before the Artemis program was announced, when the official NASA exploration goal was a human mission to an asteroid. The report declared that "when NASA was founded only a government program could undertake a voyage from the Earth to the Moon, this may not be true in the future" and that "by taking full advantage of the combined talents of government and the American private sector, our next journeys beyond Earth will come sooner and we will catalyze new industries and economic growth in the process."[243] As we have come to see, this narrative has proven true through public-private partnerships to advance NASA's and industry's goals.

Conclusion

The era of commercial space development from 2011 to the present is the product of several generations of support for and pursuit of a future in which humanity may live, work, and play beyond Earth's cradle. NASA and its antecedents seeded the future we live in by adapting and expanding commercial space development mechanisms era after era. Since 2011, private investment in the space sector has soared to create multiple aerospace unicorns; nongovernment funded R&TD has grown to a sizeable portion of total space R&TD investment; the franchise of access to space has expanded beyond all but science fiction's expectations; and NASA has found such strong partners in the companies it has nurtured over the years that today it seems almost unthinkable to build a sustained presence anywhere without collaborating closely with industry. The future of commercial space has never been brighter, and NASA will continue to push boundaries to achieve even more than it already has.

Conclusion: Lessons Learned from a Moment in Time

NASA has employed the 17 mechanisms described in this document since the earliest days of the NACA. In reviewing the execution of these mechanisms during the four eras of commercial space development, we have seen that some mechanisms were used more often than others at various times and that execution of the mechanisms has evolved with the development of the commercial space sector, and that NASA continues to be deeply tied to the growth of this flagship of American economic development. This qualitative summary of the mechanism can be built upon through assessing the relative impacts of the mechanisms, identifying conditions for appropriate use, and completing quantitative assessments.

Today we are living in the most dynamic and exciting period of commercial space development, in both a public and a private sense. Without NASA's support to industry companies, the growing space economy that is present today would not be possible. This report has documented over 111 years of NACA and NASA support and guidance to U.S. industry. Although the mechanisms that NASA has used to support commercial space development have evolved over time, they are also remarkably consistent and demonstrate a long-run institutional commitment to the support of commercial development in the aviation and space sectors. NASA is experimenting with more extensively using commercial space development mechanisms than ever before. In effect, NASA is running a wide variety of economic experiments regarding the potential of commercial space development. We need to be objective about what we learn from these experiments if we are going to be able to best deploy the 17 commercial space development mechanisms in the future as part of NASA's mandate to encourage commercial space activities. NASA's Office of Inspector General reports on the Agency's activities, such as the annual Top Management and Performance Challenges report,[244] are important resources for accountability. NASA's success over the next 111 years will depend not only on commercial space capabilities but also on learning to deploy commercial space development mechanisms with ever-increasing sophistication and flexibility.

Aknowledgements

This report has been developed by the Agency Chief Economist in the Office of Technology Policy and Strategy, Alexander MacDonald and Senior Policy Advisor Patrick Besha, with support from BryceTech team members Jordan Sotudeh, Alyse Beauchemin, Warren Ferster and Phil Smith.

This document's creators would like to acknowledge the significant contributions of reviewers and experts consulted in the making of this work: Suzy Bills (BryceTech), Joe Kroner (NASA MSD), Margaret Roberts (NASA OGC), Biran Odom and James Anderson (NASA Historians), Karla Jackson (NASA OP), Phil McAlister (NASA SOMD), Jenn Gustetic, John Nelson, Matt Deans, Amy Kaminski, and Dan Lockney (NASA STMD), Gib Kirkham (NASA OIIR/SMD), Lori Glaze (NASA ESDMD), Mike Kincaid and Diane DeTroye (NASA OSTEM), Jon Montgomery and Toy Springer (NASA ARMD).

Appendix A: Table of Mechanism Execution and Outcomes

Mecahnisms	Origins of NASA *1957–1960*		The Race to the Moon and the Expansion of NASA's Role in the Economy *1961–1980*		The Rise of Internationalism and Commercial Space Development at NASA *1981–2010*		Commercial Space Acceleration and The Future *2011–2024*	
	Means of Execution	Outcome	Means of Execution	Outcome	Means of Execution	Outcome	Means of Execution	Outcome
Procurement Contracts	Development contracts	Spacecraft hardware	Development contract for Saturn V first stage Contracts to develop communications satellite technology	Commercial launch vehicle technology. Advanced nascent satellite telecom industry, both in services and manufacturing	JEAs, SAAs, performance-based contracts	More effective or efficient public-private partnerships	COTS, CRS, and CCP	Commercial owned and operated space vehicles capable of delivering crew and cargo to the ISS
Research and Development (R&D)	Fundamental and applied research programs under the NACA and NASA	Innovation by industry in the NACA era and preliminary specifications for a crewed capsule	Satellite telecom technology development	Advancements later applied commercially	Establishment of NASA offices and programs to aid in commercial innovation	Innovative forms of public-private research and development programs	R&D performance and funding	Enabled private sector R&D
Disseminating Research and Scientific Data	Published reports and proprietary rights policy under the NACA	An informed commercial sector on the latest aero-nautical research	Earth Resources Technology Satellite (Landsat) program	Laid foundation for commercial remote sensing	Privatization of Landsat program, disseminating Hubble data via the internet, and development of the M3 for the Chandrayaan-1 mission.	Failure in the case of Landsat privatization, proof of internet as valuable means of data dissemination, determination of water molecules in lunar poles	The internet, memos, NASA public access plan, data gathered from LCROSS	Easily accessible data, particularly concerning lunar characteristics

Mecahnisms	Origins of NASA *1957–1960*		The Race to the Moon and the Expansion of NASA's Role in the Economy *1961–1980*		The Rise of Internationalism and Commercial Space Development at NASA *1981–2010*		Commercial Space Acceleration and The Future *2011–2024*	
	Means of Execution	Outcome	Means of Execution	Outcome	Means of Execution	Outcome	Means of Execution	Outcome
Education and Workforce Development	Informal relationships with academia in the NACA era	External engagement and mobility to industry	Contract with MIT Instrumentation Lab for Apollo guidance computer	Technology decisions helped spur the Silicon Valley tech revolution	NASA funded opportunities for education and workforce development	Encouragement and inspiration for students to pursue space-related careers	MSI Accelerator and Incubator programs, workforce diversification, internship programs, creation of OSTEM Engagement	Encouragement and inspiration for students to pursue space-related careers
Workforce External Engagement and Mobility	NASA employees transitioning to industry	New knowledge and experience seeded into industry	NASA nurtured highly skilled civil servants who went on to blaze trails in commercial space	David W. Thompson co-founded Orbital Sciences Corp., an early player in commercial launch, LEO telecom, and remote sensing	Providing employees with valuable experiences for professional development	Experience gained by commercial companies when workforce mobility occurred	Providing employees with valuable experiences for professional development	Source of commercial space company founders and employees
Technology Transfer	Technical publications in the NACA era and patents in the NASA era	Industry innovation	NASA in 1962 created Industrial Applications Program for tech transfer	Within a decade, NASA fielded 70,000 requests for Agency-developed technology	NTRs, patent licenses, and software usage agreements	Industry innovation	Creation of technologies that benefit the commercial development of space, technology transfer licenses	Industry innovation
Technical Support	Technical expertise via research agreements with companies in the NACA era	Industry innovation	NASA assisted General Dynamics in effort to develop cryogenic upper stage	Centaur upper stage still operating today on commercial launch vehicles	Enabling of commercial launch markets	Pegasus rocket deployment, COTS program	Technical capabilities and knowledge, CCDev and CLPS, NASA CATALYST Program	Industry Innovation
Enabling Infrastructure	Industry use of NACA centers and infra-structure such as wind tunnels	Airplane manufacturing innovations in NACA era	NASA infrastructure used to test Centaur upper stage	Centaur upper stage still operating today on commercial launch vehicles	Industry use of NASA facilities for product testing and research	Industry knowledge of how to launch satellites to orbit and how materials react in microgravity	Industry use of launch pads, equipment loans, use and the Deep Space Network, etc.	Enabling commercial development
Launch	N/A	N/A	NASA launched commercial telecom satellites in the 1960s	Satellite telecom is the most successful commercial space enterprise to date	The Space Shuttle and COMET Program	Failure due to Challenger and COMET launch failures	CRS, CCP, and launch support for commercial payloads	Increased commercial access to space
Direct in-Space Support	N/A	N/A	NASA provided ground-station support for early telecom satellites	Satellite telecom is the most successful commercial space enterprise to date	Astronaut research time via the Space Shuttle and ISS	Executed commercial space research	Commercial payloads on the ISS and ISS National Lab, assistance to IM-1	Enabled commercial activity in space

Mecahnisms	Origins of NASA *1957–1960*		The Race to the Moon and the Expansion of NASA's Role in the Economy *1961–1980*		The Rise of Internationalism and Commercial Space Development at NASA *1981–2010*		Commercial Space Acceleration and The Future *2011–2024*	
	Means of Execution	Outcome	Means of Execution	Outcome	Means of Execution	Outcome	Means of Execution	Outcome
Standards and Regulatory Framework Support	Promotion of aviation standards in the NACA era, and satellite communications policy in the NASA era	Aviation safety and organized commercial operational practices	NASA supported FCC in telecom satellite license reviews	Satellite telecom is the most successful commercial space enterprise to date	NASA-created safety and hardware standards	Safety and hardware standards to guide commercial development	International docking system standards and lunar spectrum management	Guides for commercial development and operations in space
Public Outreach	Dedicated resources and the establishment of offices dedicated to public outreach	Public inspiration to pursue careers in the space sector	NASA pushed for live coverage of Apollo launches; Apollo 11 captured worldwide audience of up to 650 million	Apollo inspired a generation to pursue space careers, including in commercial sector	Industry partnerships, public attractions, and use of the internet	Public inspiration to pursue careers in the space sector	Proliferation of social media platforms and introduction of NASA+ platform	Instantaneous public access to NASA mission information
Industry Engagement	Industry representation on NACA and NASA committees	Greater engagement and feedback to government on industry needs	NASA kept industry apprised of activities and plans in various forums	U.S. industry has long been a global leader in space technology	Industry representation NASA Commercial Task Force and creation of Office of Commercial Programs.	Advocation of public-private partnerships, the expansion of commercial activities, and direct avenues for NASA-industry engagement	COTS contracts, RFIs, and industry days	Effective industry engagement
Venture Capital Engagement	N/A	N/A	N/A	N/A	Partnership with strategic investment firm Red Planet Capital, inc.	Failure to attract significant non-NASA capital	N/A	N/A
Market Stimulation Funding	N/A	N/A	N/A	N/A	COTS, SAAs, CCDS	Success in market stimulation via COTS and SAAs, failure with CCDS	COTS, SAAs, STMD Tipping Point awards, and Commercial LEO Destinations	Stimulation of market capabilities for commercial LEO human spaceflight capabilities
Economic Analysis and Due Diligence Capabilities	N/A	N/A	N/A	N/A	Financial advice on the development of COTS	Enabled growth of the commercial launch market	Funded economic studies via the Emerging Space Office	Creation of NASA Chief Economist position to perform economic analysis and advice related to the emerging commercial space economy
Narrative Encourage-ment	N/A	N/A	NASA regularly reported on its activities to support the satellite telecom industry	Satellite telecom is the most successful commercial space enterprise to date	NASA Press releases, strategic plans, and a space resources report	Infused confidence in industry to partner with NASA for commercial development	NASA publications and public statements	Support for LEO and lunar economies

Bibliography

Arrighi, Robert S. “Renowned Woman Scientist Got Start at NACA in Cleveland in the 1950s.” NASA, March 13, 2023. https://www.nasa.gov/history/renowned-woman-scientist-got-start-at-naca-in-cleveland-in-the-1950s-2/.

Bahan-Szucs, June C. “NASA Headquarters NACA Oral History Project: Oral History Transcript.” Interview by Sandra Johnson. NASA, September 29, 2005. https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/NACA/Bahan-SzucsJC_9-29-05.pdf.

Becker, John V. “NASA Headquarters NACA Oral History Project Oral History Transcript: John V. Becker.” Interview by Rebecca Wright. NASA, May 3, 2008.

Bilstein, Roger E. Orders of Magnitude: A History of the NACA and NASA, 1915–1990. NASA, 1989. https://ntrs.nasa.gov/api/citations/19890017434/downloads/19890017434.pdf.

Boyd, John W., “NASA Headquarters NACA Oral History Project Oral History Transcript: John W. Boyd.” Interview by Jennifer Ross-Nazzal. NASA, October 3, 2005, https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/NACA/BoydJW_10-3-05.pdf.

Butrica, Andrew J. “The Commercial Launch Industry, Reusable Space Vehicles, and Technological Change.” Business and Economic History 27, no. 1 (Fall 1998).

Ceruzzi, Paul E. “The Other Side of Moore’s Law: The Apollo Guidance Computer, the Integrated Circuit, and the Microelectronics Revolution, 1962–1975,” in NASA Spaceflight: A History of Innovation, eds. Roger Launius and Howard McCurdy, 98–119. Palgrave Macmillan, 2018.

Chaikin, Andrew. “How the Spaceship Got Its Shape.” Air & Space Magazine, November 2009. https://www.smithsonianmag.com/air-space-magazine/how-the-spaceship-got-its-shape-137293282/.

Christian, C. A., and A. Kinney, “The Public Impact of Hubble Space Telescope.” Office of Public Outreach Monograph, 1999. https://www.stsci.edu/~carolc/publications/public_impact.PDF.

Comstock, Douglas A., and Daniel Lockney. “NASA’s Legacy of Technology Transfer and Prospects for Future Benefits.” AIAA Space 2007 Conference & Exposition, September 18–20, 2007. https://spinoff.nasa.gov/sites/default/files/2021-07/hist_techtransfer.pdf.

Congressional Research Service. “The National Space Council.” Updated December 12, 2016. https://crsreports.congress.gov/product/pdf/R/R44712.

Dawson, Virginia P. Engines and Innovation: Lewis Laboratory and American Propulsion Technology. NASA History Series, 1991. https://ntrs.nasa.gov/api/citations/19910006662/downloads/19910006662.pdf.

Ferguson, Robert G. “Evolution of Aeronautics Research at NASA.” In NASA’s First 50 Years: Historical Perspectives, ed. Steven J. Dick, 205–222. NASA, 2010. https://www.nasa.gov/wp-content/uploads/2023/02/607087main_NASAsFirst50YearsHistoricalPerspectives-ebook.pdf?emrc=3e2a2a.

Ferguson, Robert G. NASA’s First A: Aeronautics from 1958 to 2008. NASA, 2013. https://www.nasa.gov/history/history-publications-and-resources/nasa-history-series/nasas-first-a-aeronautics-from-1958-2008/#:~:text=By%20Robert%20G.%20Ferguson%20Aeronautics%2C%20the%20first%20A,in%20the%20shadows%20of%20NASA%E2%80%99s%20marquee%20space%20programs.

Ferster, Warren. “Avascent Buys Futron’s Space Practice.” SpaceNews. July 9, 2014. https://spacenews.com/41185avascent-buys-futrons-space-practice/.

Forbes. “Space Cowboy.” Updated June 6, 2013. https://www.forbes.com/forbes/2005/0509/058.html.

Gainor, Christopher. Not Yet Imagined: A Study of Hubble Space Telescope Operations. NASA History Program Office, 2020. https://www.nasa.gov/wp-content/uploads/2020/12/not_yet_imagined_tagged.pdf?emrc=ce2a67.

Government Employees Training Act. Public Law 85-507. 85th Congress. July 7, 1958. www.congress.gov/85/statute/STATUTE-72/STATUTE-72-Pg327.pdf.

Graham, Robert W. “NASA Headquarters NACA Oral History Transcript: Robert W. Graham.” Interview by Sandra Johnson. NASA, September 30, 2005. https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/NACA/GrahamRW_9-30-05.pdf.

Green, R. O., C. Pieters, P. Mouroulis, M. Eastwood, J. Boardman, T. Glavich, P. Isaacson, M. Annadurai, S. Besse, D. Barr, B. Buratti, D. Cate, A. Chatterjee, R. Clark, L. Cheek, J. Combe, D. Dhingra, V. Essandoh, S. Geier, J. N. Goswami, R. Green, V. Haemmerle, J. Head, L. Hovland, S. Hyman, R. Klima, T. Koch, G. Kramer, A. S. K. Kumar, K. Lee, S. Lundeen, E. Malaret, T. McCord, S. McLaughlin, J. Mustard, J. Nettles, N. Petro, K. Plourde, C. Racho, J. Rodriquez, C. Runyon, G. Sellar, C. Smith, H. Sobel, M. Staid, J. Sunshine, L. Taylor, K. Thaisen, S. Tompkins, H. Tseng, G. Vane, P. Varanasi, M. White, and D. Wilson. “The Moon Mineralogy Mapper (M^3) Imaging Spectrometer for Lunar Science: Instrument Description, Calibration, On-Orbit Measurements, Science Data Calibration, and On-Orbit Validation,” Journal of Geophysical Research: Planets 116, no. E10 (2011). https://doi.org/10.1029/2011JE003797.

Hackler, Rebecca, and Rebecca Wright. Commercial Orbital Transportation Services: A New Era of Spaceflight. NASA, 2014. https://www.nasa.gov/wp-content/uploads/2016/08/sp-2014-617.pdf?emrc=81adc8.

Henry, Keith. “NASA’s 1999 Commercial Invention of the Year.” NASA Commercial Technology Network. April 5, 2000. https://web.archive.org/web/20020209163429/http://nctn.hq.nasa.gov/success/msg00025.html.

https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/NACA/BeckerJV_5-3-08.pdf.

https://planetary.s3.amazonaws.com/assets/pdfs/FY1991-Budget-Estimates-Volume-1.pdf.

https://www.nasa.gov/wp-content/uploads/2023/08/house-approps-action-domestic-nonfed-saas-active-as-of-6-30-2023.pdf.

ISS National Laboratory. “About the ISS National Laboratory.” Accessed August 16, 2024. https://www.issnationallab.org/about/about-the-iss-national-lab/.

ISS National Laboratory. “Spaceflight R&D Spans Many Disciplines.” Accessed August 16, 2024. https://www.issnationallab.org/research-on-the-iss/areas-of-research/.

Johnson, Stephen B. The Secret of Apollo: Systems Management in American and European Space Programs. Johns Hopkins Press, 2002.

JPL. “Moon Mineralogy-Mapper.” Accessed August 14, 2024. https://www.jpl.nasa.gov/missions/moon-mineralogy-mapper-m3.

Kennedy Space Center Visitor Complex. “History of Kennedy Space Center Visitor Complex.” The Payload Blog. Published July 31, 2017, https://www.kennedyspacecenter.com/blog/31/history-of-kennedy-space-center-visitor-complex.

Launius, Roger D. “Global Instantaneous Telecommunications and the Development of Satellite Technology,” in NASA Spaceflight: A History of Innovation, eds. Roger Launius and Howard McCurdy. Palgrave Macmillan, 2018, 57–80, eBook.

Launius, Roger D. NACA to NASA to Now: The Frontiers of Air and Space in the American Century. NASA Office of Communications, 2022. https://www.nasa.gov/wp-content/uploads/2023/02/NACA-to-NASA-to-NOW_TAGGED.pdf?emrc=e914ad.

Lawler, Andrew, and Daniel J. Marcus. “NASA Sets Plan for Commercial Satellite Research Center.” Space News. January 21–February 3, 1991.

MacDonald, Alexander. The Long Space Age: The Economic Origins of Space Exploration from Colonial America to the Cold War. Yale University Press, 2017. http://www.jstor.org/stable/j.ctt1n2tvkx.

McCurdy, Howard E. “Lessons from the Past: How NASA’s Early Culture Informs Current Challenges.” ASK Magazine, September 1, 2008. https://appel.nasa.gov/2008/09/01/lessons-from-the-past-how-nasas-early-culture-informs-current-challenges/.

McCurdy, Howard E. Inside NASA: High Technology and Organizational Change in the U.S. Space Program. Johns Hopkins University Press, 1993.

McMurray, Clifford R. “A New Era for Science: Research on the International Space Station.” Ad Astra, Summer 2010, 25–27. https://space.nss.org/wp-content/uploads/2017/07/Ad-Astra-Magazine-2010-International-Space-Station-science.pdf.

McTigue, John G. “NASA Headquarters NACA Oral History Project: Oral History Transcript.” Interview by Rebecca Wright. NASA. September 29, 2005. https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/NACA/McTigueJG_9-29-05.pdf.

NASA Advisory Council. “Council Members.” Accessed August 13, 2024. https://www.nasa.gov/council-members/.

NASA. “2010s: Go for Green Run.” Updated June 18, 2024. https://www.nasa.gov/stennis/about-stennis/stennis-space-center-history/chronology/2010-2019/.

NASA. “3rd SEI Technical Interchange Proceedings.” 3rd Space Exploration Initiative Technical Interchange Meeting, Houston TX, May 5, 1992. https://ntrs.nasa.gov/citations/19920024065.

NASA. “Collier Trophy: National Advisory Committee for Aeronautics (NACA) Winners.” Updated June 28, 2024. NASA. https://www.nasa.gov/collier-trophy/.

NASA. “In Situ Resource Utilization (ISRU) Technical Interchange Meeting.” In Situ Resource Utilization (ISRU) Technical Interchange Meeting, Houston, TX, February 4–5, 1997. https://ntrs.nasa.gov/citations/19970026756.

NASA. “Isaac T. Gillam IV: Former Armstrong Center Director.” Updated June 26, 2023. https://www.nasa.gov/people/isaac-t-gillam-iv/.

NASA. “Landsat 5.” Landsat Science. Accessed August 14, 2024. https://landsat.gsfc.nasa.gov/satellites/landsat-5/.

NASA. “List of Active Space Act Agreements (as of June 30, 2023) with U.S. Non-Federal Partners.” Updated June 30, 2023.

NASA/ “About the Lunar Spectrum Manager.” Lunar Spectrum Management Portal, accessed November 22, 2024, https://www.nasalsmp.org/SitePages/About-the-Lunar-Spectrum-Manager.aspx.

NASA. “Maxime A. Faget.” August 10, 2015. https://www.nasa.gov/centers-and-facilities/langley/maxime-a-faget/.

NASA. “NASA Engages.” Accessed November 20, 2024. https://my.nasa.gov/engages/s/.

NASA. “NASA Long Range Plan, 1959.” NASA Office of Program Planning and Education. Accessed March 13, 2024. https://www.senate.gov/artandhistory/history/resources/pdf/NASALongRange1959.pdf.

NASA. “NASA Modifies Funding Support for Centers for Commercial Development.” NASA News. December 20, 1993.

NASA. “NASA Partners with Orbital Sciences for Space Transport Services.” NASA. February 19, 2008. NASA Partners With Orbital Sciences for Space Transport Services - NASA.

NASA. “NASA Technical Interchange Meeting (TIM): Advanced Technology Lifecycle Analysis System (ATLAS) Technology Toolbox.” Technical Interchange Meeting, Huntsville, AL. November 8–10, 2004. https://ntrs.nasa.gov/citations/20060005585.

NASA. “National Aeronautics and Space Administration List of Agreements with Domestic Entities.” Updated June 29, 2024. https://www.nasa.gov/wp-content/uploads/2024/07/ntaa-domestic-06-30-2024.pdf?emrc=3c5edc.

NASA. “National Aeronautics and Space Administration List of Agreements with Foreign Entities.” Updated June 30, 2024. https://www.nasa.gov/wp-content/uploads/2024/07/ntaa-international-06-30-2024.pdf?emrc=1d6677.

NASA. “Pearl I. Young.” August 10, 2015. https://www.nasa.gov/centers-and-facilities/langley/pearl-i-young/.

NASA. “Publicly Available CARA Software: Conjunction Risk Assessment.” Accessed September 16, 2024. https://www.nasa.gov/cara/publicly-available-cara-software/.

NASA. “Richard T. Whitcomb.” August 10, 2015. https://www.nasa.gov/centers-and-facilities/langley/richard-t-whitcomb/.

NASA. “Scratch-Resistant Lenses.” Wayback Machine screen capture from May 1, 2001. https://web.archive.org/web/20010501030840/http://nctn.hq.nasa.gov/success/spinoff/1996/43.html.

NASA. “Space Dynamically Responding Ultrasonic Matrix System (SpaceDRUMS).” November 26, 2010. https://web.archive.org/web/20101202160436/http://www.nasa.gov/mission_pages/station/research

/experiments/SpaceDRUMS.html.

NASA. “Space Station Partners Release International Docking Standard.” October 19, 2010. https://www.nasa.gov/news-release/space-station-partners-release-international-docking-standard/.

NASA. Commercial Development Plan for the International Space Station: Final Draft. 1998. https://www.nasa.gov/wp-content/uploads/2024/01/commercial-development-plan-for-the-international-space-station.pdf?emrc=c608a4.

NASA. Extreme Home Improvements. 2008. https://www.nasa.gov/wp-content/uploads/2023/05/287211main-sts126-press-kit2.pdf?emrc=50a012.

NASA. NASA Budget Estimates, Fiscal Year 1987. Volume I. https://planetary.s3.amazonaws.com/assets/pdfs/FY1987-Budget-Estimates-Volume-1.pdf.

NASA. NASA Budget Estimates, Fiscal Year 1991. Volume I. NASA. NASA Budget Estimates, Fiscal Year 1993. Volume I. https://planetary.s3.amazonaws.com/assets/pdfs/FY1993-Budget-Estimates-Volume-1.pdf.

NASA. NASA Budget Request, Fiscal Year 1967. Volume 1. https://planetary.s3.amazonaws.com/assets/pdfs/FY1967-Budget-Estimates-Volume-1-Summary-Data.pdf.

NASA. NASA Industry Education Initiative: Education Programs Report, 1991. NASA. 1991. https://ntrs.nasa.gov/citations/19930004060.

NASA. NASA Performance and Accountability Report, Fiscal Year 2005. NASA Headquarters. https://www.nasa.gov/wp-content/uploads/2023/10/138910main-fy-2005-par.pdf?emrc=6b2f41.

NASA. NASA Performance and Accountability Report, Fiscal Year 2008. NASA. https://www.nasa.gov/wp-content/uploads/2023/10/291255main-nasa-fy08-performance-and-accountability-report.pdf?emrc=236da8.

NASA. NASA Performance and Accountability Report, Fiscal Year 2009. NASA Headquarters. https://www.nasa.gov/wp-content/uploads/2023/10/403618main-nasa-fy09-performance-accountability-report.pdf?emrc=599d83.

NASA. NASA Performance Report, Fiscal Year 2000. NASA. https://www.nasa.gov/wp-content/uploads/2023/10/fy-2000-performance-report.pdf?emrc=a74fe5.

NASA. NASA Performance Report, Fiscal Year 2001. Washington, D.C.: NASA Headquarters. https://www.nasa.gov/wp-content/uploads/2023/10/fy-2001-performance-report.pdf?emrc=d98f04.

NASA. NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices. Revision 1. NASA Headquarters. https://www.nasa.gov/wp-content/uploads/2023/07/oce-51.pdf?emrc=c0a365?emrc=c0a365.

NASA. NASA Technical Standard: Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion. NASA-STD-6001, previously published as NHB 8-60.1C. February 9, 1998. https://nepp.nasa.gov/DocUploads/3CCCD952-3372-4220-ADD6185688CCBC3E/NASA-STD-6001.pdf.

NASA. NASA Technical Standard: Structural Design and Test Factors of Safety for Spaceflight Hardware. NASA-STD-5001. June 21, 1996.

NASA. Procurement Notice: Performance-Based Contracting. March 17, 1998. https://www.hq.nasa.gov/office/procurement/regs/pn/pn97-4.pdf.

NASA. STS-126: Extreme Home Improvements. 2008. https://www.nasa.gov/wp-content/uploads/2023/05/287211main-sts126-press-kit2.pdf?emrc=50a012.

“NASA Office Champions the Cause of Commercial Space.” Commercial Space, Fall 1986.

NASA Orbital Debris Program Office. “Debris Mitigation.” Astromaterials Research and Exploration. Accessed September 4, 2024. https://orbitaldebris.jsc.nasa.gov/mitigation/#:~:text=In%201995%20NASA%20was%20the%20first%20space%20agency,Mitigation%20Standard%20Practices%20based%20on%20the%20NASA%20guidelines.

National Aeronautics and Space Act of 1958. Public Law 85-568, 85th Congress. July 29, 1958. https://www.nasa.gov/history/national-aeronautics-and-space-act-of-1958-unamended/.

National Aeronautics and Space Administration Authorization Act, Fiscal Year 1991. Public Law 101-611. 101st Congress. November 16, 1990. https://www.congress.gov/bill/101st-congress/senate-bill/2287/text.

National Research Council. Controlling Cost Growth of NASA Earth and Space Missions: Biographies of Committee Members and Staff. National Academies Press, 2010. https://nap.nationalacademies.org/read/12946/chapter/7.

Naval Appropriations Act of 1916. Public Law 271, 63rd Congress, 3rd session. March 3, 2015.

Newman, Lauri K., Alinda K. Mashiku, Mathew D. Hejduk, Megan R. Johnson and Joseph D. Rosa. “NASA Conjunction Assessment Risk Analysis Updated Requirements Architecture.” AAS/AIAA Astrodynamics Specialist Conference, Portland, ME, August 11–15 2019. https://ntrs.nasa.gov/api/citations/20190029214/downloads/20190029214.pdf.

Nolan-Proxmire, Don. “Test Pilots to Testbeds—NASA Cushions Liftoff and Eases Bedsores.” NASA Commercial Technology Network. May 6, 1998. https://web.archive.org/web/20011214100533/http://nctn.hq.nasa.gov/success/msg00018.html.

Odom, Brian C., et al. “The Rise of the Commercial Space Industry.” Palgrave Macmillan Cham. September 13, 2024. https://link.springer.com/book/10.1007/978-3-031-63410-9.

Parks, Clinton. “Space Law Pioneer Eilene Galloway Does at 102.” SpaceNews. October 1, 2011. HYPERLINK “https://spacenews.com/space-law-pioneer-eilene-galloway-dies-102/” https://spacenews.com/space-law-pioneer-eilene-galloway-dies-102/ .

Planetary Society. “FY 1967 NASA Budget Request—Volume 1—Summary Data.” https://planetary.s3.amazonaws.com/assets/pdfs/FY1967-Budget-Estimates-Volume-1-Summary-Data.pdf.

Roberts, Christina. “Knowledge Infrastructure in the History of Science Education—Part 1 of 2.” November 29, 2020. https://spacehistorian.com/tag/history-of-education/.

Roland, Alex. Model Research: The National Advisory Committee for Aeronautics 1915-1958, Volume 1. NASA History Series, 1985. https://ntrs.nasa.gov/api/citations/19850015372/downloads/19850015372.pdf.

Rumerman, Judy A. NASA Historical Data Book Volume VI: NASA Space Applications, Aeronautics and Space Research and Technology, Tracking and Data Acquisition/Support Operations, Commercial Programs, and Resources 1979–1988. NASA History Series, 2000. https://ntrs.nasa.gov/api/citations/20000033402/downloads/20000033402.pdf.

Rumerman, Judy. "The National Advisory Committee for Aeronautics (NACA)." U.S. Centennial of Flight Commission. Accessed November 20, 2024. https://www.centennialofflight.net/essay/Evolution_of_Technology/NACA/Tech1.htm.

Schaefer, David. "Victor Ganzer Helped Design B-47, First Jet Bomber at Boeing." Seattle Times, September 26, 1993. https://archive.seattletimes.com/archive/?date=19930926&slug=1723065.

Space Act Agreements Manual (NAII 1050-1). Effective December 30, 1998. https://nodis3.gsfc.nasa.gov/1050-1.html.

Space Foundation. "Payton, Wylie and Fuller Join Space Business Forum: New York Line-Up." May 1, 2009. https://www.spacefoundation.org/2009/05/01/payton-wylie-and-fuller-join-space-business-forum-new-york-line-up/.

Starr, Kristen Amanda. "NASA's Hidden Power: NACA/NASA Public Affairs and the Cold War, 1945–1961." PhD diss., Auburn University, 2008. https://etd.auburn.edu/xmlui/bitstream/handle/10415/1466/Starr_Kristen_10.pdf?sequence=1&isAllowed=y.

Suckow, Elizabeth. "NACA History Overview." NASA. Updated April 23, 2009. https://www.nasa.gov/wp-content/uploads/2023/02/NACA-to-NASA-to-NOW_TAGGED.pdf?emrc=e914ad.

Syvertson, Clarence A. "NASA Headquarters NACA Oral History Project: Oral History Transcript." Interview by Rebecca Wright. NASA, September 29, 2005. https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/NACA/SyvertsonCA_9-29-05.pdf.

Unitary Wind Tunnel Plan Act of 1949. Public Law 415, 81st Congress, 1st session, October 27, 1949 (63 Stat. 936).

Uri, John. "40 Years Ago: STS-5, Columbia's First Satellite Deploy Mission." NASA, November 10, 2022. https://www.nasa.gov/history/40-years-ago-sts-5-columbias-first-satellite-deploy-mission/.

Uri, John. "65 Years Ago: The International Geophysical Year Begins." NASA, July 5, 2022. https://www.nasa.gov/centers-and-facilities/johnson/65-years-ago-the-international-geophysical-year-begins/.

Webb, Timothy, Christopher Guo, Jennifer Lamping Lewis, and Daniel Egel. Venture Capital and Strategic Investment for Developing Government Mission Capabilities. RAND Corporation, 2014. https://www.rand.org/pubs/research_reports/RR176.html.

White House. "The National Space Council." Accessed August 13, 2024. https://www.whitehouse.gov/spacecouncil/.

Endnotes

1. National Aeronautics and Space Administration Authorization Act, Fiscal Year 1991, Public Law 101-611, 101st Congress, November 16, 1990, https://www.congress.gov/bill/101st-congress/senate-bill/2287/text.
2. NASA, Partnering With NASA, April 23, 2024, https://www.nasa.gov/partnerships/how-to-partner/. The NASA Partnerships Guide (https://nodis3.gsfc.nasa.gov/OPD_Docs/NAII_1050_3C_.pdf) offers reference material on how NASA sees its various partnership authorities.
3. Idem.
4. NASA Communications, "Sputnik and the Creation of NASA: A Personal Perspective," September 28, 2017, https://www.nasa.gov/history/sputnik-and-the-creation-of-nasa-personal-perspective/.
5. Roger D. Launius, NACA to NASA to Now: The Frontiers of Air and Space in the American Century (Washington D.C.: NASA Office of Communications, 2022), 4.
6. Howard E. McCurdy, Inside NASA: High Technology and Organizational Change in the U.S. Space Program (Johns Hopkins University Press, 1993).
7. Roger D. Launius, NACA to NASA to Now: The Frontiers of Air and Space in the American Century (NASA Office of Communications, 2022), 4.
8. Elizabeth Suckow, "NACA History Overview," NASA, last modified April 23, 2009, https://www.nasa.gov/wp-content/uploads/2023/02/NACA-to-NASA-to-NOW_TAGGED.pdf?emrc=e914ad.
9. "NASA Long Range Plan, 1959," NASA Office of Program Planning and Education, accessed March 13, 2024, https://www.senate.gov/artandhistory/history/resources/pdf/NASALongRange1959.pdf.
10. Stephen B. Johnson, The Secret of Apollo: Systems Management in American and European Space Programs (Johns Hopkins Press, 2002), 152–153.
11. Alex Roland, Model Research: The National Advisory Committee for Aeronautics 1915–1958, Volume 1 (The NASA History Series, 1985), 300.
12. National Aeronautics and Space Act of 1958, Public Law 85-568, 85th Congress, July 29, 1958, https://www.nasa.gov/history/national-aeronautics-and-space-act-of-1958-unamended/.
13. Virginia P. Dawson, Engines and Innovation: Lewis Laboratory and American Propulsion Technology (NASA History Series, 1991) 130.
14. Naval Appropriations Act of 1916, Public Law 271, 63rd Congress, 3rd session, March 3, 2015.
15. Dawson, Engines and Innovation, 130.
16. Launius, NACA to NASA to Now, 60–61.
17. Launius, NACA to NASA to Now, 58.
18. Andrew Chaikin, "How the Spaceship Got Its Shape," Air & Space Magazine, November 2009, https://www.smithsonianmag.com/air-space-magazine/how-the-spaceship-got-its-shape-137293282/.
19. Dawson, Engines and Innovation, 135.
20. Dawson, Engines and Innovation, 135.
21. Dawson, Engines and Innovation, 136.
22. Launius, NACA to NASA to Now, 58.
23. John V. Boyd, "NASA Headquarters NACA Oral History Project Oral History Transcript: John V. Boyd," interview by Jennifer Ross-Nazzal, NASA, October 3, 2005, https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/NACA/BoydJW_10-3-05.pdf.

24. Launius, NACA to NASA to Now, 20.

25. "Pearl I. Young," NASA, August 10, 2015, https://www.nasa.gov/centers-and-facilities/langley/pearl-i-young/. This source also contains additional information about Young and her legacy.

26. Howard E. McCurdy, "Lessons From the Past: How NASA's Early Culture Informs Current Challenges," ASK Magazine, September 1, 2008, https://appel.nasa.gov/2008/09/01/lessons-from-the-past-how-nasas-early-culture-informs-current-challenges/.

27. Boyd, "NASA Headquarters NACA Oral History Project Oral History Transcript: John V. Boyd."

28. Government Employees Training Act, Public Law 85-507, 85th Congress, July 7, 1958. www.congress.gov/85/statute/STATUTE-72/STATUTE-72-Pg327.pdf.

29. Robert W. Graham, "NASA Headquarters NACA Oral History Transcript: Robert W. Graham," interview by Sandra Johnson, NASA, September 30, 2005, https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/NACA/GrahamRW_9-30-05.pdf.

30. Cole, "NACA Oral History Project."

31. David Schaefer, "Victor Ganzer Helped Design B-47, First Jet Bomber at Boeing," The Seattle Times, September 26, 1993, https://archive.seattletimes.com/archive/?date=19930926&slug=1723065.

32. Robert S. Arrighi, "Renowned Woman Scientist Got Start at NACA in Cleveland in the 1950s," NASA, March 13, 2023, https://www.nasa.gov/history/renowned-woman-scientist-got-start-at-naca-in-cleveland-in-the-1950s-2/. This source also contains additional information about Simon and her legacy.

33. Dawson, Engines and Innovation, 137.

34. "Richard T. Whitcomb," NASA, August 10, 2015, https://www.nasa.gov/centers-and-facilities/langley/richard-t-whitcomb/.

35. Robert S. Arrighi, "Renowned Woman Scientist."

36. "Collier Trophy: National Advisory Committee for Aeronautics (NACA) Winners," NASA, updated June 28, 2024, https://www.nasa.gov/collier-trophy/.

37. NASA, "Collier Trophy."

38. J. D. Anderson, "The Tuck-Under Problem: An Aerodynamic High-Speed Compressibility Disaster for the Lockheed P-38 and How NACA Engineers Fixed It," in A Wartime Necessity, https://www.nasa.gov/history/a-wartime-necessity/ (2024), 171–194.

39. Dawson, Engines and Innovation, 127.

40. Dawson, Engines and Innovation, 130.

41. Dawson, Engines and Innovation, 127.

42. Douglas A. Comstock and Daniel Lockney, "NASA's Legacy of Technology Transfer and Prospects for Future Benefits," AIAA Space 2007 Conference & Exposition (September 18–20 2007), 2, https://spinoff.nasa.gov/sites/default/files/2021-07/hist_techtransfer.pdf.

43. Launius, NACA to NASA to Now, 23.

44. Clarence A. Syvertson, "NASA Headquarters NACA Oral History Project: Oral History Transcript," interview by Rebecca Wright, NASA, September 29, 2005, https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/NACA/SyvertsonCA_9-29-05.pdf.

45. John V. Becker, "NASA Headquarters NACA Oral History Project Oral History Transcript: John V. Becker," interview by Rebecca Wright, NASA, May 3, 2008, https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/NACA/BeckerJV_5-3-08.pdf.

46. Alexander MacDonald, The Long Space Age: The Economic Origins of Space Exploration From Colonial America to the Cold War (Yale University Press, 2017), 151, http://www.jstor.org/stable/j.ctt1n2tvkx.

47. Robert G. Ferguson, "Evolution of Aeronautics Research at NASA," in NASA's First 50 Years: Historical Perspectives, ed. Steven J. Dick (NASA, 2010), 208–209, https://www.nasa.gov/wp-content/uploads/2023/02/607087main_NASAsFirst50YearsHistoricalPerspectives-ebook.pdf?emrc=3e2a2a.

48. Unitary Wind Tunnel Plan Act of 1949, Public Law 415, 81st Congress, 1st session, October 27, 1949 (63 Stat. 936).

49. MacDonald, The Long Space Age, 151.

50. John G. McTigue, "NASA Headquarters NACA Oral History Project: Oral History Transcript," interview by Rebecca Wright, NASA, September 29, 2005, https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/NACA/McTigueJG_9-29-05.pdf.

51. Judy Rumerman, "The National Advisory Committee for Aeronautics (NACA)," U.S. Centennial of Flight Commission, accessed November 23, 2024, https://www.centennialofflight.net/essay/Evolution_of_Technology/NACA/Tech1.htm.

52. Roger D. Launius, "Global Instantaneous Telecommunications and the Development of Satellite Technology," in NASA Spaceflight: A History of Innovation, eds. Roger Launius and Howard McCurdy (Palgrave Macmillan, 2018), 64, eBook.

53. Launius, "Global Instantaneous Telecommunications," 67.

54. Kristen Amanda Starr, "NASA's Hidden Power: NACA/NASA Public Affairs and the Cold War, 1945–1961" (PhD diss., Auburn University, 2008), 3, https://etd.auburn.edu/xmlui/bitstream/handle/10415/1466/Starr_Kristen_10.pdf?sequence=1&isAllowed=y.

55. June C. Bahan-Szucs, "NASA Headquarters NACA Oral History Project: Oral History Transcript," interview by Sandra Johnson, NASA, September 29, 2005, https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/NACA/Bahan-SzucsJC_9-29-05.pdf.

56. Graham, "NASA Headquarters NACA Oral History Transcript: Robert W. Graham."

57. "NASA Engages," NASA, accessed November 23, 2024, https://my.nasa.gov/engages/s/.

58. Christina Roberts, "Knowledge Infrastructure in the History of Science Education—Part 1 of 2," November 29, 2020, https://spacehistorian.com/tag/history-of-education/.

59. Starr, "NASA's Hidden Power," 3.

60. Margaret Weitekamp, "Lovelace's Woman in Space Program," https://www.nasa.gov/history/lovelaces-woman-in-space-program/.

61. Roger E. Bilstein, Orders of Magnitude: A History of the NACA and NASA, 1915–1990 (NASA, 1989) 27, https://ntrs.nasa.gov/api/citations/19890017434/downloads/19890017434.pdf.

62. Robert G. Ferguson, NASA's First A: Aeronautics from 1958 to 2008 (NASA, 2013) 37, https://www.nasa.gov/history/history-publications-and-resources/nasa-history-series/nasas-first-a-aeronautics-from-1958-2008/#:~:text=By%20Robert%20G.%20Ferguson%20Aeronautics%2C%20the%20first%20A,in%20the%20shadows%20of%20NASA%E2%80%99s%20marquee%20space%20programs.

63. Boyd, "NASA Headquarters NACA Oral History Project Oral History Transcript: John V. Boyd."

64. For more information about NACA's inspections, see https://www1.grc.nasa.gov/glenn-history/naca-inspections/background-and-evolution/.

65. Congressional Research Service, "The National Space Council," updated December 12, 2016, summary, https://crsreports.congress.gov/product/pdf/R/R44712.

66. Congressional Research Service, "The National Space Council," 3.

67. "The National Space Council," the White House, accessed August 13, 2024, https://www.whitehouse.gov/spacecouncil/.

68. "Council Members," NASA Advisory Council, accessed August 13, 2024, https://www.nasa.gov/council-members/.

69. "Historical NASA Budget Data," The Planetary Society, accessed August 15, 2024, https://docs.google.com/spreadsheets/u/0/d/e/2PACX-1vTU9FhDV4U6X4suHtvoiMLYDN-y56ipoGh-N7n9fNq7BW1PiMsx5fVlj10LsgvTYVbu3CiUDO_WD0We/pubhtml?pli=1.

70. Based on NASA's 2023 New Start Inflation Index (https://www.nasa.gov/ocfo/sid-publications/).

71. Paul E. Ceruzzi, "The Other Side of Moore's Law: The Apollo Guidance Computer, the Integrated Circuit, and the Microelectronics Revolution, 1962–1975," in NASA Spaceflight: A History of Innovation, eds. Roger Launius and Howard McCurdy (Palgrave Macmillan, 2018), 119.

72. APPEL News Staff, "This Week in NASA History—Intelsat 1: The 'Early Bird' of Satellites," NASA, February 25, 2010, https://appel.nasa.gov/2010/02/25/ao_1-7_sf_history-html/.

73. "Applications Technology Satellite," NASA, accessed August 15, 2024, https://science.nasa.gov/mission/ats/.

74. NASA Compendium of Satellite Communications Programs, December 1975, https://ntrs.nasa.gov/api/citations/19760014165/downloads/19760014165.pdf.

75. James Haggerty, Spinoff 1977: An Annual Report, Washington, D.C. (NASA, 1977), 23, chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://spinoff.nasa.gov/back_issues_archives/1977.pdf.

76. Henry Kosmal, "NASA Glenn Research Center Hall of Fame 2021 Inductee," NASA, accessed August 15, 2024, https://www.nasa.gov/centers-and-facilities/glenn/glenn-history/henry-kosmahl/.

77. "NASA Landsat Science, Landsat-1," NASA, https://landsat.gsfc.nasa.gov/satellites/landsat-1/.

78. Jolyon Thurgood, "Space Imaging EOSAT: An update," Photogrammetric Week (1997), https://phowo.ifp.uni-stuttgart.de/publications/phowo97/thurgood.pdf.

79. Samuel N. Goward et al., "Landsat's Enduring Legacy: Pioneering Global Land Observations from Space, American Society of Photogrammetry and Remote Sensing" (January 2017), 209.

80. "Technology Utilization Office," NASA Tech Briefs 1, no. 1 (1976), https://ntrs.nasa.gov/api/citations/20100027475/downloads/20100027475.pdf.

81. The associated commercial ad-supported website is privately owned and is not an official website of NASA, nor is the website sponsored by NASA.

82. "Meet Dr. Valerie Thomas, Landsat Image Processing Specialist," NASA, accessed August 15, 2024, https://mynasadata.larc.nasa.gov/stem-career-connections/meet-dr-valerie-l-thomas-landsat-image-processing-specialist.

83. T. L. K Smull, "NASA University Program Review Conference," Kansas City, Missouri, March 1–3. 1965, p. iii, https://ntrs.nasa.gov/api/citations/19660003112/downloads/19660003112.pdf.

84. Paul Ceruzzi, "Apollo Guidance Computer and the First Silicon Chips, Smithsonian National Air and Space Museum," accessed August 15, 2024, https://airandspace.si.edu/stories/editorial/apollo-guidance-computer-and-first-silicon-chips.

85. "Fairchildren," "Computer History Museum," accessed August 15, 2024, https://computerhistory.org/fairchildren/#1960s.

86. Christina Roberts, "Education as Science Communication," accessed August 15, 2024, https://spacehistorian.com/.

87. A. J. S. Rayl, "NASA Engineers and Scientists-Transforming Dreams Into Reality," 50th Magazine, October 16, 2006.

88. Alice George, "Margaret Hamilton Led the NASA Software Team That Landed Astronauts on the Moon," Smithsonian Magazine, March 14, 2019, https://www.smithsonianmag.com/smithsonian-institution/margaret-hamilton-led-nasa-software-team-landed-astronauts-moon-180971575/.

89. George, "Margaret Hamilton."

90. John C. Abell, "Sept. 9, 1982: 3-2-1...Liftoff! The First Private Rocket Launch," Wired.com, September 9, 2009, https://www.wired.com/2009/09/dayintech0909privaterocket/.

91. "Wake Shield Facility Program," University of Houston, accessed August 15, 2024, https://uh.edu/svec/wsfp-desc.html; Margalit Fox, "Maxime Faget, 83, Pioneering Aerospace Engineer, Dies," New York Times, October 12, 2004, https://www.nytimes.com/2004/10/12/obituaries/maxime-faget-83-pioneering-aerospace-engineer-dies.html.

92. Douglas Comstock and Daniel Lockney, "NASA's Legacy of Technology Transfer and Prospects for Future Benefits," AIAA, Space Conference & Exhibition, Long Beach, CA, September 18–20, 2007, https://spinoff.nasa.gov/sites/default/files/2021-07/hist_techtransfer.pdf.

93. NASA, “New Technology Reporting System,” accessed August 20, 2024, https://invention.nasa.gov/.

94. Elizabeth Howell, “Telstar: Satellite Beamed 1st Signals Across the Sea,” Space.com, February 12, 2013, https://www.space.com/19756-telstar.html.

95. “Centaur: America’s Workhorse in Space,” NASA, accessed August 15, 2024, https://www.nasa.gov/history/centaur-americas-workhorse-in-space/.

96. “Centaur: America’s Workhorse in Space.”

97. “Centaur Program,” NASA Glenn Research Center, accessed August 15, 2024, ps://www1.grc.nasa.gov/historic-facilities/rockets-systems-area/centaur-program/.

98. “Centaur: America’s Workhorse in Space.”

99. “Centaur,” Gunter’s Space Page, accessed November 23, 2024, https://space.skyrocket.de/doc_stage/centaur.htm.

100. “Origins of the Commercial Space Industry,” FAA, accessed August 15, 2024, https://www.faa.gov/sites/faa.gov/files/about/history/milestones/Commercial_Space_Industry.pdf.

101. Erica Carlson, “Marketing the Moon: How PR Made the Lunar Landing a Cultural Moment,” Astronomy, last updated May 18, 2023, https://www.astronomy.com/observing/marketing-the-moon-how-pr-made-the-lunar-landing-a-cultural-moment/.

102. Neil Ruzik, Spinoff 1976: A Bicentennial Report (NASA, 1976), 11, https://spinoff.nasa.gov/back_issues_archives/1976.pdf.

103. NASA-Industry Program Plans Conference, Washington, D.C., NASA, February 11–12, 1963, p. vii, https://ntrs.nasa.gov/api/citations/19630005481/downloads/19630005481.pdf.

104. NASA, “Chronology on Science Technology and Policy, 1970” (Library of Congress, 1972), https://www.nasa.gov/wp-content/uploads/2023/04/1970.pdf.

105. NASA Eighth Semiannual Report to Congress, July 1–December 31, 1962 , 88, https://babel.hathitrust.org/cgi/pt?id=uc1.b4263902&view=1up&seq=114.

106. NASA Eleventh Semiannual Report to Congress, January 1–June 20, 1964, 77 https://babel.hathitrust.org/cgi/pt?id=mdp.39015024399118&view=1up&seq=7.

107. Charlie Dean Archives, “Space Shuttle—1970s,” accessed August 15, 2024, https://www.youtube.com/watch?v=KyB0SFkyCXI.

108. Space Resources and Space Settlements (NASA, 1977), https://history.arc.nasa.gov/hist_pdfs/nasa_sp428.pdf.

109. NASA Budget Estimates, Fiscal Year 1993, Volume I, NASA, RD 2-3, https://planetary.s3.amazonaws.com/asss/pdfs/FY1993-Budget-Estimates-Volume-1.pdf.

110. NASA Budget Estimates, Fiscal Year 1993, Volume I. AS-7.

111. NASA Budget Estimates, Fiscal Year 1993, Volume I. RD 11-6.

112. NASA Budget Estimates, Fiscal Year 1991, Volume I, NASA, RD 11-2, https://planetary.s3.amazonaws.com/assets/pdfs/FY1991-Budget-Estimates-Volume-1.pdf.

113. Space Act Agreements Manual (Revalidated w/o Changes 11/21/03), NASA Advisory Implementing Instructions, NAII 1050-1, effective December 30, 1998, expiration December 30, 2004, https://nodis3.gsfc.nasa.gov/1050-1.html.

114. “NASA Office Champions the Cause of Commercial Space,” Commercial Space, Fall 1986, 30.

115. NASA Budget Estimates, Fiscal Year 1987, Volume I, NASA, RD 12-4, https://planetary.s3.amazonaws.com/assets/pdfs/FY1987-Budget-Estimates-Volume-1.pdf.

116. NASA, Centennial Challenges, Accessed September 4, 2024, https://www.nasa.gov/prizes-challenges-and-crowdsourcing/centennial-challenges/, https://www.nasa.gov/prizes-challenges-and-crowdsourcing/centennial-challenges/.

117. NASA, The Vision for Space Exploration, February 2004, https://www.nasa.gov/wp-content/uploads/2023/01/55583main_vision_space_exploration2.pdf?emrc=fac10e.

118. Office of Management and Budget, Memorandum M-10-11, "Guidance on the Use of Challenges and Prizes to Promote Open Government," March 8, 2010, https://obamawhitehouse.archives.gov/sites/default/files/omb/assets/memoranda_2010/m10-11.pdf.

119. NASA, NASA Performance Report, Fiscal Year 2001 (NASA, 2001), 152, https://www.nasa.gov/wp-content/uploads/2023/10/fy-2001-performance-report.pdf?emrc=d98f04.

120. NASA, "Commercial Orbital Transportation Services," February 2014, p. 18, https://www.nasa.gov/wp-content/uploads/2016/08/sp-2014-617.pdf?emrc=81adc8.

121. Garber, S., & Anderson, J. (2023). The Ballad of Clementine, NASA History News & Notes 40, no. 3, 8–12, https://www.nasa.gov/wp-content/uploads/2023/09/news-notes-40-3.pdf?emrc=673987fb42370.

122. Landsat Science, "Landsat 5," accessed August 14, 2024, https://landsat.gsfc.nasa.gov/satellites/landsat-5/.

123. Landsat Science, "Landsat 5."

124. Christopher Gainor, Not Yet Imagined: A Study of Hubble Space Telescope Operations (NASA History Program Office, 2020) 310, https://www.nasa.gov/wp-content/uploads/2020/12/not_yet_imagined_tagged.pdf?emrc=ce2a67.

125. Gainor, Not Yet Imagined, 312.

126. Gainor, Not Yet Imagined, 313.

127. C. A. Christian and A. Kinney, "The Public Impact of Hubble Space Telescope" (Public Outreach Monograph, 1999), 5, https://www.stsci.edu/~carolc/publications/public_impact.PDF.

128. Gainor, Not Yet Imagined, 338.

129. R. O. Green et al., "The Moon Mineralogy Mapper (M^3) Imaging Spectrometer for Lunar Science: Instrument Description, Calibration, On-orbit Measurements, Science Data Calibration, and On-Orbit Validation," Journal of Geophysical Research: Planets 116, no. E10 (2011), https://doi.org/10.1029/2011JE003797.

130. "Moon Mineralogy-Mapper," JPL, accessed August 14, 2024, https://www.jpl.nasa.gov/missions/moon-mineralogy-mapper-m3/.

131. NASA, NASA Performance and Accountability Report, Fiscal Year 2009 (NASA, 2009), https://www.nasa.gov/wp-content/uploads/2023/10/403618main-nasa-fy09-performance-accountability-report.pdf?emrc=599d83.

132. NASA, NASA Industry Education Initiative: Education Programs Report, 1991 (NASA, 1991), https://ntrs.nasa.gov/citations/19930004060.

133. NASA, NASA Performance and Accountability Report, Fiscal Year 2005 (NASA, 2005) 108, https://www.nasa.gov/wp-content/uploads/2023/10/138910main-fy-2005-par.pdf?emrc=6b2f41.

134. NASA, NASA Performance Report, Fiscal Year 2001 (NASA, 2001), 89.

135. NASA, NASA Performance Report, Fiscal Year 2005 (NASA, 2005), 106.

136. NASA, NASA Performance Report, Fiscal Year 2000 (NASA, 2000), 124, https://www.nasa.gov/wp-content/uploads/2023/10/fy-2000-performance-report.pdf?emrc=a74fe5.

137. While the first Ariane launch occurred earlier, in 1979, Arianespace did not take over commercial operation of the European Space Agency–developed vehicle until 1984. Federal Aviation Administration, "Origins of Commercial Space Industry," accessed September 10, 2024, https://www.faa.gov/sites/faa.gov/files/about/history/milestones/Commercial_Space_Industry.pdf.

138. Andrew J. Butrica, "The Commercial Launch Industry, Reusable Space Vehicles, and Technological Change," Business and Economic History 27, no. 1 (Fall 1998): 220.

139. "Space Cowboy," Forbes, published May 9, 2005, updated June 6, 2013, https://www.forbes.com/forbes/2005/0509/058.html.

140. Abbey Donaldson, "After Three Years on Mars, NASA's Ingenuity Helicopter Mission Ends," January 24, 2024, https://www.nasa.gov/news-release/after-three-years-on-mars-nasas-ingenuity-helicopter-mission-ends/.

141. National Research Council, Controlling Cost Growth of NASA Earth and Space Missions: Biographies of Committee Members and Staff, “Appendix B: Biographies of Committee Members” (National Academies Press, 2010), https://nap.nationalacademies.org/read/12946/chapter/7.

142. “Payton, Wylie and Fuller Join Space Business Forum: New York Line-Up,” Space Foundation, May 1, 2009, https://www.spacefoundation.org/2009/05/01/payton-wylie-and-fuller-join-space-business-forum-new-york-line-up/.

143. National Research Council, Controlling Cost Growth, Appendix B: Biographies of Committee Members.

144. Warren Ferster, “Avascent Buys Futron’s Space Practice,” SpaceNews, July 9, 2014, https://spacenews.com/41185avascent-buys-futrons-space-practice/.

145. Keith Henry, “NASA’s 1999 Commercial Invention of the Year,” NASA Commercial Technology Network, April 5, 2000, https://web.archive.org/web/20020209163429/http://nctn.hq.nasa.gov/success/msg00025.html.

146. Don Nolan-Proxmire, “Test Pilots to Testbeds—NASA Cushions Liftoff and Eases Bedsores,” NASA Commercial Technology Network, May 6, 1998, https://web.archive.org/web/20011214100533/http://nctn.hq.nasa.gov/success/msg00018.html.

147. “Scratch-Resistant Lenses,” NASA Spinoff 1996, Wayback Machine screen-capture from May 1, 2001, https://web.archive.org/web/20010501030840/http://nctn.hq.nasa.gov/success/spinoff/1996/43.html.

148. More information about NASA technology transfer can be found at https://spinoff.nasa.gov/.

149. Judy A. Rumerman, NASA Space Applications, Aeronautics and Space Research and Technology, Tracking and Data Acquisition/Support Operations, Commercial Programs, and Resources 1979–1988, (NASA History Series, 2000), 358, https://ntrs.nasa.gov/api/citations/20000033402/downloads/20000033402.pdf.

150. “2010s: Go for Green Run,” NASA Stennis, page updated June 18, 2024, https://www.nasa.gov/stennis/about-stennis/stennis-space-center-history/chronology/2010-2019/.

151. “List of Active Space Act Agreements (as of June 30, 2023) with U.S. Non-Federal Partners,” NASA, last modified June 30, 2023, https://www.nasa.gov/wp-content/uploads/2023/08/house-approps-action-domestic-nonfed-saas-active-as-of-6-30-2023.pdf.

152. “NASA, Students Go On to Careers in Engineering,” Wings in Orbit, NASA, 2010, 477–479, https://ntrs.nasa.gov/api/citations/20110011792/downloads/20110011792.pdf.

153. Redwire Corporation, “Redwire Acquires Techshot, the Leader in Space Biotechnology,” November 2, 2021, https://redwirespace.com/newsroom/redwire-acquires-techshot-the-leader-in-space-biotechnology/.

154. NASA Office of the Inspector General, Review of NASAs Microgravity Flight Services, 2010, https://oig.nasa.gov/wp-content/uploads/2024/06/ig-10-015.pdf?emrc=6709f8f6ceb56.

155. T. Thompson, NASA Awards Contract to Increase Water Recovery on Space Station, NASA, June 28, 2016, https://www.nasa.gov/news-release/nasa-awards-contract-to-increase-water-recovery-on-space-station/.

156. John Uri, “40 Years Ago: STS-5, Columbia’s First Satellite Deploy Mission,” NASA, November 10, 2022, https://www.nasa.gov/history/40-years-ago-sts-5-columbias-first-satellite-deploy-mission/.

157. Butrica, “The Commercial Launch Industry,” 220.

158. The Virginia Commercial Space Flight Authority, Business Plan: The Virginia Space Flight Center. NASA Technical Reports Server, accessed November 24, 2024, https://ntrs.nasa.gov/api/citations/19980006275/downloads/19980006275.pdf.

159. Rebecca Hackler and Rebecca Wright, Commercial Orbital Transportation Services: A New Era of Spaceflight (NASA, 2014), 14, https://www.nasa.gov/wp-content/uploads/2016/08/sp-2014-617.pdf?emrc=81adc8.

160. NASA, Commercial Development Plan for the International Space Station: Final Draft (NASA, 1998), 2, https://www.nasa.gov/wp-content/uploads/2024/01/commercial-development-plan-for-the-international-space-station.pdf?emrc=c608a4.

161. “Spaceflight R&D Spans Many Disciplines,” Research on the ISS, ISS National Laboratory, accessed August 16, 2024, https://www.issnationallab.org/research-on-the-iss/areas-of-research/.

162. "About the ISS National Laboratory," ISS National Laboratory, accessed August 16, 2024, https://www.issnationallab.org/about/about-the-iss-national-lab/.

163. Clifford R. McMurray, "A New Era for Science: Research on the International Space Station," Ad Astra, Summer 2010, 25, https://space.nss.org/wp-content/uploads/2017/07/Ad-Astra-Magazine-2010-International-Space-Station-science.pdf.

164. "Space Dynamically Responding Ultrasonic Matrix System (SpaceDRUMS)," ISS Program Scientist's Office, NASA, November 26, 2010, https://web.archive.org/web/20101202160436/http://www.nasa.gov/mission_pages/station/research/experiments/SpaceDRUMS.html.

165. NASA, STS-126: Extreme Home Improvements (NASA, 2008), 69, https://www.nasa.gov/wp-content/uploads/2023/05/287211main-sts126-press-kit2.pdf?emrc=50a012.

166. NASA, NASA Technical Standard: Structural Design and Test Factors of Safety for Spaceflight Hardware, NASA-STD-5001, June 21, 1996; NASA, STS-126: Extreme Home Improvements (NASA, 2008), 69, https://www.nasa.gov/wp-content/uploads/2023/05/287211main-sts126-press-kit2.pdf?emrc=50a012.

167. "Space Station Partners Release International Docking Standard," NASA, October 19, 2010, https://www.nasa.gov/news-release/space-station-partners-release-international-docking-standard/.

168. NASA, NASA Technical Standard: Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion (NASA-STD-6001), previously published as NHB 8-60.1C, February 9, 1998, https://nepp.nasa.gov/DocUploads/3CCCD952-3372-4220-ADD6185688CCBC3E/NASA-STD-6001.pdf.

169. "Debris Mitigation," Astromaterials Research and Exploration, NASA Orbital Debris Program Office, accessed September 4, 2024, https://orbitaldebris.jsc.nasa.gov/mitigation/#:~:text=In%201995%20NASA%20was%20the%20first%20space%20agency,Mitigation%20Standard%20Practices%20based%20on%20the%20NASA%20guidelines.

170. Lauri K. Newman et al., "NASA Conjunction Assessment Risk Analysis Updated Requirements Architecture," AAS/AIAA Astrodynamics Specialist Conference, Portland, ME, August 11–15 2019, 1, https://ntrs.nasa.gov/api/citations/20190029214/downloads/20190029214.pdf.

171. "Publicly Available CARA Software: Conjunction Risk Assessment," NASA, accessed September 16, 2024, https://www.nasa.gov/cara/publicly-available-cara-software/.

172. NASA, NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices, Revision 1, (NASA, 2023), 1, https://www.nasa.gov/wp-content/uploads/2023/07/oce-51.pdf?emrc=c0a365?emrc=c0a365.

173. "History of Kennedy Space Center Visitor Complex," The Payload Blog, Kennedy Space Center Visitor Complex, July 31, 2017, https://www.kennedyspacecenter.com/blog/31/history-of-kennedy-space-center-visitor-complex.

174. Rumerman, NASA Historical Data Book, 357.

175. Rumerman, NASA Historical Data Book, 359.

176. Rumerman, NASA Historical Data Book, 358.

177. Rumerman, NASA Historical Data Book, 355.

178. Rumerman, NASA Historical Data Book, 355.

179. Rumerman, NASA Historical Data Book, 360.

180. NASA, "3rd SEI Technical Interchange Proceedings," 3rd Space Exploration Initiative Technical Interchange Meeting, Houston TX, May 5, 1992, https://ntrs.nasa.gov/citations/19920024065.

181. NASA, "In Situ Resource Utilization (ISRU) Technical Interchange Meeting," In Situ Resource Utilization (ISRU) Technical Interchange Meeting, Houston, TX, February 4–5, 1997, https://ntrs.nasa.gov/citations/19970026756.

182. NASA, "NASA Technical Interchange Meeting (TIM): Advanced Technology Lifecycle Analysis System (ATLAS) Technology Toolbox," Technical Interchange Meeting, Huntsville, AL, November 8–10, 2004, https://ntrs.nasa.gov/citations/20060005585.

183. Hackler and Wright, Commercial Orbital Transportation Services, 79.

184. “Isaac T. Gillam IV: Former Armstrong Center Director,” NASA, page updated June 26, 2023, https://www.nasa.gov/people/isaac-t-gillam-iv/.

185. “NASA Office Champions the Cause of Commercial Space,” Commercial Space, 30.

186. Timothy Webb et al., Venture Capital and Strategic Investment for Developing Government Mission Capabilities, (RAND Corporation, 2014), 18, https://www.rand.org/pubs/research_reports/RR176.html.

187. “NASA Partners With Orbital Sciences for Space Transport Services,” NASA, February 19, 2008, https://www.nasa.gov/news-release/nasa-partners-with-orbital-sciences-for-space-transport-services/.

188. NASA, Procurement Notice: Performance-Based Contracting, PN 97-4, March 17, 1998, https://www.hq.nasa.gov/office/procurement/regs/pn/pn97-11.pdf.

189. NASA, “Commercial Orbital Transportation Services,” February 2014, p. 18, https://www.nasa.gov/wp-content/uploads/2016/08/sp-2014-617.pdf?emrc=81adc8.

190. Rumerman, Historical Data Book, vol. 6, 369.

191. Andrew Lawler and Daniel J. Marcus, “NASA Sets Plan for Commercial Satellite Research Center,” Space News, January 21–February 3, 1991.

192. “NASA Modifies Funding Support for Centers for Commercial Development,” NASA News, December 20, 1993.

193. NASA, “National Aeronautics and Space Administration Fiscal Year 2003 Budget Estimates,” HSF 2-2, https://planetary.s3.amazonaws.com/assets/pdfs/FY2003-Request.pdf.

194. Rebecca Hackler and Rebecca Wright, Commercial Orbital Transportation Services: A New Era in Spaceflight, NASA/SP-2014-617, 2014, 21, https://www.nasa.gov/wp-content/uploads/2016/08/sp-2014-617.pdf?emrc=81adc8.

195. SpaceNews, “NASA Congratulates SpaceShipOne’s X Prize Win,” October 4, 2004, https://spacenews.com/nasa-congratulates-spaceshipones-x-prize-win/.

196. Dwayne Brown, “NASA to Host Conference Exploring Commercial Interest in Space Station Living Quarters,” NASA, August 17, 1999, accessed May 10, 2024, https://web.archive.org/web/20130806035921/http:/www.nasa.gov/audience/formedia/archives/MP_Archive_99.html.

197. NASA, “NASA Strategic Plan” (NASA, 1998), https://www.nasa.gov/wp-content/uploads/2023/10/nasa-strategic-plan-1998.pdf?emrc=e77115.

198. NASA, “NASA Strategic Plan,” (NASA, 2000), https://www.nasa.gov/wp-content/uploads/2023/10/nasa-strategic-plan-2000.pdf?emrc=44126d.

199. Mary Fae McKay et al., “Space Resources” (NASA, 1992), https://ntrs.nasa.gov/api/citations/20020086598/downloads/20020086598.pdf.

200. More information about the CCP is available at https://www.nasa.gov/humans-in-space/commercial-space/commercial-crew-program/commercial-crew-program-overview/.

201. Matthew Weinzierl and Angella Acocella, “Blue Origin, NASA, and New Space (A)” (Harvard, 2016), https://economicsofspace.hbs.harvard.edu/files/economicsofspace/files/blue_origin_nasa_and_new_space_a.pdf.

202. Axiom Space, “Ax-1 Mission Research,” Axiom Space, accessed July 10, 2024, https://www.axiomspace.com/missions/ax1/research.

203. NASA, Commercial Orbital Transportation Services (NASA, 2014), 13, https://www.nasa.gov/wp-content/uploads/2016/08/sp-2014-617.pdf?emrc=81adc8.

204. Greg Henderson, “First Satellite Developed by High Schoolers Sent into Orbit,” November, 19, 2013, https://www.npr.org/sections/thetwo-way/2013/12/12/246244688/first-satellite-developed-by-high-schoolers-sent-into-space; Joshua Buck, “NASA Helps Launch Student-Built Satellites as Part of CubeSat Launch Imitative,” NASA, November 20, 2013, https://www.nasa.gov/news-release/nasa-helps-launch-student-built-satellites-as-part-of-cubesat-launch-initiative/.

205. “State-of-the-Art of Small Spacecraft Technology,” NASA, 2023, https://www.nasa.gov/smallsat-institute/sst-soa/, accessed March 12, 2024.

206. National Center for Science and Engineering Statistics, Survey of Federal Funds for Research and Development 2022–2023, 2024, https://ncses.nsf.gov/surveys/federal-funds-research-development/2022-2023.

207. Ryan Brukardt and Jesse Klempner, “Space R&D: Who Is Actually Funding It?” McKinsey & Company, December 10, 2021, https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/r-and-d-for-space-who-is-actually-funding-it.

208. Matt Gasch et al., “Qualification of Domestic Lyocell Based Phenolic Impregnated Carbon Ablator (Pica-D) for NASA Missions,” June 2022, https://ntrs.nasa.gov/api/citations/20220006119/downloads/MGasch FAR Paper v5.pdf.

209. Abby Tabor, “NASA Helps Emerging Space Companies ‘Take the Heat,’” NASA, March 7, 2024, https://www.nasa.gov/general/nasa-helps-emerging-space-companies-take-the-heat/.

210. Executive Office of the President, “Increasing Access to the Results of Federally Funded Scientific Research,” February 22, 2013, https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/ostp_public_access_memo_2013.pdf.

211. Executive Office of the President, “Ensuring Free, Immediate, and Equitable Access to Federally Funded Research,” August 25, 2022, https://www.whitehouse.gov/wp-content/uploads/2022/08/08-2022-OSTP-Public-access-Memo.pdf.

212. NASA, “NASA Software Catalog,” accessed June 12, 2024, https://software.nasa.gov/.

213. NASA, “NASA’s Public Access Plan,” February 21, 2023, https://www.nasa.gov/wp-content/uploads/2021/12/nasa-ocs-public-access-plan-may-2023.pdf.

214. NASA, “Science Information Policy,” last updated June 2024, https://science.nasa.gov/researchers/science-information-policy/.

215. NASA, “Commercial SmallSat Data Acquisition (CSDA) Program,” last updated August 14, 2024, https://www.earthdata.nasa.gov/esds/csda.

216. Abbey Tabor, “What Is LCROSS, the Lunar Crater Observation and Sensing Satellite?” March 8, 2019, https://www.nasa.gov/general/what-is-lcross-the-lunar-crater-observation-and-sensing-satellite/.

217. JPL, “NASA Selects Minority-Serving Institution Proposals to Receive Support,” June 3, 2022, https://www.nasa.gov/learning-resources/stem-engagement-at-nasa/nasa-selects-minority-serving-institution-proposals-to-receive-support/; NASA, “NASA Minority University Research and Education Project (MUREP) Innovation and Tech Transfer Idea Competition (MITTIC),” last updated September 9, 2024, https://www.nasa.gov/learning-resources/minority-university-research-education-project/murep-innovation-tech-transfer-idea-competition-mittic/.

218. NASA, “Past ElaNa CubeSat Launches,” last updated July 24, 2024, https://www.nasa.gov/kennedy/launch-services-program/cubesat-launch-initiative/past-elana-cubesat-launches/.

219. NASA, “Upcoming ElaNa CubeSat Launches,” last updated July 24, 2024, https://www.nasa.gov/upcoming-elana-cubesat-launches/.

220. NASA, “Established Program to Stimulate Competitive Research,” last updated June 25, 2024, https://www.nasa.gov/learning-resources/established-program-to-stimulate-competitive-research/.

221. NASA, “FY 2020 Volume of Integrated Performance,” 92, accessed June 20, 2024, https://www.nasa.gov/wp-content/uploads/2023/10/nasa-fy2020-volume-of-integrated-performance.pdf?emrc=803c3a.

222. NASA, “FY 2021 Volume of Integrated Performance,” 95, accessed June 20, 2024, https://www.nasa.gov/wp-content/uploads/2015/01/fy2021_volume_of_integrated_performance.pdf?emrc=891a73.

223. NASA, “FY 2022 Volume of Integrated Performance,” 81, accessed June 20, 2024, https://www.nasa.gov/wp-content/uploads/2015/01/nasa_fy22_volume_of_integrated_performance.pdf?emrc=6f83bd.

224. To explore more of the innovations NASA has brought to society, go to https://homeandcity.nasa.gov/.

225. Jim Skeen, “NASA MIRO: 30 Years of Providing Research Opportunities,” NASA, October 5, 2022, https://www.nasa.gov/centers-and-facilities/armstrong/nasa-miro-30-years-of-providing-research-opportunities/.

226. NASA STMD, “Announcement of Collaboration Opportunity,” January 29, 2020, https://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=728930/solicitationId=%7B74267B46-BF77-E243-E2B0-3A370BD599EE%7D/viewSolicitationDocument=1/ACO_2020_Appendix_1_29_20 Amendment 2.pdf.

227. BryceTech, “2023 Orbital Launches Year in Review,” March 27, 2024, https://brycetech.com/reports.

228. NASA, “VADR Launch Services Contract,” last updated June 12, 2023, https://public.ksc.nasa.gov/lspeducation/vadar-launch-services-contract/#:~:text=The%20VADR%20launch%20services%20contract%20embraces%20a%20commercial,missions%20or%20as%20rideshare%20payloads%20on%20other%20launches.

229. NASA, “Artemis 1,” NSSDCA/COSPAR ID: 2022-156A, October 28, 2022, https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2022-156A.

230. NASA,”About the lunar spectrum manager,”June 24, 2022, https://www.nasalsmp.org/SitePages/About-the-Lunar-Spectrum-Manager.aspx .

231. NASA Ames, “Welcome to the Clickworkers Study,” 2001, https://web.archive.org/web/20040711055051/http://clickworkers.arc.nasa.gov/top.

232. Overlook Horizon, “NASA Wins 6 Webby Awards, 8 Webby People’s Voice Awards,” April 23, 2024, https://overlookhorizon.com/nasa-wins-6-webby-awards-8-webby-peoples-voice-awards/.

233. Television Academy, “Awards and Nominations,” accessed November 23, 2024, https://www.emmys.com/bios/nasa.

234. NASA, “Commercial Orbital Transportation Services,” February 2014, 66, https://www.nasa.gov/wp-content/uploads/2016/08/sp-2014-617.pdf?emrc=81adc8.

235. Jimmi Russel, “NASA Refines National Space Technology Development Priorities,” NASA, April 16, 2024, https://www.nasa.gov/directorates/stmd/nasa-refines-national-space-technology-development-priorities/#:~:text=NASA%20aims%20to%20collect%20broad%20aerospace%20community%20feedback,of%2-0future%20operations%20on%20the%20Moon%20and%20Mars.

236. Roxana, Bardan, “NASA Creates In-Space Servicing, Assembly, Manufacturing Consortium,” NASA, April 19, 2023, https://www.nasa.gov/news-release/nasa-creates-in-space-servicing-assembly-manufacturing-consortium/.

237. NASA, “Apophis 2029 Innovation (A29I) Listening Workshop,” January 22, 2024, https://www.nasa.gov/organizations/otps/save-the-date-apophis-2029-innovation-listening-workshop/.

238. “NASA’s Low Earth Orbit Microgravity Strategy,” NASA, September 14, 2023, https://www.nasa.gov/leomicrogravitystrategy/.

239. JPL, “NASA Selects Minority-Serving Institution Proposals to Receive Support,” June 3, 2022, https://www.nasa.gov/learning-resources/stem-engagement-at-nasa/nasa-selects-minority-serving-institution-proposals-to-receive-support/; NASA, “NASA Minority University Research and Education Project (MUREP) Innovation and Tech Transfer Idea Competition (MITTIC),” last updated September 9, 2024, https://www.nasa.gov/learning-resources/minority-university-research-education-project/murep-innovation-tech-transfer-idea-competition-mittic/.

240. BryceTech, “Start-Up Space Report,” 2023, https://brycetech.com/reports/report-documents/Bryce_Start_Up_Space_2023.pdf.

241. All past Start Up Space reports are available at https://brycetech.com/reports.

242. P. Besha and A. MacDonald, A. (eds.), Economic Development of Low Earth Orbit (NASA, 2016), https://www.nasa.gov/wp-content/uploads/2016/01/economic-development-of-low-earth-orbit_tagged_v2.pdf.

243. A. MacDonald, A. (ed.), Emerging Space, (NASA, 2014), https://www.nasa.gov/wp-content/uploads/2015/06/emerging_space_report.pdf

244. NASA Office of the Inspector General, “Top Management and Performance Challenges,” 2024, https://oigforms.nasa.gov/challenges.html.

National Aeronautics and Space Administration

NASA Headquarters
300 Hidden Figures Way SW
Washington, DC

www.nasa.gov