Old Space, New Space:
A Commercial Revolution in Innovation?*

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Abstract

The emergence of firms like SpaceX and Blue Origin has made space a leading example of how private enterprise drives innovation, marking what many see as a sharp break between *Old Space* and *New Space*. Yet little systematic evidence documents when the transition to this new phase of space innovation occurred and which firms drove it. We use patent data to provide this measurement and find that the largest surge in space innovation occurred in the 1990s, coinciding with demand-side market creation, and preceding the entry of high-profile startups after 2005. Throughout this period and since, incumbent aerospace firms account for the majority of space-related patenting, with entrants contributing a growing but minority share. The same geographic regions that dominated space innovation during the post-Apollo era remain dominant today. These patterns are consistent with directed technical change: incumbents direct R&D toward policy-created markets accessible from existing capabilities, while entrants bring science-based insights into domains requiring new paradigms. Our findings suggest that New Space is more closely connected to Old Space than prevailing narratives imply, and that government's most consequential role in space innovation may lie in constructing appropriable markets. We make patent data on space-related technologies publicly available for future research.

JEL Codes: O31; O38; L64

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1 Introduction

The cost of delivering payload to low Earth orbit has fallen substantially over the past two decades. This cost reduction has led to a sizable expansion in the space launch industry demonstrated in Figure 1.[1] During 2024, a record 259 launches deployed 2,695 satellites into Earth orbit, bringing the total number of operational satellites to 11,539, up from 3,371 in 2020. According to McKinsey and the World Economic Forum, the global space economy will be worth $1.8 trillion by 2035, up from $630 billion in 2023—almost twice the rate of global GDP growth (Acket-Goemaere et al., 2024).

A powerful narrative has emerged to explain this transformation. The space industry, long dominated by government programs and legacy contractors, *Old Space*, has given way to a new era of entrepreneurial dynamism. *New Space* firms like SpaceX and Blue Origin have disrupted incumbent aerospace giants, driven down costs through technological innovation, and opened access to orbit. In this telling, the break between old and new is sharp: a stagnant, bureaucratic past yielding to a competitive, innovative future. This framing is common in discussions of space commercialization, where the emergence of venture-backed startups after 2000 is often described as a turning point in the industry (Paikowsky, 2017; Weinzierl, 2018; Davidian, 2020; Nicoli et al., 2024).

Yet little systematic evidence documents when the recent shift in space innovation occurred and which firms drove it. We use patent data to provide this measurement and find patterns that challenge the view of a sharp break between Old Space and New Space. The largest surge in space-related patenting occurred not after 2005, when high-profile startups became active, but rather in the 1990s. This earlier expansion was driven by satellite technologies and space-enabled communications, coinciding with demand-side market creation: spectrum allocation for commercial satellite services, licensing regimes that established property rights for private operators, and growing demand from internet, telecommunications, and GPS applications. Throughout this period and since, incumbent aerospace firms—not entrants—have accounted for the majority of space-related

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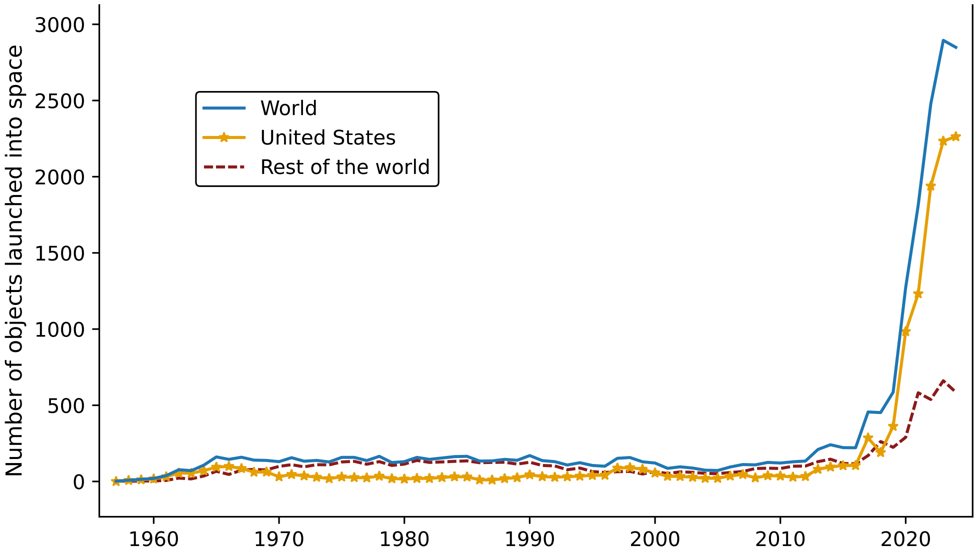
[1] The numbers in the figure reflect objects launched into outer space that were reported by countries adhering to the Registration Convention of 1974 for inclusion in the United Nations Register of Objects Launched into Outer Space. They likely understate the true total. The United Nations Office for Outer Space Affairs reports that "approximately 85% of all satellites, probes, landers, crewed spacecraft and space station flight elements launched into Earth orbit or beyond have been registered with the Secretary-General." Underreported elements are more likely to include military-purposed satellites shielded by national security concerns, as well as commercial objects whose legal jurisdictional is shared by multiple launching entities. For a discussion of gaps in the register, see Nelson (2018) and Jakhu et al. (2018).

Figure 1: **Yearly number of objects launched into space**



Notes: Data from the United Nations Office for Outer Space Affairs (2026) with major processing from "Our World in Data" (Mathieu et al., 2022). Retrieved February 19, 2026 from `https://archive.ourworldindata.org/20260225-085658/grapher/yearly-number-of-objects-launched-into-outer-space.html`.

patenting. These patterns suggest that government's most consequential role in space innovation may lie in constructing appropriable markets rather than in directly funding technology development, and that the allocation of innovation across firm types depends on alignment between policy-created markets and firms' accumulated capabilities.

These questions connect to broader debates in the economics of innovation. The classical demand-pull formulation (Schmookler, 1996) emphasizes that innovation follows market opportunities, while the directed technical change framework (Acemoglu, 2002) formalizes conditions under which profit incentives direct innovation toward technologies serving larger or more appropriable markets. Applied to the space sector, this framework suggests that demand-side policies—spectrum allocation, licensing, procurement guarantees—may have shaped innovation by expanding the markets that private R&D could address. The framework also generates predictions about which firms respond: incumbents possessing capabilities aligned with policy-created markets should capture innovation rents, while entrants may gain traction in domains requiring new technological paradigms outside incumbent expertise. We use this framework to interpret our findings, while emphasizing that the patent evidence is descriptive and does not permit causal claims about specific policy channels.

The first wave of space innovation was government-led, culminating in the Apollo program. Kantor and Whalley (2025) estimate the economic effects of NASA spending during the Space

Race, finding that the program functioned as applied industrial policy—accelerating and combining existing technologies to achieve a specific geopolitical objective. Following Apollo, NASA's budget declined from its 1966 peak of nearly 1 percent of U.S. GDP to less than 0.2 percent by the late 1970s, where it has remained (Weinzierl, 2018). The locus of commercial activity shifted toward satellite services—a shift enabled by a sequence of policy changes that created appropriable markets for private investment.

Three categories of demand-side policy merit attention. First, spectrum allocation: the FCC's decisions to allocate electromagnetic spectrum for satellite communications created the foundational resource upon which commercial satellite businesses could be built. Second, licensing regimes: the Commercial Space Launch Act of 1984 established the legal framework for private launch activities, while subsequent regulatory changes clarified property rights and liability rules enabling commercial entry. Third, procurement commitments: beginning in the 1990s and accelerating in the 2000s, NASA structured demand through programs such as Commercial Orbital Transportation Services (COTS, 2006), Commercial Resupply Services (CRS, 2008), and the Commercial Crew Program (2010). The timing of these interventions varied—spectrum allocation and licensing developed primarily in the 1980s and 1990s, while procurement commitments supporting launch vehicle development came later.

Several additional economic forces bear on the relationship between policy, entry, and innovation. Su et al. (2026) estimate a dynamic model of the U.S. space launch industry incorporating learning-by-doing, where past launches improve rocket reliability and lower costs. This dynamic suggests that early procurement commitments may have compounding effects on industry structure. Jaffe et al. (1998) analyze patent citations to assess knowledge spillovers from NASA research, finding that spillovers are concentrated within a federal lab complex of states—California, Texas, Ohio, DC/Virginia-Maryland, and Alabama. Geographic concentration of space-related innovation persists, suggesting that localized knowledge flows complement formal intellectual property in transmitting technical knowledge. This paper uses patent data to examine how innovation in the space sector responded to the policy changes and firm entry described above. Patents provide a consistent measure of innovative activity over time, allowing us to trace the timing of technological change against the timing of policy interventions. We distinguish between incumbent aerospace firms and new entrants, and we examine whether innovation responses align with the predictions of directed technical change.

Patents are subject to well-known limitations as innovation measures: propensity to patent differs across technologies, and the value of individual patents varies substantially (Griliches, 1990; Pakes, 1986). Software innovation is a notable blind spot (Bessen and Hunt, 2007). However, space innovation relies heavily on hardware and materials advances that are well-captured by patents. SpaceX's reusable rocket breakthrough, for instance, required innovations in guidance algorithms, but these were only viable given complementary advances in engine design, high-temperature materials, and fault-tolerant computing (Xiong et al., 2022). The complementarity between software and patentable hardware suggests that patent data, while incomplete, can be informative about space-related innovation.

Linking patenting activity to specific economic sectors is inherently difficult, as innovations often draw on knowledge developed in multiple domains and may have applications across a range of industries (Lybbert and Zolas, 2014). This challenge is especially pronounced in the space sector, a heterogeneous and rapidly evolving field where many technologies are dual-use and are originally developed in other fields (Weinzierl and Rosseau, 2025). To address this, we study multiple definitions of space technology. We first examine a narrow definition using patent office classifications of space launch vehicle innovations. We then broaden this using text embeddings to include technologies similar to those classified as space launch vehicles. Finally, we consider a broad measure harvested from a recent space-tech taxonomy developed by the European Space Agency and Dealroom. Examining trends across these three definitions provides a more comprehensive view of space-specific innovation.

Our analysis yields three main findings. First, regarding timing: the largest surge in space-related patenting occurred in the 1990s, not after 2005, and was driven primarily by broader space technologies (e.g., satellites, software, communications) rather than narrowly defined space transportation (e.g., rockets and launch vehicles). This expansion coincided with demand-side market creation and predates the organizational changes commonly associated with New Space. Measures of breakthrough innovation and ICT relatedness both peak or rise sharply during this period, indicating that space technologies became early complements to digital infrastructure.

Second, regarding composition: incumbents dominate space patenting throughout the sample period and account for most of the absolute increase in innovation. Entrants contribute a growing but still minority share and their contribution is concentrated in areas covered by the broader space technology classification. This pattern aligns with directed technical change: incumbents respond to markets accessible from existing capabilities, while entrants gain traction in domains favoring new technological paradigms. Government-assigned patents exhibit the highest reliance on scientific knowledge, followed by entrants, with incumbents least science-intensive—consistent with a division of labor where entrants introduce more novel, science-based ideas while incumbents focus on cumulative innovation.

Third, regarding geography: the spatial distribution of space patenting displays striking persistence. Regions dominant during the Cold War era remain dominant today, with little evidence of convergence. We contrast this with automobile innovation, another transportation technology domain exposed to broad advances in digital and related technologies, but not to the same kind of policy-driven market creation that characterized space. Unlike in automobiles, where innovative activity has spread more broadly across regions, space innovation remains heavily concentrated in established hubs, highlighting the continued importance of incumbents and the persistence of accumulated regional capabilities.

Our primary contribution is to document the timing and composition of space innovation using multiple measurement approaches. We develop three definitions of space technology in patent data—narrow, extended, and broad—addressing the dual-use challenge through examiner-assigned CPC codes and text-based methods, and validating our classifications using assignee characteristics. This measurement framework should prove applicable to other sectors with imperfectly defined boundaries where technology taxonomies are available. The stylized facts we establish—particularly the timing of the innovation surge in the 1990s and the persistent dominance of incumbents—provide a foundation for future work examining causal mechanisms. Our geographic findings also contribute to the literature on the spatial concentration of innovation. Foundational work established that knowledge spillovers are geographically localized (Jaffe et al., 1993) and that innovative activity clusters beyond what production concentration would predict (Audretsch and Feldman, 1996). More recent work documents 150 years of changing spatial concentration, finding that regional innovation leadership displays persistence but that persistence has weakened over time (Andrews and Whalley, 2022). The space sector presents a striking contrast: geographic concentration has remained remarkably stable from the Cold War through the New Space era, suggesting that sector-specific factors—perhaps the continued importance of government procurement relationships and specialized testing infrastructure—sustain spatial lock-in even as broader innovation geography becomes more fluid.

Our paper complements a growing literature on the space economy. Weinzierl (2018) provides a foundational treatment of the economic principles underlying commercial space, updated in Weinzierl (2025) and extended in Weinzierl and Rosseau (2025). Corrado et al. (2023) estimate that space activity has produced positive spillovers, and Nagaraj (2022) examines how space-derived data creates terrestrial economic value. Song et al. (2024) trace the emergence of the small satellite ecosystem over thirty years, documenting the slow process by which diverse actors came together around a new value proposition. We complement this qualitative work with quantitative evidence on innovation timing, finding patterns consistent with demand-side market creation.

Our analysis of incumbent and entrant innovation connects to foundational work on competition and technological change. Arrow (1962) introduced the notion of "replacement effect," highlighting why incumbents may have weaker incentives to innovate. A related line of work emphasizes how architectural innovation can erode incumbents' embedded knowledge (Henderson and Clark, 1990). Christensen (2015) and Igami (2017) document that cannibalization makes incumbents reluctant to innovate, while Aghion et al. (2005, 2009) show that competition can spur incumbent innovation through "escape-competition" behavior. Teece (1986) emphasizes that complementary assets often determine who profits from innovation. Galasso and Schankerman (2015) show that patent rights held by large patentees can block follow-on innovation by smaller firms. In the telecommunications context, Watzinger and Schnitzer (2022) show that reduced incumbent dominance can accelerate cumulative invention. Our data document that established aerospace firms remained responsible for the majority of patenting throughout the period, consistent with the importance of complementary assets that facilitate the response to technology transitions (Adner and Kapoor, 2016; O'Reilly III and Tushman, 2013; Furr and Snow, 2024).

Finally, our findings relate to debates about directed technical change and government's role in market creation. Recent work examines how industrial policy creates markets for emerging technologies (Nemet, 2009; Mazzucato, 2021), how such interventions interact with private incentives (Juhász et al., 2024), and how startup commercialization depends on markets for ideas (Gans et al., 2002). The timing coincidence we document—policy changes in the 1980s and early 1990s followed by an innovation surge in satellites and communications—is descriptively consistent with market creation effects. The theoretical literature on public versus private ownership (Hart et al., 1997) suggests private firms have stronger cost-reduction incentives, while Howell (2017) shows that early-stage public funding can crowd in private R&D. The limited role of VC-backed firms in our data, despite substantial entry, is consistent with demand-side reforms activating different mechanisms than supply-side reforms—though we emphasize that our descriptive evidence does not permit causal claims about specific policy channels.

2 From Apollo to New Space: Institutional and technological evolution of the U.S. space sector

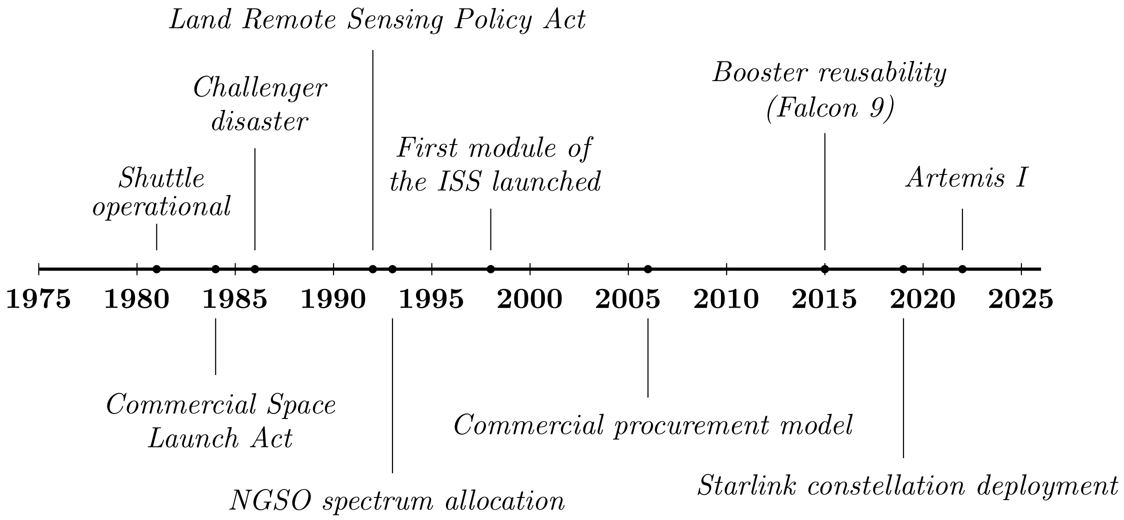
In this section, we outline the main technological and policy developments that shaped the organization of the U.S. space sector from the end of the Apollo era to the present day. We trace the gradual evolution from a government-dominated system centered on exploration missions, in which NASA defined program architectures and private firms executed under cost-plus contracts, to an environment in which commercial markets for satellite services and launch capabilities acquired increasing economic importance. Over time, private firms moved from operating primarily as contractors within government-directed programs to participating more actively in competitive markets serving both public and non-government customers. This context offers a lens through which we interpret the empirical patterns documented in Section 4. The main policy and technological junctures discussed below are summarized in the timeline presented in Figure 2.

2.1 After Apollo: The Shuttle era and the legal foundations of commercial launch (1975–1990)

The modern space age is usually dated to the Soviet launch of Sputnik 1 in October 1957. The U.S.–Soviet space race that followed culminated in the Apollo program, which achieved six crewed Moon landings between 1969 and 1972. With Apollo completed, the U.S. space program shifted from short, high-visibility missions toward a longer-run objective: making access to low Earth orbit more routine. By the mid-1970s, NASA's central bet for this new phase was the Space Shuttle program, conceived as a partially reusable space transportation system: the orbiter and solid rocket boosters were recovered for reuse, while the external tank was not (Heppenheimer, 1999). In practice, however, preparing the vehicle for its next mission required months of inspection and refurbishment. Turnaround times remained long and operating costs high, limiting the Shuttle's ability to deliver the low-cost, frequent launch cadence that had originally guided the program's design (McCleskey, 2005).

The Shuttle became operational in April 1981, and NASA ultimately built five orbiters that flew in space (Columbia, Challenger, Discovery, Atlantis, and Endeavour), in addition to the prototype Enterprise used for atmospheric test flights. The orbiters were designed as versatile workhorses for low Earth orbit: carrying astronauts and large payloads, launching satellites, and in some cases

Figure 2: **Policy and technological developments in the U.S. space sector (1975-present)**



retrieving, repairing, and redeploying spacecraft. They also supported in-orbit research—most notably through the Spacelab module—and enabled high-profile deployments such as the Hubble Space Telescope in 1990.

Institutionally, the Shuttle remained a firmly government-led enterprise. NASA acted as system architect and integrator, allocating responsibilities across its field centers: Johnson Space Center in Texas managed orbiter operations, Marshall Space Flight Center in Alabama oversaw propulsion and launch elements, and Kennedy Space Center in Florida handled assembly and launch operations. Engineering, manufacturing, and vehicle processing were carried out by a broad network of established aerospace contractors, including Rockwell International, Martin Marietta, McDonnell Douglas, and other major defense firms (Heppenheimer, 1999). These companies produced key Shuttle components and provided technical and operational support, while NASA retained responsibility for overall system architecture, integration, and mission design. Private industry participated extensively, but within a hierarchical, government-directed system.

By the mid-1980s, however, some institutional adjustments began to signal a gradual change in direction. The Commercial Space Launch Act of 1984 authorized the Department of Transportation to regulate commercial launches (and later reentries) and explicitly tasked it with promoting commercial space transportation (United States Congress, 1984). In practical terms, the Act established a federal licensing framework for private launch providers. Although commercial activity remained limited at the time, the legislation laid a legal foundation that would later prove essential. For the first time, U.S. policy created a regulatory pathway distinct from NASA for privately provided launch services.

The Space Shuttle Challenger disaster on January 28, 1986 prompted a major reassessment of Shuttle safety and U.S. launch strategy. President Ronald Reagan convened the Rogers Commission, which reported later that year. In the months that followed, policy moved to restrict NASA's involvement in routine commercial satellite launches. Contemporary reporting indicates that this question was central to policy discussions at the time: in August 1986, for example, the front page of *The New York Times* reported extensively on the administration's decision to shift commercial launching to the private sector and discussed concerns about the implications for other NASA programs.[2] The National Security Decision Directive 254, signed by President Reagan on December 27, 1986, stated that NASA would provide commercial launches only for payloads requiring the Shuttle's unique capabilities or for special foreign policy considerations (National Security Council, 1986). This directive reinforced a shift toward expendable launch vehicles for most commercial satellites and marked an early structural separation between government missions and commercial launch markets.

2.2 The post–Cold War: Creating a market for satellite communications (1990–2005)

The end of the Cold War coincided with the rapid expansion of global telecommunications and digital networks. During the 1990s, satellites became increasingly central to the delivery of broadcast television, long-distance communications, and data transmission supporting the rising demand for internet connectivity. The growth of direct-to-home satellite television, international telephony, and mobile-satellite services expanded the commercial role of space-based infrastructure. Space activity remained important for defense and science, but it was now closely tied to communication and information services embedded in everyday economic activity (Johnson, 2007).

Policy developments during this period helped structure that expansion. Satellite communications depend on access to radio frequency spectrum, allocated domestically by the Federal Communications Commission and coordinated internationally through the International Telecommunication Union. In the early 1990s, the FCC clarified licensing frameworks for both geostationary satellite systems and a new category of non-geostationary satellite orbit (NGSO) systems—satellites that move relative to the Earth and typically operate as fleets or "constellations" (Stevens, 1994). In 1993 and 1994, it also established service and licensing rules for frequencies in the L-band

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[2] "Commercial Launching by NASA Ordered Shifted To Private Sector", *The New York Times*, August 16, 1986.

(the portion of the radio spectrum around 1–2 GHz, including the specific slices used by NGSO mobile-satellite systems) enabling competing Low Earth Orbit constellations such as Iridium Communications and Globalstar to receive U.S. licenses. At the same time, direct broadcast satellite (DBS) licensing decisions facilitated the entry of providers such as DirecTV (1994) and EchoStar (1996). The Telecommunications Act of 1996 further supported satellite television adoption by limiting local restrictions on consumer satellite dishes.

Commercial satellite activity during this period was not confined to telecommunications. The Land Remote Sensing Policy Act of 1992 established a licensing framework for privately operated Earth observation satellites, authorizing firms to collect and sell high-resolution imagery subject to national security review (Williamson and Baker, 2004). This clarified the legal status of commercial remote sensing and enabled companies such as DigitalGlobe and GeoEye to supply imagery to government and private customers. At the same time, the civilian use of the Global Positioning System expanded steadily. The discontinuation of Selective Availability in 2000 significantly improved positioning accuracy for non-military users, accelerating the integration of satellite navigation into a wide range of economic activities (O'Connor, 2026).

This expansion of satellite applications was mirrored by changes in the launch market. Following the 1986 decision to limit the Shuttle's role in commercial satellite launches, Congress passed the Launch Services Purchase Act of 1990, directing NASA to procure launch services from commercial providers whenever feasible rather than operating launch vehicles itself (United States Congress, 1990). This formalized a shift already underway: the federal government increasingly acted as a customer purchasing launch services rather than as the operator of launch systems. In practice, launches were carried out primarily using expendable vehicles. The most widely used were the Delta rockets—originally produced by McDonnell Douglas and later by Boeing following its 1997 acquisition of the firm—and the Atlas rockets developed by General Dynamics and later managed by Lockheed Martin (Federal Aviation Administration, 1998). These firms served both as commercial satellite operators and government customers. Over time, continued consolidation led to the creation of the United Launch Alliance (ULA) in 2006, which combined the Delta and Atlas programs under a single joint venture between Boeing and Lockheed Martin.

While commercial telecommunications and satellite services expanded, NASA continued to pursue large-scale scientific and exploration missions under a governance model that remained firmly government-directed. Construction of the International Space Station began in 1998, marking a new phase of sustained human presence in low Earth orbit and international collaboration among the United States, Russia, Europe, Japan, and Canada. Robotic planetary exploration advanced as well, including Mars Pathfinder and the twin Mars Exploration Rovers launched in 2003. In both cases, NASA defined overall system architecture, mission objectives, and technical requirements, while established aerospace contractors developed and manufactured major components under predominantly cost-plus contracts. Private contractors were still involved in central engineering roles, but within budgets, specifications, and risk frameworks determined by NASA within government-directed programs.

2.3 The emergence of New Space (2005–present)

By the mid-2000s, space activity entered a new phase characterized by greater private participation and a broader range of commercial applications. A number of privately financed firms began developing launch vehicles and satellite systems with the intention of serving both government and non-government customers. Companies such as SpaceX and Blue Origin invested in proprietary launch technologies, while new entrants explored opportunities in satellite manufacturing, Earth observation, and in-orbit services. Venture capital funding, largely absent in earlier decades, became increasingly visible in parts of the sector.

An important institutional change during this period concerned NASA's approach to procurement. Beginning in 2006, the agency introduced the Commercial Orbital Transportation Services (COTS) program, followed by Commercial Resupply Services (CRS) and later the Commercial Crew Program. Under these initiatives, NASA specified performance objectives but relied on fixed-price, milestone-based contracts rather than traditional cost-plus arrangements. Firms retained greater control over vehicle design and bore a larger share of development risk, while NASA acted primarily as an anchor customer purchasing transportation services to the International Space Station. This marked a shift from the earlier model in which NASA defined system architectures in detail and contractors executed under reimbursement-based contracts (Lindenmoyer and Stone, 2010; Weinzierl, 2018).

Launch technology also evolved during this period. SpaceX's Falcon 9 rocket, first launched in 2010, demonstrated the feasibility of routinely recovering and reusing first-stage boosters beginning in 2015. Reusability, combined with higher launch cadence and vertically integrated manufacturing, contributed to lower per-launch costs and shorter development timelines (Baiocco, 2021). Although expendable vehicles continued to operate, the introduction of partially reusable systems altered the economics of access to orbit and increased competition in segments of the launch market.

At the same time, satellite technology became increasingly influenced by advances in electronics and software. Smaller satellites, standardized components, and the use of commercial off-the-shelf hardware reduced development costs and shortened production cycles. Large constellations of satellites in Low Earth Orbit emerged as viable business models (Song et al., 2024). Systems such as Starlink, which began deploying operational satellites in 2019, aimed to provide global broadband connectivity through hundreds and eventually thousands of satellites. Other firms expanded commercial Earth observation capabilities, while new companies pursued in-orbit servicing, debris mitigation, and satellite life-extension services. Space-based infrastructure became more closely integrated with digital platforms, logistics networks, and data-intensive applications (Weinzierl and Rosseau, 2025).

Government exploration programs continued alongside these commercial developments. NASA initiated the Artemis program, aimed at returning astronauts to the Moon, and advanced plans for the Lunar Gateway in cislunar orbit. The program's first uncrewed mission was launched in 2022, and a crewed mission was completed in April 2026. Scientific missions and planetary probes remained central to the agency's portfolio. Unlike earlier decades, however, these initiatives unfolded within a more diversified industrial ecosystem in which private firms developed systems with potential applications beyond a single government customer.

2.4 The main areas of space technology

Over the past several decades, the U.S. space sector has evolved into a technologically heterogeneous domain encompassing launch systems, satellite development and operation, exploration missions, and a broader ecosystem of supporting technologies and services. To organize this heterogeneity in our empirical analysis, we draw on a space-tech taxonomy developed by Dealroom, a data provider that tracks technology trends, startups, and investment activity.[3] Dealroom classifies space technology into five major areas. The paragraphs below briefly describe these categories and highlight the main technological shifts within each domain that are relevant for interpreting patterns of innovation.

Satellite design, construction, manufacturing, and operation. From the 1970s through the early 2000s, satellites were typically built as large, mission-specific systems—an approach

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[3] The full taxonomy and description is available at `https://spacetech.dealroom.co/taxonomy` (accessed September 2025). This taxonomy is provided as part of a comprehensive database of space start-ups and innovation developed by Dealroom together with the European Space Agency and Fondazione E. Amaldi.

that ensured reliability but entailed long development cycles and high costs. Starting in the late 1990s and accelerating after 2010, innovation shifted toward smaller satellites, standardized designs such as CubeSats, and the use of commercial off-the-shelf electronics. The focus shifted toward accepting shorter satellite lifetimes and relying on constellation deployment, so that overall system performance depended less on the durability of any single spacecraft (Underwood et al., 2001; Poghosyan and Golkar, 2017; Sweeting, 2018). These changes made large constellations economically feasible and redirected innovation toward improving system-level performance and accelerating iteration and deployment (Villela et al., 2019).

Space transportation. Space transportation encompasses the vehicles and systems used to carry payloads from Earth to orbit and to move them once in space. Until the early 2000s, commercial launch services relied primarily on expendable rockets in which major components were not recovered after flight. Innovation focused on improving propulsion performance, reliability, and payload capacity within this basic architecture. Beginning in the 2000s and accelerating after 2010, attention shifted toward partial and full reusability, higher launch cadence, and cost reduction (Bart et al., 2023). At the same time, innovation expanded beyond launch vehicles to include in-space transportation systems such as orbital transfer vehicles, satellite deployment mechanisms, and logistics platforms. Research into advanced propulsion modes supported more flexible movement and repositioning of satellites once deployed. These developments shifted innovation from incremental improvements in largely single-use systems toward more integrated transportation architectures spanning launch, deployment, and orbital operations (OECD, 2022).

Space exploration. Technologies for space exploration were historically developed as bespoke systems optimized for a single mission, given the technical demands of operating far from Earth and the high cost of failure (Schenker et al., 2003). More recent research emphasizes modular and infrastructure-like capabilities: autonomy and robotics that can be reused across missions, on-orbit assembly, and architectures designed to be improved over time rather than be rebuilt from scratch for each new objective (Li et al., 2022; Lester and Thronson, 2011). As a result, innovation in space exploration increasingly centers on capabilities—such as robotics, autonomy, sensing, software, and assembly interfaces—that can support multiple missions.

In-space operations, services, and supporting software. Early efforts in on-orbit servicing focused on inspection, repair, and refueling to extend the life of high-value satellites (Flores-Abad et al., 2014). By the late 2010s, the ecosystem had expanded to include upgrade and assembly, treating satellites as maintainable infrastructure capable of ongoing improvement (Davis et al., 2019). At the same time, active debris removal emerged as a complementary activity, relying on technologies such as robotic capture, nets, and harpoons to address the growing accumulation of space debris (Shan et al., 2016).

Parts, structures, payloads, components, and materials. The space economy relies on a wide range of physical components and materials, including satellite buses, propulsion units, payload instruments, radiation-tolerant electronics, and specialized sensors. Historically, these components were designed as mission-specific systems emphasizing reliability and the ability to withstand launch stresses and the thermal extremes of space. Over time, advances in miniaturization and semiconductor technology enabled the increasing use of commercial off-the-shelf components in small satellites, particularly in CubeSat architectures (Poghosyan and Golkar, 2017; Sweeting, 2018). Additive manufacturing shortened prototyping cycles and enabled more complex structural designs (Gibson et al., 2015). Research on in-situ resource utilization explores how to produce structural elements using locally available materials such as lunar regolith (Naser, 2019). These developments reflect a gradual shift from application-specific components toward more modular and scalable approaches to spacecraft construction and orbital operations.

2.5 Looking ahead

The organization of the U.S. space sector since the mid-1970s has gone through three broad phases. The Shuttle era was characterized by centralized, government-directed development in which private firms operated primarily as contractors within NASA-defined architectures. During the 1990s and early 2000s, growth in telecommunications and navigation demand, combined with policy changes such as spectrum allocation and licensing reforms, enabled the emergence of commercially viable satellite services and a private market for launch. After the mid-2000s, new procurement models, reusable launch systems, and advances in electronics and software broadened participation and diversified applications. These institutional and technological developments provide the background to interpret the patterns of patenting activity that we study in the remainder of the paper.

3 Data and measurement: Identifying space-tech patents

Our main source of data is patents granted by the United States Patent and Trademark Office (USPTO) since 1976. We obtain patent-level information from PatentsView, including filing and grant dates, Cooperative Patent Classification (CPC) codes, inventors and assignees and their geographic locations, titles, abstracts, full descriptions, and citations to other U.S. patents. We complement these patent records with a range of additional indicators, including characteristics of the assignee, measures of novelty and impact, and references to scientific articles. We introduce these measures later when analyzing specific outcomes.

This section focuses on our primary measurement exercise: identifying, within the universe of USPTO patents, those that are relevant to space technologies. Defining and measuring space-related innovation is nontrivial, and the lack of a transparent and widely accepted classification motivates a central part of our empirical contribution.

There are several conceptual challenges in identifying space-tech patents. First, as is common in efforts to link patents to industries, technologies are rarely unique to a single application and are often used across multiple sectors (Lybbert and Zolas, 2014). In the space sector, this challenge is amplified by the inherent heterogeneity of the domain, which encompasses a wide range of technologies that include—and extend beyond—those described in Section 2, many of which are dual-use. Second, standard patent classification systems (such as the CPC or the legacy U.S. Patent Classification system) are not well suited to cleanly delineate the space sector. While some CPC classes are explicitly space-related, many technologies that are essential to space activities are classified under broader categories that also encompass non-space applications. For example, CPC class G01C, which covers distance measurement and navigation, overlaps directly with space technologies but also includes a wide range of terrestrial and maritime applications, such as navigation in open water and land-based positioning systems. As a result, relying exclusively on classification codes either excludes relevant space-related inventions or includes large sets of patents whose relevance to space technologies is limited and difficult to assess. Third, the space sector is evolving rapidly. As new technologies and applications continuously emerge, the scope of space-related innovation expands, and what constitutes a space-related invention today may differ from what constituted one in the past. Some existing efforts have proposed classifications of space-related patents based on predefined lists of technology-industry relations or keyword searches (e.g., Collette, 2018; OECD, 2022; Cornet et al., 2026; Corrado et al., 2025). While these approaches are useful for documenting broad trends in space innovation, they are not designed to provide clear guidance on how sectoral boundaries are defined within the heterogeneous space domain, nor to offer a granular view of technological developments within the sector.

To address these challenges, we construct three complementary classifications of space-tech patents. Each is designed to capture space-related technologies at a different scope and level of confidence, reflecting alternative perspectives on what constitutes "space technology." Together, these classifications allow us to analyze both a narrowly defined core of space transportation technologies and a broader ecosystem of space-related innovation, while making explicit alternative boundaries that can be drawn around space-related technological activity. We provide extensive validation and discuss how the classifications differ and overlap in terms of technological coverage and time trends.

3.1 Narrowly defined space transportation patents

The first classification relies on an intentionally narrow but highly precise CPC category. We identify patents that list at least one CPC code in class B64G ("Cosmonautics; vehicles or equipment therefor"). This class directly targets space transportation technologies and yields a set of patents for which the risk of misclassification is minimal. While this approach provides a high-confidence measure of space transportation innovation, it is necessarily restrictive and excludes many technologies that are critical to space activities but are classified elsewhere. We refer to this set as *Space transportation (narrow)*.

Since 1976, 6,762 patents have been granted that fall into this category (out of a total of over 8 million grants). Among them, 6,323 list at least one CPC code in subclass B64G1 ("Cosmonautic vehicles"), and 992 list at least one of the other subclasses, including those covering the observation or tracking of cosmonautic vehicles, tools specially adapted for use in space, and space suits. Overall, the inventions captured by this classification primarily relate to space transportation and space exploration. While their relevance to space technologies is clear and unambiguous, this set is confined to a subset of the broader set of technologies and applications that directly interface with or operate in outer space.

3.2 Extending the set of space transportation patents

The second classification builds on this high-confidence core and extends it using a predictive approach based on a large language model. Starting from patents classified in B64G, we use semantic information from patent texts to identify additional patents that are sufficiently close in technological content to the narrow space transportation set. This approach allows us to capture adjacent, enabling, and related technologies that are relevant to the space transportation ecosystem but are not explicitly labeled as such by CPC codes, while preserving transparency and allowing for extensive validation. We refer to this set as *Space transportation (extended)*.

To construct this extended set, we proceed in three main steps. First, we produce text embeddings (vector representations of patent text in semantic space) for all patent documents in our sample.[4] Second, we use a simple classification model to assign each patent a score reflecting its semantic proximity to the narrow space transportation core. Third, we select a threshold and classify patents with scores above that cutoff as space-related. We then validate the resulting set.

Text representation through embeddings. We begin by constructing vector representations of each patent in our sample based on its textual content. For each patent, we concatenate the title, abstract, and brief summary text and generate a text embedding using the *all-MiniLM-L6-v2* sentence-transformers model. These embeddings provide a high-dimensional representation of the semantic content of each patent and allow us to measure similarity across patents in a flexible and systematic way.

Predictive model. Using these embeddings as inputs, we estimate a logistic regression to predict whether a patent belongs to the narrow space transportation category. Patents classified in CPC class B64G serve as positive observations, while the negative class is constructed by randomly sampling 100,000 patents from the remainder of the USPTO corpus. Because some non-B64G patents may nevertheless be genuinely related to space transportation, this negative class is potentially contaminated, introducing label noise into the training data (a setting commonly referred to as "positive–unlabeled learning"). This framework is well suited to contexts in which positive examples can be identified with high confidence but the absence of a label does not reliably indicate a true negative, a situation that frequently arises in text-based classification tasks. The fitted model assigns to each patent a predicted probability of being space-related, which we interpret as a continuous measure of semantic closeness to the narrow space transportation set.

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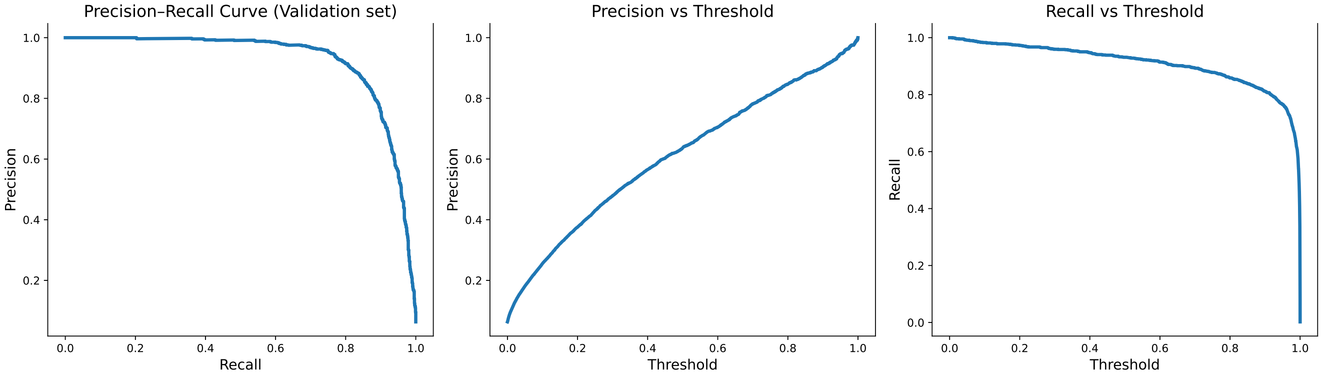
[4] The use of text embeddings is now widespread in the economics of innovation as a way to represent technological content in a continuous semantic space for the purpose of measuring similarity, technological distance, and diffusion patterns beyond discrete classification codes. See, among others, Koffi and Marx (Forthcoming), Lerner et al. (2024), and Berkes and Gaetani (2026).

Figure 3: **Identifying space-tech patents: Precision–recall tradeoff**



Notes: The left panel shows the highest achievable level of precision (probability a patent belongs to B64G given that its score is above the threshold) for any given level of recall (probability that a patent's score is above the threshold given that patent belongs to B64G). The middle and right panels show the levels of precision and recall, respectively, for varying values of the threshold.

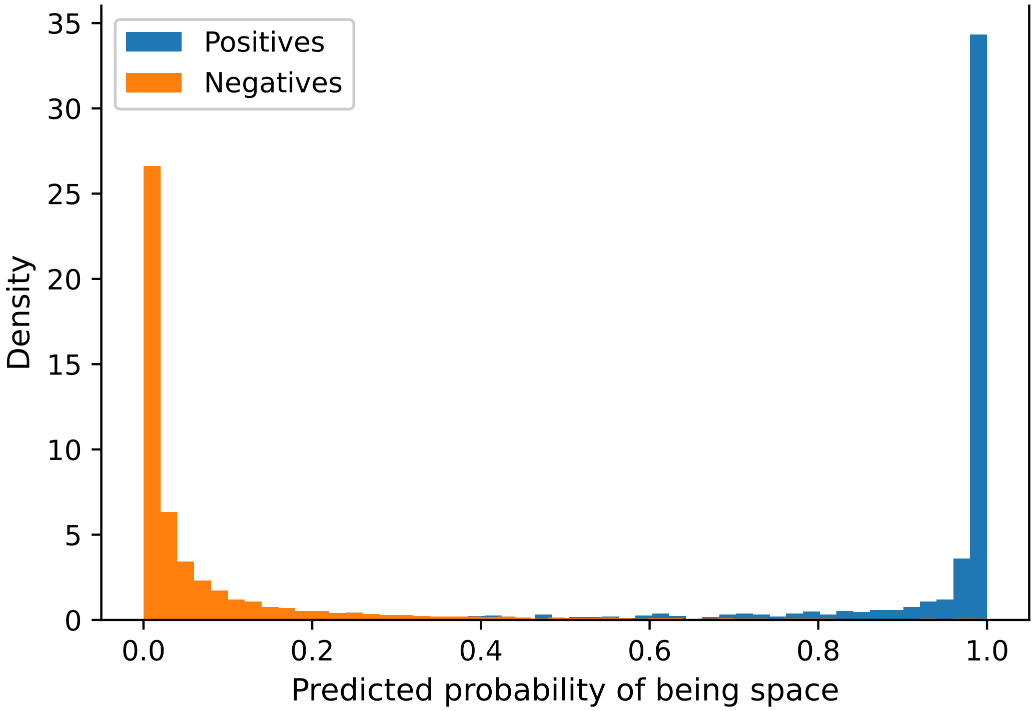
Threshold selection and classification. To construct a discrete classification from these predicted probabilities, we select a threshold that balances *precision* (the probability that a patent classified as space-related is indeed so) and *recall* (the probability that a space-related patent is classified as such). Figure 3 summarizes this tradeoff, which is inherent to probability-based classifications. The left panel reports the precision–recall curve on the validation set, showing the maximum achievable precision for each level of recall. The middle and right panels display how precision and recall vary as functions of the classification threshold. As the threshold increases, precision rises, reflecting greater confidence in the relevance of classified patents, while recall declines, narrowing the coverage of space-related inventions.

We select a cutoff that yields a targeted precision of 95% when evaluated against the B64G benchmark, with a corresponding recall of 74%. Using this threshold, we define the *Space transportation (extended)* set as the union of all patents in the narrow B64G-based classification and all additional patents whose predicted probability exceeds the chosen cutoff.

Validation. The histogram in Figure 4 displays the distribution of predicted probabilities for patents classified in B64G (in blue) and for patents in the comparison group (in orange), illustrating the degree of separation achieved by the predictive model. The vast majority of patents outside of B64G receive low predicted scores, indicating limited semantic proximity to the narrow space transportation group. Consistent with this, the 95th percentile of the predicted-score distribution for non-B64G patents is 0.41, while fewer than 5% of B64G patents fall below this threshold.

Applying our baseline classification threshold to the full corpus yields a total of 25,973 patents in

Figure 4: **Distribution of predicted space scores**



Notes: Distribution of predicted space scores for patents belonging to CPC class B64G (in blue) and all other patents (in orange).

the extended space transportation set. Of these, 6,762 patents are part of the original B64G-based classification, while an additional 19,211 patents fall outside of B64G but exceed the threshold for space relatedness. These additional patents include technologies that are semantically close to the narrow space transportation core and directly relevant to space transportation and exploration but do not appear under B64G, possibly because CPC codes are assigned to facilitate prior-art search rather than to delineate areas of application. For example, among non-B64G patents with the highest predicted space score are patent 4,939,976, which introduces "a [...] propulsion method and operating system [...] for propelling high-mass payloads to orbital velocities" (filed in 1998); patent 6,459,206, describing a "system and method for adjusting the orbit of an orbiting space object" (filed in 2000); and patent 10,105,909, filed by NASA in 2016, which proposes a "protection system [...] to mitigate atmospheric effects faced by exploration of space beyond the ISS."

3.3 Patents in broadly defined space technologies

The third classification adopts a broader, industry-oriented perspective on space technology. It is based on the space-tech taxonomy developed by Dealroom and the European Space Agency already introduced in Section 2.4. The taxonomy organizes space technology into five major areas: (1) satellite design, construction, manufacturing, and operation; (2) space transportation; (3) space exploration; (4) in-space operations, services, and supporting software; and (5) parts, structures, payloads, components, and materials. For each area, the taxonomy provides a concise (749 words in total) but detailed description covering the broad categories of space technologies that are currently being actively pursued across the sector. Our use of an industry defined technology taxonomy echos the approach in Kantor and Whalley (2025) who use CIA reports of Soviet space technology to define space race relevant technologies.

We use this taxonomy to construct a text-based classification of space-related patents, reflecting how space technologies are defined and discussed from an industry and investment perspective. Relative to CPC-based approaches, this classification captures space technologies more broadly defined and is well suited to studying the emergence of new areas of activity that are salient to entrepreneurial firms and investors in the space sector. For each area, the taxonomy provides a concise (749 words in total) but detailed description covering the broad categories of space technologies that are currently being actively pursued across the sector. We refer to this set as *Broader space technology.*

Extracting space-related terms. We process the textual description of the space-tech taxonomy and extract a set of terms related to each of the five main areas in the taxonomy. After removing punctuation and stop words, we compile a list of individual terms and combinations of adjacent words (n-grams). We standardize these expressions by harmonizing spelling and accounting for singular and plural forms, and we expand the text to ensure that all relevant phrases are properly captured. For example, the phrase "designing and manufacturing satellites" is spelled out into multiple standardized combinations, such as "designing satellites" and "manufacturing satellites."

This procedure yields an initial list of 578 candidate n-grams. We then manually review this list to remove general or ambiguous terms that are unlikely to be informative about space-related activity. This filtering step results in a final set of 128 n-grams with clear relevance for space technologies. Of these, 34 are unigrams, such as "rover", "spacecraft", and "spacesuit", while the remaining terms are multi-word expressions (n-grams with $n > 1$), such as "spacecraft servicing" and "orbital transfer vehicle".

Patent classification. We classify a patent as space-related by searching its text (title, abstract, and brief description) for the occurrence of these selected terms. We apply a simple rule-based criterion: A patent is classified as space-related if it contains at least five distinct unigrams from the selected list or at least one multi-word n-gram. Some expressions, such as "propulsion system" or "remote sensing data", are treated as unigrams for the purposes of this rule: while they are relevant to space technologies, they are not sufficiently informative on their own to classify a patent as space-related without additional supporting terms. This classification yields a total of 39,651 patents in our sample. While there is some overlap with the extended space transportation category, the overlap is far from complete: 9,869 patents appear in both classifications.

Categories of space-tech patents within the taxonomy. To better understand how patents identified under the broader space technology definition are distributed across different segments of the space sector, we further assign each patent to one of the five broad categories defined in the space-tech taxonomy. To do so, we first compute, for each n-gram, its relative frequency within each category of the taxonomy (that is, the frequency of a given n-gram relative to all n-grams of the same length appearing in that category's description). For each patent, we then sum these relative frequencies across all matched n-grams separately for each category and assign the patent to the category with the highest total score.[5]

By far the largest category is *Satellite design, construction, manufacturing & operation*, which accounts for 24,899 patents, followed by *Space exploration* with 10,713 patents. Table 1 reports the degree of overlap between these categories and the extended CPC-based classification. The satellite category exhibits relatively limited overlap, with less than 20% of its patents appearing in the CPC-based classification. In contrast, more than 75% of patents classified under *In-space operations, services, & supporting software* and more than 52% of those classified under *Space transportation* overlap with the CPC-based set.

These patterns highlight how the taxonomy-based classification substantially broadens coverage, particularly by capturing satellite-related technologies and applications that are largely missed by the CPC-based approach. Examples of patents captured by the broader classification but not by the CPC-based definition include patent 6,253,080, filed by Globalstar in 1999, describing a "low earth orbit distributed gateway communication system"; patent 7,034,771, filed by Boeing in 2003, describing an "antenna system for communication satellites"; and patent 10,651,558, filed by Lockheed Martin in 2016, describing "omni-directional antennas [...] to allow a spacecraft to

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[5] We do not observe ties in practice, so each patent is assigned to one and only one category.

Table 1: **Patents by category in the space-tech taxonomy**

Category	Total patents	In Space Transp. (ext)	*Not* in Space Transp. (ext)	% in Space Transp. (ext)
Satellite design, construction, manufacturing & operation	24,899	4,878	20,021	19.6%
Space transportation	296	155	141	52.4%
Space exploration	10,713	3,135	7,578	29.3%
In-space operations, services & supporting software	1,349	1,018	331	75.5%
Parts, structures, payloads, components & materials	2,394	683	1,711	28.5%
Total	39,651	9,869	29,782	0.249

Notes: Patents in the *Broader space technology* group by category and overlap with the *Space transportation (extended)* group.

communicate with a ground station regardless of the spacecraft's orientation in space."

3.4 Validating the space patent classifications using space organizations

As additional validation of the classifications, we examine whether patents filed by organizations that are primarily engaged in the space sector are systematically more likely to be classified as space-related. We construct a list of organizations active in the space sector, including NASA, established space firms, and space-focused startups.[6] We then estimate a simple linear regression in which the dependent variable is an indicator for whether a patent is classified as space-related, and the explanatory variable is an indicator for whether the patent is assigned to a space organization.

Results are reported in Table 2. The probability that a patent filed by a space organization is classified as space-related is between 10 and 20 percentage points higher than for patents filed by non-space organizations, whether space patents are defined using the narrow (column 1) or

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[6] The list of space-focused startups includes companies in the *Space Tech* category of Dealroom, a data provider that tracks trends in investment in the space sector (`https://app.dealroom.co/sector/industries/space/companies`), and in the "Space" stream of the Creative Destruction Lab, a global program that supports seed-stage, science-based startups (`https://creativedestructionlab.com/companies/`).

extended (column 3) space transportation classifications, or the broader space technology category (column 5). These findings provide additional support for the classifications: patents originating from organizations whose activities are closely tied to space technologies are substantially more likely to fall within the space patent sets.

To put these magnitudes in perspective, it is useful to compare them to the baseline prevalence of space-related patents in the full sample, reported in the bottom row of Table 2. Relative to that baseline, patents filed by space organizations are between 50 and 100 times more likely to be classified as space-related. At the same time, a substantial share of patents assigned to space organizations falls outside our space-technology classifications. This pattern is to be expected and reflects two features of the data. First, many technologies developed by space organizations are inherently dual-use and apply to a range of non-space contexts, making their classification as space-related less clear-cut. Second, the notion of a "space organization" is itself broad: many of the firms and institutions in our sample engage in activities that extend beyond space technologies. As a result, not all patents assigned to these organizations are expected to fall within the boundaries of space-related innovation as defined by our classifications.

When separating NASA from other space organizations (columns 2, 4, and 6), non-NASA space firms exhibit a stronger association with space-related patent classifications than NASA, although NASA's patents are still significantly more likely to be classified as space-related than those of non-space organizations. This pattern likely reflects the broader technological scope of the agency's activities, which includes basic research and general-purpose technologies that extend beyond the space sector.

3.5 Space patent data availability

The list of space-related patents, together with the predicted space score and their classification by group and, within broader space technologies, by category according to the space-tech taxonomy, is publicly available on the Zenodo repository (`https://zenodo.org/`) for use in future research (`doi.org/10.5281/zenodo.18806387`).

3.6 Comparison groups

The decades covered by our data witnessed several major shifts in the innovation landscape. Patenting increasingly reflected the growing importance of software and related digital technologies (Bessen and Hunt, 2007), while inventive effort was redirected toward cleaner technologies in sectors

Table 2: **Space classification and organizations**

	Narrow space transportation		Extended space transportation		Broader space technologies	
	(1)	(2)	(3)	(4)	(5)	(6)
Space organization	0.100*** (0.0004)		0.163*** (0.001)		0.203*** (0.001)	
NASA		0.070*** (0.0004)		0.115*** (0.001)		0.139*** (0.001)
Non-NASA space firm		0.231*** (0.001)		0.372*** (0.002)		0.481*** (0.002)
N	8,262,840	8,262,840	8,262,840	8,262,840	8,262,840	8,262,840
R^2	0.007	0.010	0.005	0.007	0.005	0.007
Filing year f.e.	✓	✓	✓	✓	✓	✓
Share of space patents	0.0008		0.0031		0.0048	

Notes: Standard errors in parenthesis. ***: $p < 0.01$.

such as automobiles (Aghion et al., 2016). These shifts were accompanied by significant changes in the geographic distribution of innovation activities (Andrews and Whalley, 2022; Berkes et al., 2025). To better interpret trends in space innovation in the context of these broader changes, we define a set of comparison groups that serve as useful reference points.

First, we consider patents classified in CPC class B62D ("Motor vehicles; trailers"), the broadest class covering motor land vehicles (we refer to this group as *Land motor vehicles*). This group provides a benchmark for innovation in a mature and capital-intensive manufacturing sector with substantial engineering content. Second, we consider strictly defined *Information and communication technology* (ICT) patents, identified as those classified in CPC classes G06, "Computing or Calculating; Counting", and H04, "Electric Communication Technique", which capture computing, data processing, and communication technologies. Finally, we define a broad residual comparison group, *Non-space*, consisting of all patents that are not classified as space-related under any of our three space-technology classifications.

These groups are used solely as points of comparison to contextualize trends and patterns observed in space-related innovation, and to illustrate how the trajectory of space technologies compares to that of other major technological domains. We do not interpret them as control groups that are expected to follow parallel trends or to be differentially affected by specific shocks.

4 The Timing, composition, and geography of space innovation

Using the classifications described above, together with additional data sources introduced throughout this section, we now examine—through the lens of patent data—how space innovation has evolved over the past five decades. This analysis allows us to study systematically the progression outlined in Section 2, identifying when major shifts in space innovation occurred and how they changed the origin and nature of space technology. We begin by documenting the overall trends in space-related patenting, comparing patterns across our alternative definitions and technological categories, and benchmarking these trends against relevant comparison groups. We then turn to the composition and direction of innovation. We analyze who produces space technologies—distinguishing between government and private assignees, incumbents and entrants, and venture-backed and non–venture-backed firms—and examine how innovation differs across these groups in its novelty, reliance on science, and relatedness to ICT. Finally, we study the location of space patenting, assessing how its geographical distribution has evolved over time and whether it exhibits persistence or convergence across regions.

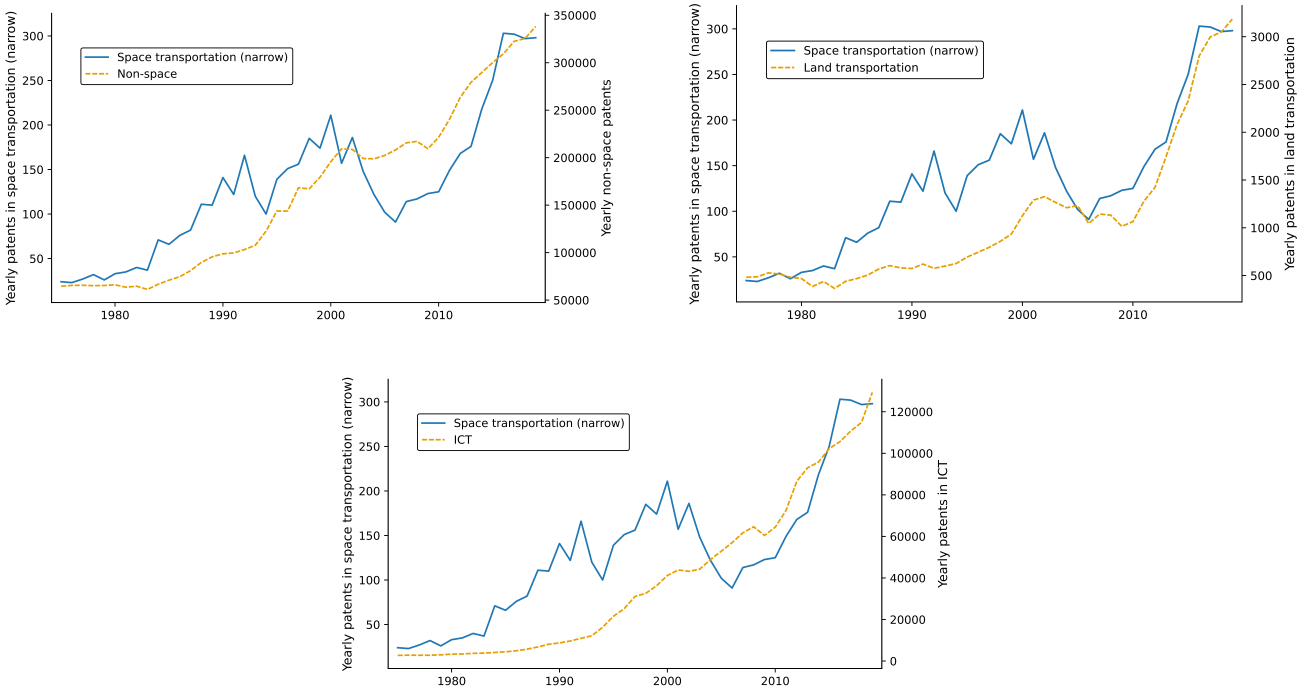
4.1 Timing: When did the expansion of space innovation begin?

Figure 5 plots the yearly number of patents filed since 1975 in the narrow space transportation category, benchmarked against three comparison groups: all non-space patents (top-left panel), land transportation (top-right panel), and ICT (bottom panel).

Over this period, patenting in the residual non-space group increased steadily, rising from fewer than 100,000 patents per year in the mid-1970s to more than 300,000 in recent years. Land transportation patenting grew gradually until the early 2010s, after which it accelerated sharply with the diffusion of electric vehicles (Aghion et al., 2016) and the emergence of autonomous driving. ICT patenting exhibits the most pronounced long-run expansion, growing from negligible levels in the late 1970s to more than 120,000 annual patents in the recent years, reflecting the rise of computers as a general-purpose technology with broad applications across sectors (Bresnahan and Trajtenberg, 1995; Bessen and Hunt, 2007).

Relative to these broader trends, patenting in the narrow space transportation category displays substantial but uneven growth. After rising through the 1980s, space patenting declined around

Figure 5: **Trends in space transportation (narrow) and comparison groups**

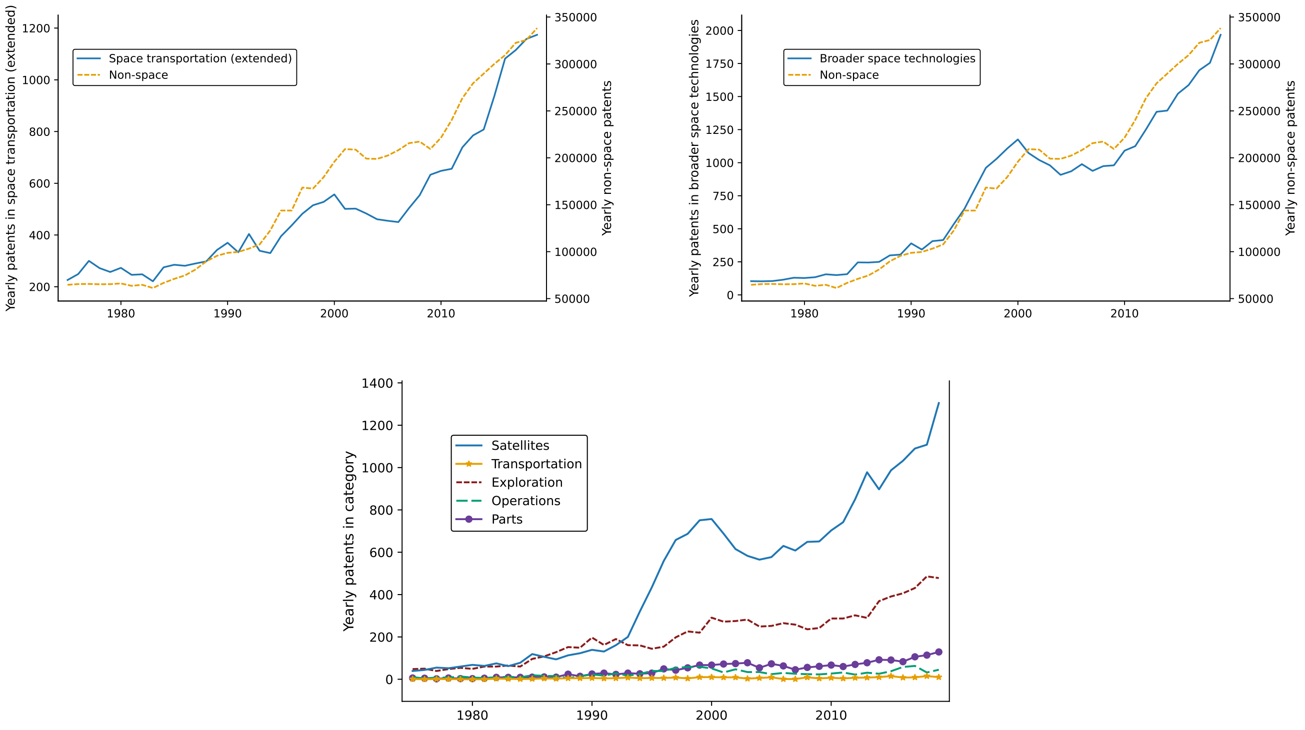


Notes: Patents filed per year in the narrow space transportation group (blue solid line) and residual non-space group (yellow dashed line, top-left panel), land motor vehicles (yellow dashed line, top-right panel), and ICT (yellow dashed line, bottom panel).

the end of the Cold War. Beginning in the early to mid-1990s, however, space patenting entered a sustained period of expansion. This growth predates the entry of the high-profile private space firms of the late 2000s and represents the first major and durable increase in post–Cold War space innovation. Patenting slowed in the early 2000s, with activity falling back toward pre-1990s levels. Since the late 2000s, space transportation patenting has increased again, reaching roughly 300 annual patents within the narrow classification in recent years.

Similar but smoother patterns emerge in the extended space transportation and broader space technology classifications, shown in Figure 6. Across all definitions, the first sustained post–Cold War acceleration occurs in the 1990s. Differences across classifications help clarify the nature of this expansion. The broad space technology category exhibits its largest increase during the 1990s, whereas the extended space transportation group shows relatively stronger growth in the later part of the sample. This distinction suggests that the initial expansion was concentrated in satellite, navigation, and communication technologies, which are more extensively covered by the broad classification and exhibit their strongest growth in the 1990s. By contrast, transportation-focused definitions show relatively stronger growth later in the sample, indicating that subsequent

Figure 6: **Trends in space transportation (extended) and broader space technology**



Notes: Top panels: Patents filed per year in the extended space transportation group (blue solid line, top-left), broader space technology (blue solid line, top-right), and residual non-space group (yellow dashed line). Bottom panel: Patents filed per year in each of the five categories in the space-tech taxonomy.

expansion increasingly involved transportation and launch-related innovations.

The source of the 1990s expansion becomes clearer when decomposing patenting within the broader space technology category. The bottom panel of Figure 6 presents patent counts across the five areas of the space-tech taxonomy. The bulk of long-run growth is accounted for by satellite technologies, which begin to expand sharply in the early 1990s and become the largest and fastest-growing component of space patenting. As discussed in Section 2, this period coincides with rising demand for telecommunications, GPS, and internet-related services that rely on space-based infrastructure. It also aligns with regulatory and institutional changes that facilitated commercial activity in these domains, including spectrum allocations and the establishment of licensing frameworks for satellite communications. Space exploration technologies, though not exhibiting a sharp takeoff in the early 1990s, expand steadily and remain a persistent component throughout the sample, accounting for roughly 500 annual patents in the recent years.

Taken together, these patterns indicate that the primary post–Cold War expansion in space innovation begins in the 1990s and is initially concentrated in satellite and communication technologies, laying the foundation for subsequent growth in transportation and launch-related activities.

4.2 Composition: How has the organization of space innovation evolved?

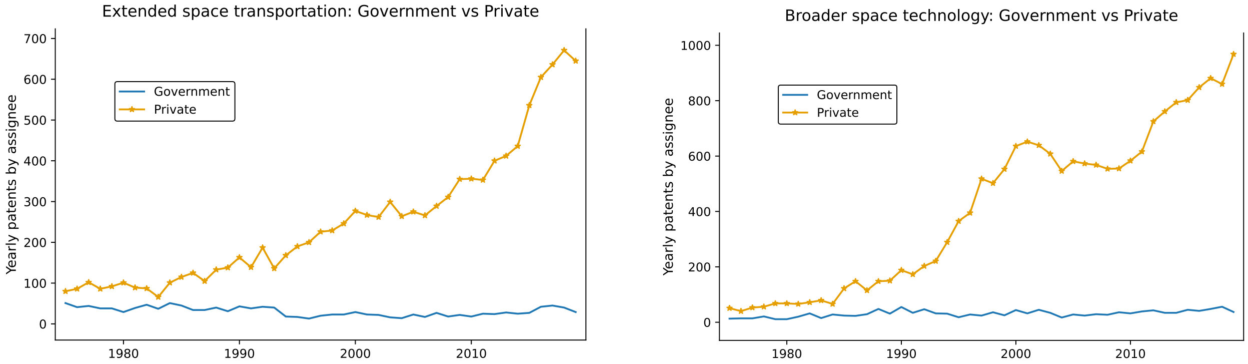
Having documented the timing of the sector's expansion, we now examine how the origin and nature of space innovation have changed over the same period. We distinguish between public and private assignees, between incumbents and entrants, and between venture-backed and non–venture-backed firms. We also study the characteristics of space-related patents along several dimensions, including reliance on scientific knowledge, the prevalence of novel and high-impact inventions, and relatedness to ICT. These patterns clarify the organizational sources of the post–Cold War expansion and the evolving technological profile of the sector.

Government and private firms. The role of government in innovation can take multiple forms. The public sector may be directly involved in research and patented inventions, or may shape the rate and direction of technical change indirectly through public funding, procurement, regulation, or the creation of appropriable markets (Finkelstein, 2004; Gross and Sampat, 2023; Azoulay et al., 2025; Moretti et al., 2025). As discussed in Section 2, U.S. space policy underwent a gradual shift beginning in the late 1980s and early 1990s, moving from direct government provision toward the construction of commercial markets for launch and satellite services. We now examine how this transition is reflected in our patent data.

The top panels of Figure 7 present the split between public- and private-sector patenting in space technologies. Patentsview provides assignee-level disambiguation for each patent, together with an indicator identifying whether the assignee is part of the government or a private firm. For this analysis, we focus on patents assigned to U.S.-based assignees, excluding patents assigned to foreign organizations. The top-left panel focuses on extended space transportation technologies and the top-right panel on the broader space technology category.

Both panels reveal a sustained shift in the origin of space innovation over time. In the mid-1970s, public-sector organizations accounted for a substantial share of space patenting: roughly one third of patents in space transportation and about 26 percent of patents in the broader space technology category in 1976. The divergence between government and private patenting becomes clearly visible in the early 1990s, coinciding with the broader expansion documented above. This shift is particularly pronounced in the broader space technology category, where private-sector patenting increases sharply while public-sector activity remains relatively flat. In extended space transportation, the transition toward private dominance follows a similar direction but is more

Figure 7: **Origin of space patenting: Government and private firms**



Notes: Patents in the extended space transportation group (left panel) and broader space technologies (right panel) by assignee type. Government and private assignees are identified using the Patentsview indicators.

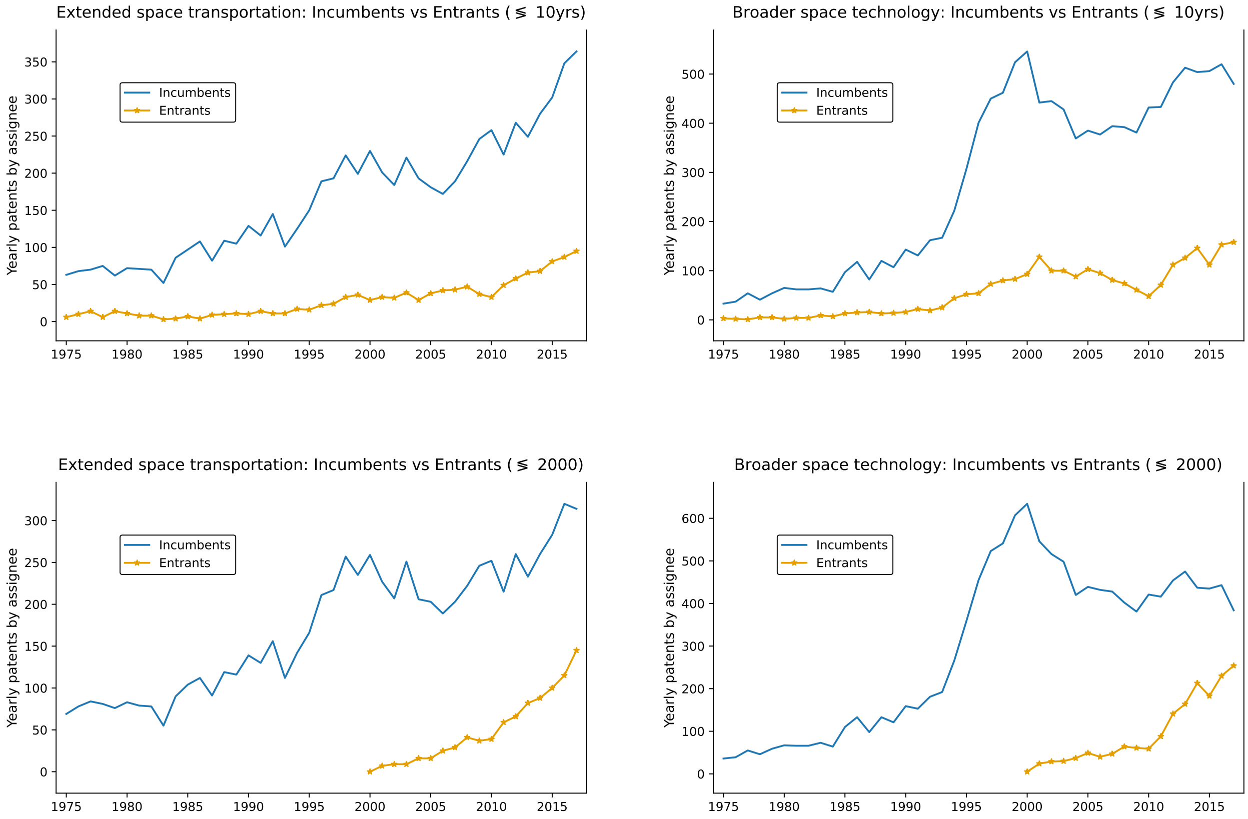
gradual. Since the early 1990s, the relative role of public assignees has continued to decline steadily. By 2019, public-sector patents account for less than 5 percent of space transportation patenting and less than 4 percent of patenting in the broader space technology category.

While the shift toward private-sector innovation unfolds progressively over several decades, the divergence becomes particularly pronounced during the 1990s expansion—especially in the broader space technology category, where private patenting accelerates sharply. This timing coincides with the emergence of appropriable markets for private launch and satellite services following the institutional changes in the late 1980s and early 1990s. By the time high-profile entrepreneurial firms entered the sector, the overwhelming majority of patenting activity was already concentrated in private organizations.

Incumbents and entrants. Theories of endogenous innovation predict that new or expanded markets increase inventive effort, with the response concentrated among firms possessing relevant capabilities and prior knowledge (Romer, 1990; Acemoglu and Linn, 2004). If the institutional changes that expanded commercial opportunities in the space sector raised expected rents in domains adjacent to existing aerospace capabilities, incumbent firms would be expected to be the main drivers of the resulting increase in invention rates. We now examine whether this pattern appears in the patent data.

The top panels of Figure 8 decompose private-sector space patenting into incumbents and entrants, with the top-left panel focusing on extended space transportation technologies and the top-right panel on the broader space technology category. In our baseline classification, incumbents are defined at each point in time as assignees founded more than ten years earlier, using founding-year information from Founding Patents (Ewens and Marx, 2023), which links patent records to

Figure 8: **Origin of space patenting: Incumbents and entrants**



Notes: Patents in the extended space transportation group (left panels) and broader space technologies (right panels) by assignee type. Incumbents are defined as firms founded ten years or more than the filing date of the patent (top panels), or as firms founded before 2000 (bottom panels), as reported in the Ewens and Marx (2023) dataset.

firm-level data from OpenCorporates.[7]

Throughout the sample period, incumbents are the dominant source of space innovation, accounting for the majority of space patents in both classifications. The sharp acceleration in space patenting observed in the early 1990s is driven primarily by incumbent firms, while entrant activity remains limited in absolute terms. The contribution of entrants increases steadily over time, but remains secondary in absolute terms. In 1985, entrants accounted for 6.7 percent of patents in extended space transportation and 11.8 percent in broader space technologies. By 2017, these shares had risen to 20.7 percent and 32.9 percent, respectively.

The rise of entrants is more visible, at least in relative terms, in the broader space technology category, where satellite-based applications, increased reliance on software, and the use of modular and off-the-shelf components may have lowered barriers to entry. In contrast, entry remains more

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[7] We end our analysis window at 2017, as founding year coverage is less complete for space patent data after 2017.

limited in extended space transportation, where accumulated know-how, scale economies, and vertical integration continue to play an important role. In this domain, a more noticeable increase in entry occurs only in the 2000s.

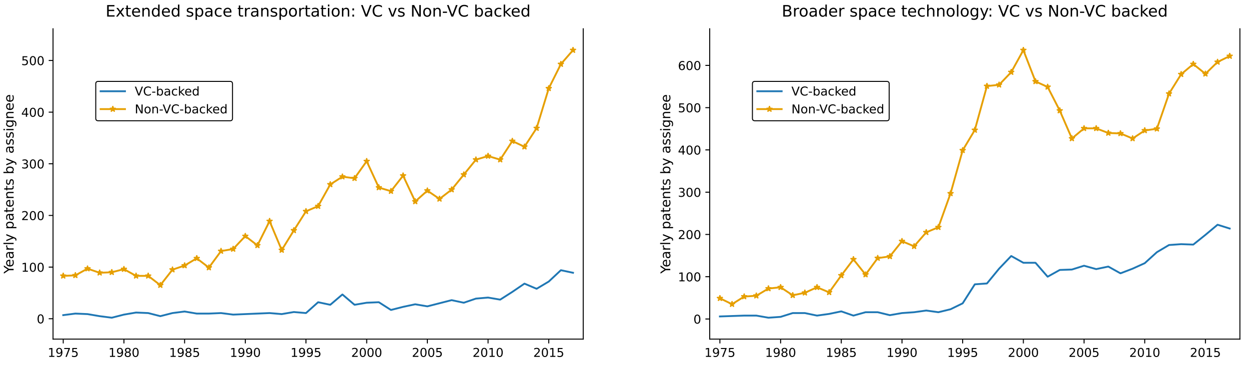
An implication of the baseline definition is that firms founded in the 2000s are eventually classified as incumbents once they pass the ten-year threshold. As a result, high-profile entrants such as Blue Origin, founded in 2000, and SpaceX, founded in 2002, are treated as incumbents in the later part of the sample. To separately assess the contribution of post-2000 entrants, we consider an alternative classification in which we define incumbents as firms established before 2000, a cutoff that coincides with the founding of Blue Origin and broadly precedes the emergence of firms commonly associated with the new space era. The resulting time series is shown in the bottom panels of Figure 8. Pre-2000 incumbents remain the primary contributors to space patenting throughout the sample, including in the most recent years. At the same time, post-2000 entrants account for a growing share of innovation, particularly in the broader space technology category, but continue to represent a minority of total patenting.

In summary, incumbents play a central role in the expansion of space innovation, particularly during the 1990s acceleration documented above. While the contribution of entrants increases over time, especially in recent years and in broader space technologies, pre-2000 incumbents continue to account for the majority of patenting activity. These patterns are consistent with a reorientation of R&D by established organizations toward policy-created market opportunities aligned with their existing capabilities, alongside a growing but still smaller role for newer entrants.

Venture capital and space innovation. The same data allow us to distinguish private-sector assignees based on whether they are backed by venture capital. Figure 9 repeats the analysis by separating patents assigned to VC-backed firms from those assigned to firms without venture capital backing, for extended space transportation technologies (left panel) and the broader space technology category (right panel).

Two patterns emerge. First, the large majority of space patenting throughout the sample period originates from firms that are not backed by venture capital. While patenting by VC-backed firms increases over time—particularly in relative terms and in the broader space technology category—it remains small compared to patenting by non–VC-backed firms. Second, most of the absolute growth in space patenting over the past decades is driven by firms without venture capital backing, which include large, established companies and organizations already active in space-related markets.

Figure 9: **Origin of space patenting: The role of VC-backed firms**



Notes: Patents in the extended space transportation group (left panel) and broader space technologies (right panel) by whether the assignee is a VC-backed or non-VC-backed entity, as reported in the Ewens and Marx (2023) dataset.

The increase in VC-backed patenting becomes more visible in the later part of the sample, particularly after the mid-2000s. However, this rise occurs well after the 1990s acceleration documented above and does not account for the bulk of the sector's expansion. In this sense, the patterns for venture-backed firms mirror those observed for entrants more broadly: although their presence grows over time, the primary expansion of space innovation reflects continued activity by organizations already established in space-related markets.

Reliance on scientific research. We now turn to the technological characteristics of space innovation, beginning with the extent to which space-related patents rely on scientific research and how this reliance varies across types of innovators. Using the dataset of Marx and Fuegi (2022), which links patents to citations to academic publications, we measure reliance on science both as the probability that a patent cites at least one scientific article and as the average number of scientific citations per patent.

Reliance on scientific research provides a window into how closely innovation draws on frontier knowledge and the extent to which firms are engaging with emerging technological opportunities. A substantial literature shows that startups play a central role in commercializing scientific discoveries (Kolev et al., 2022; Marx and Hsu, 2022). When innovation builds on new scientific insights that are not easily integrated into existing routines, incumbent firms may face disadvantages stemming from organizational rigidity or capability misalignment (Henderson and Clark, 1990). In such settings, entrants can have an edge in translating frontier science into commercial applications. In the context of space technologies, this distinction suggests that while incumbents may direct R&D toward opportunities aligned with their accumulated capabilities, entrants may be more likely to

Table 3: **Reliance on scientific research in space patents by assignee type**

	Any science	Avg. # science	# pat.
	Space Transportation (extended)		
Government	0.108	0.306	1,565
Incumbents	0.082	0.202	7,274
Entrants	0.097	0.286	1,449
	Broader Space Technology		
Government	0.222	0.674	1,532
Incumbents	0.143	0.340	11,986
Entrants	0.202	1.190	2,713

Notes: "Any science": share of patents in each group by each assignee type with at least one citation to scientific papers. "Avg. # science": average number of citations to scientific papers by patents in each group by each assignee type. Only citations to papers in the body of the patents are counted. "# pat.": Total number of patents in each group by each assignee type. Incumbents are defined as assignees whose founding year is at least ten years before the patent's filing. Citations to scientific papers are obtained from the "Reliance on science" dataset described in Marx and Fuegi (2022).

introduce science-based insights in domains requiring new technical approaches.

Table 3 provides a detailed view of this heterogeneity across assignee types.[8] Government-assigned patents exhibit the highest reliance on science, consistent with the role of public organizations in supporting and conducting research closer to the scientific frontier (Dyevre, 2024; Gazzani et al., 2025). Among private firms, entrants are more science-reliant than incumbents in both transportation and broader space technologies. Incumbents—who account for the bulk of patenting in the sector—tend to rely less on scientific knowledge, consistent with models in which established organizations exploit accumulated capabilities and incremental improvements, while entrants are more likely to introduce innovations rooted in newer or more science-intensive knowledge bases.

Figure 10 shows that reliance on scientific research in space patents remains broadly stable over time. The share of patents citing at least one academic publication fluctuates around a relatively constant level throughout the sample (roughly 15%), with no clear upward trend. Similar patterns are observed in land transportation (although the average reliance on science is significantly smaller) and in the residual non-space sector. Differences across space technology categories

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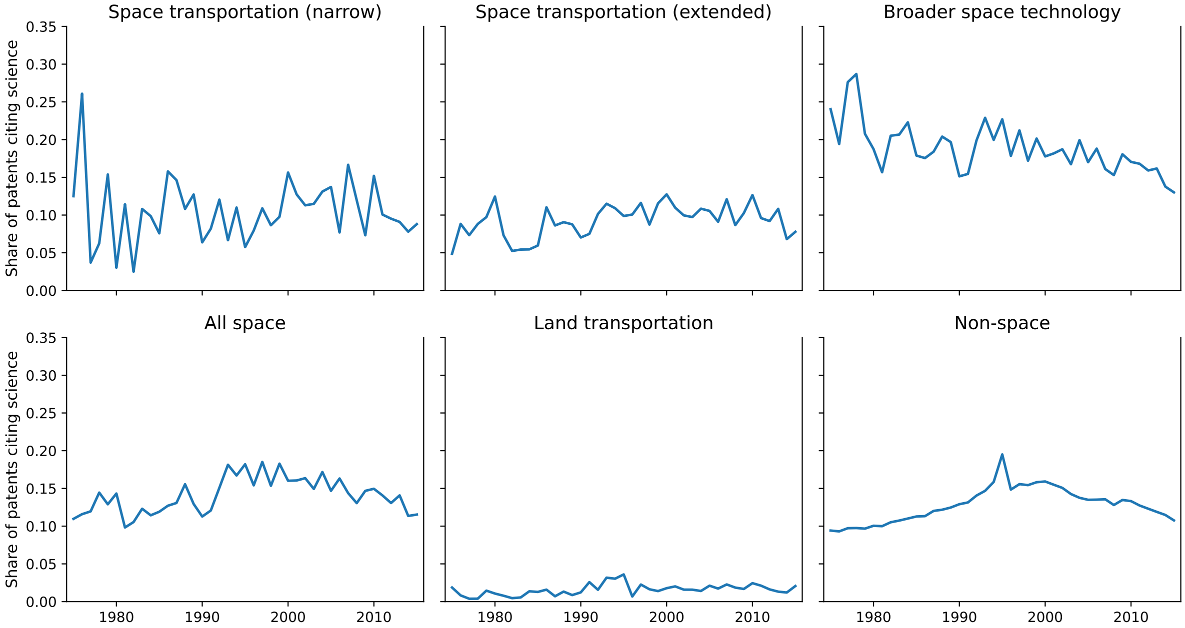
[8] For this analysis, we again define incumbents as assignees whose founding year is at least ten years before the patent's filing, as reported in the Ewens and Marx (2023) data.

Figure 10: **Space innovation and reliance on scientific research**



Notes: Share of patents in each group with at least one citation to a scientific publication, as reported in "Reliance on science" dataset described in Marx and Fuegi (2022). Only citations to papers in the body of the patents are counted.

are nonetheless informative. Patents in the broader space technology classification are consistently more science-reliant than patents in narrow or extended space transportation. This gap reflects the technological domains captured by the broader classification, which include satellite, communication, and navigation applications that draw more directly on advances in electronics, computing, and materials science. Consistent with the patterns documented above, this is also the domain in which entrants increase their relative contribution most visibly. The association between higher scientific reliance and a greater presence of entrants is in line with the view that newer firms may be more active in domains that draw on scientific knowledge, even in the absence of strong aggregate trends over time.

Novelty, impact, and relatedness to ICT. A central question in interpreting the expansion of space innovation over the last decades is whether it reflected incremental growth within established technological trajectories or a repositioning within the broader technological frontier. The innovation literature emphasizes that novel research is more impactful (Uzzi et al., 2013) and novel inventions have higher value (Kelly et al., 2021). At the same time, the integration of a sector with a general-purpose technology such as computing can signal that it is becoming embedded within broader economy-wide technological transformations (Bresnahan and Trajtenberg, 1995).

We first examine the integration of space technologies with information and communication technologies (ICT). Using CPC classes G06 and H04 (see Section 3.6), we construct two complementary measures of ICT relatedness: one based on CPC co-occurrence and one based on citations to ICT-classified patents. Figure 11 plots the share of ICT-related patents (for both classifications) in space technologies, land transportation, and the residual non-space sector. ICT relatedness increases over time across all sectors, reflecting the broad diffusion of digital technologies. However, the increase is substantially stronger and more abrupt in space-related patents. In particular, ICT relatedness in space innovation rises sharply during the 1990s, driven primarily by the broader space technology category. Most of the increase in ICT intensity occurs within this decade, after which the share stabilizes at a higher level. In contrast, land transportation and the residual sector exhibit more gradual increases over a longer horizon. The digitization of space innovation thus appears concentrated in the 1990s rather than unfolding progressively in the late 2000s.

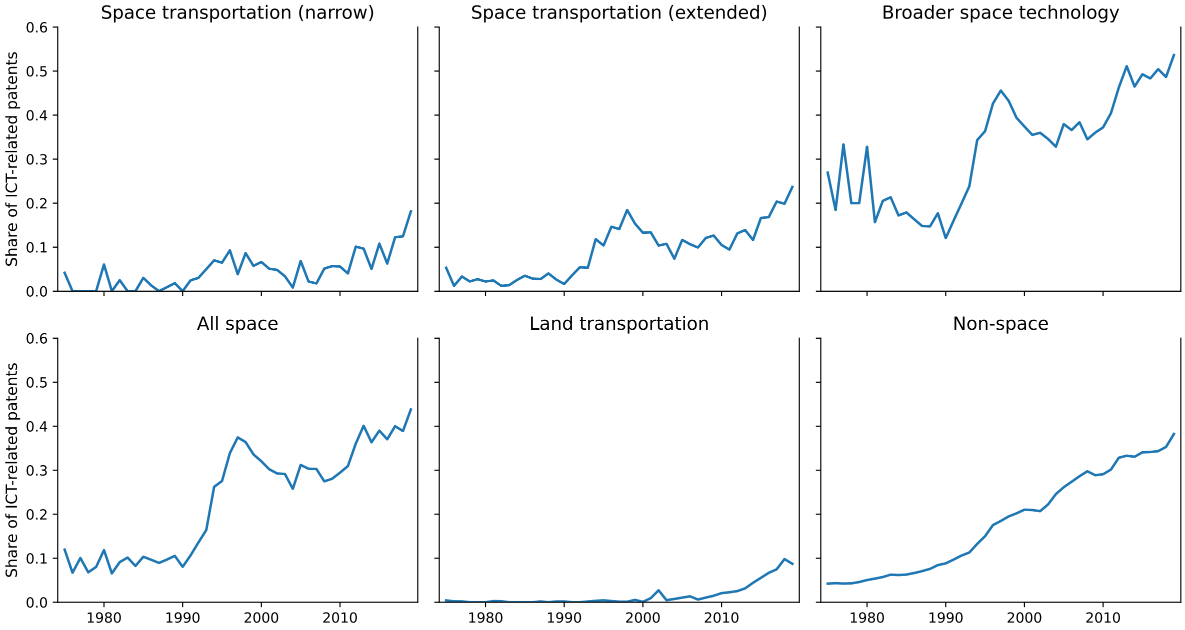
We next examine whether this period was also associated with a shift in the novelty and forward impact of space innovation. To do so, we use the semantic similarity measure developed by Kelly et al. (2021), which captures the extent to which a patent departs from prior technologies while anticipating subsequent ones. The measure is defined as the ratio of a patent's similarity to later inventions (filed in the five years after the focal patent) to its similarity to earlier inventions (filed in the five years before). Following Kelly et al. (2021), we classify patents in the top 10 percent of this distribution as *breakthrough* inventions. At the individual level, such patents are commonly interpreted as both novel and influential; at the sectoral level, the measure indicates how strongly innovation aligns with emerging technological trajectories.

Figure 12 shows a pronounced increase in the share of breakthrough patents in space technologies that peaks in the mid-1990s. No comparable surge is observed in the late 2000s. Relative to the residual non-space sector, the increase in breakthrough activity is substantially stronger in space during this period, while land transportation exhibits little comparable rise until much later, alongside the transition toward electric and autonomous vehicles. These results indicate that the 1990s expansion in space innovation was associated to a qualitative shift: space technologies became more tightly connected to ICT and more closely aligned with frontier technological developments.

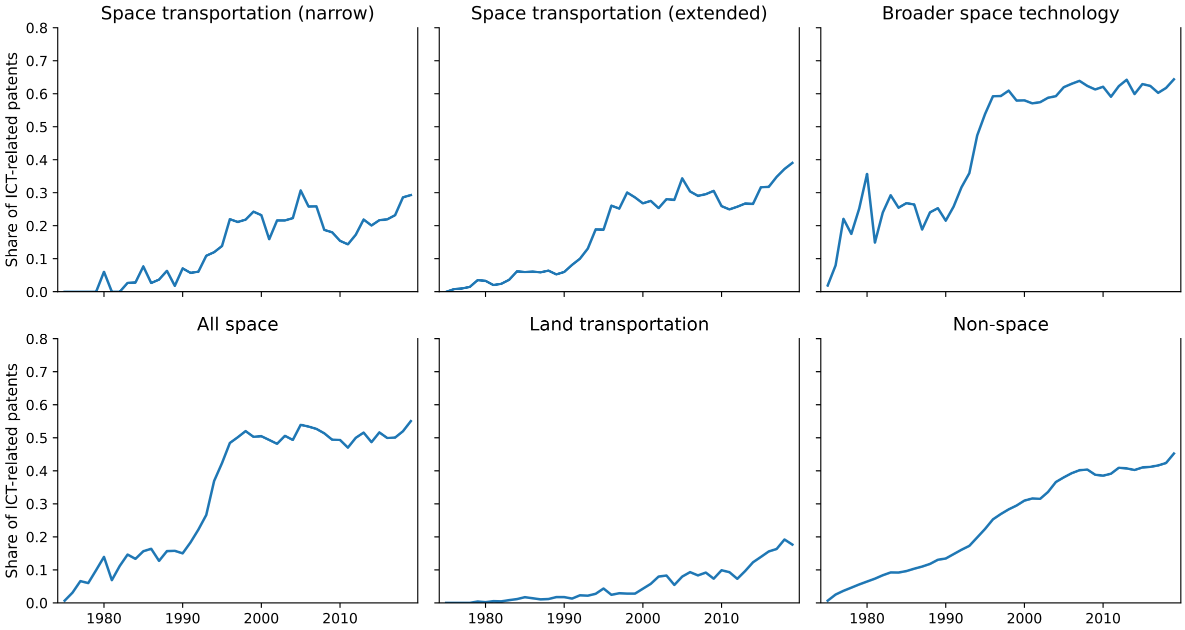
Overall, these patterns are consistent with the view that satellite, communication, and navigation technologies made space an early complement to the development of internet and digital infrastructures rather than late adopters of ICT.

Figure 11: **Space innovation and relatedness to ICT**

Based on co-occurrence of ICT-related CPC classes

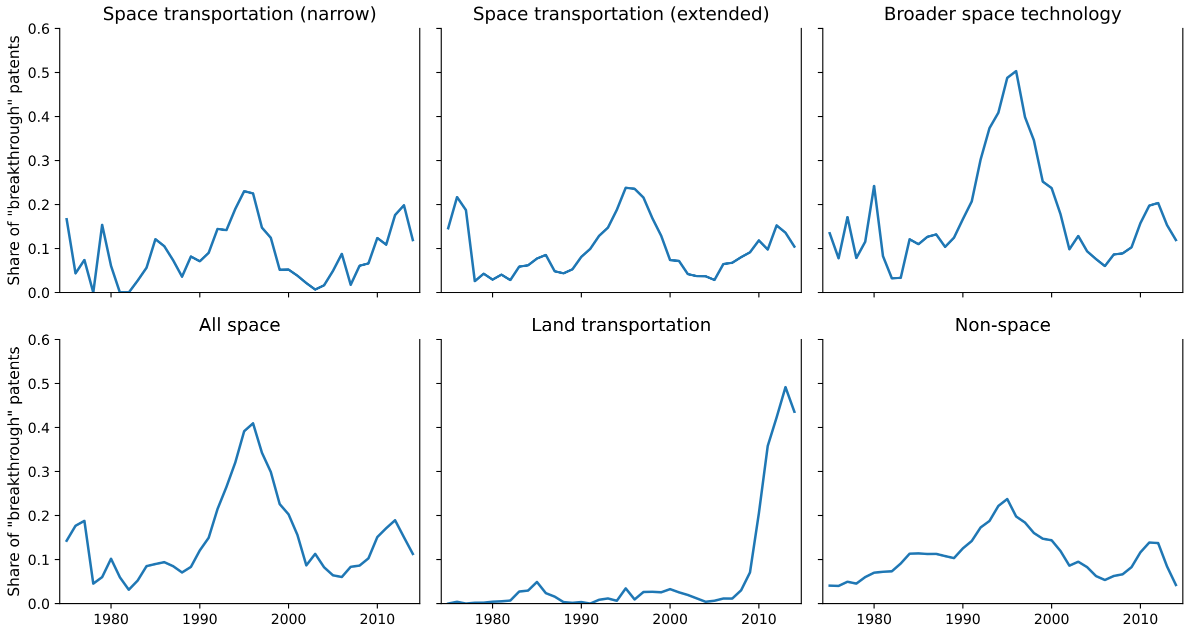


Based on patents citations to ICT-related CPC classes



Notes: The top panels plot the share of patents in each group with at least one co-occurrence of CPC classes G06 and H04. The bottom panels plot the share of patents in each group providing at least one citation to patents in CPC classes G06 and H04.

Figure 12: **High-novelty and high-impact ("breakthrough") patents**



Notes: Share of "breakthrough" patents in each group, defined as patents in the top 10 percent of the distribution of the ratio of forward to backward similarity (Kelly et al., 2021).

4.3 Geography: Persistence or convergence in the location of space innovation?

The transformations documented above raise a related question: were these shifts accompanied by a meaningful reshuffling in the geography of inventive activity? If space technologies increasingly required interaction with new industries and knowledge domains, one might expect innovation to diffuse toward a broader set of regions where exposure to such complementary capabilities is available. Alternatively, if innovation in space technologies continues to rely primarily on industry-specific assets—specialized infrastructure and labor pools, established supplier networks, and long-standing relationships with government customers—then inventive activity may further concentrate in established hubs.

These two forces correspond to classic mechanisms in urban economics. Marshallian agglomeration emphasizes within-industry externalities and specialization (Marshall, 1890), whereas Jacobs-type externalities highlight the role of cross-industry knowledge spillovers and local diversity in fostering regional growth (Jacobs, 1969; Glaeser et al., 1992). The degree of divergence or convergence in space innovation thus informs which agglomeration mechanisms—within-industry clustering or cross-industry spillovers—have played a more important role in the evolution of the space economy.

To examine this question empirically, we geo-locate patents at the level of 1990 commuting zones (CZs) using inventor location information from PatentsView. Patents with multiple inventors are allocated fractionally to inventors' CZs. To limit the influence of CZs with negligible activity, we restrict attention to CZs with population of at least 100,000 in 1970. For simplicity, we define space patents as those classified as space-related under any of our categorizations. The maps in Figure 13 display CZs by their quantile in the distribution of total space patents, and overlay the locations of NASA research centers. We construct three separate maps, each corresponding to one of the three periods in which we organized the sector's evolution in Section 2: Cold War (1975–1989), post–Cold War (1990–2004), and New Space (2005–2019).

The salient pattern that emerges from the maps is the remarkable persistence in the location of space innovation. Despite the technological shifts documented above and despite the growing presence of entrants after the mid-2000s, the relative ranking of major space innovation hubs remains largely stable. Some regions become more prominent in the later period (e.g., parts of the West Coast, Austin, and the Research Triangle), but these changes occur within a spatial structure that does not experience a dramatic reshuffling.

To quantify persistence versus convergence, in the spirit of the urban growth literature (e.g., Glaeser et al., 1992; Glaeser et al., 1995), we estimate CZ-level regressions of local patenting on initial conditions. In particular, for each CZ c, we denote by $P^g_{c,t}$ the number of patents in period t and group g (e.g., space, non-space, land transportation). We then estimate the following regression:

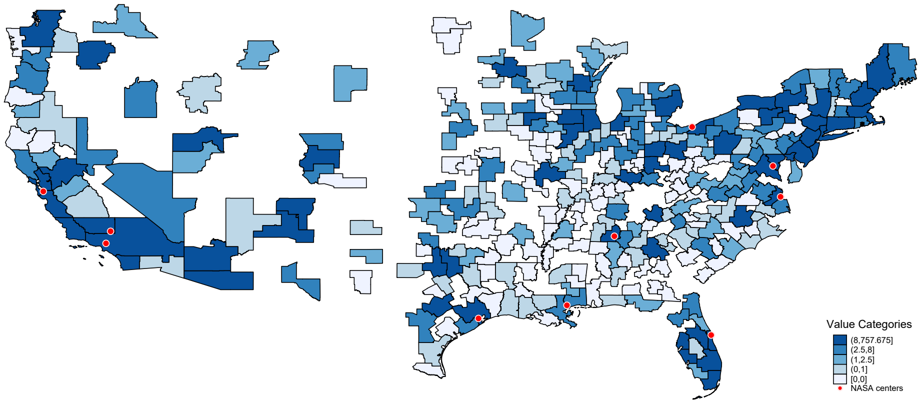
$$\text{IHS}(P^g_{c,t}) = \alpha^g_t + \beta^g_t \,\text{IHS}(P^g_{c,1975-1989}) + \epsilon^g_{c,t}, \tag{1}$$

where $t \in \{1990 - 2004, 2005 - 2019\}$. We use the inverse hyperbolic sine transformation to accommodate zero counts while preserving a growth interpretation, with the common caveats highlighted in the econometrics literature (Chen and Roth, 2024).

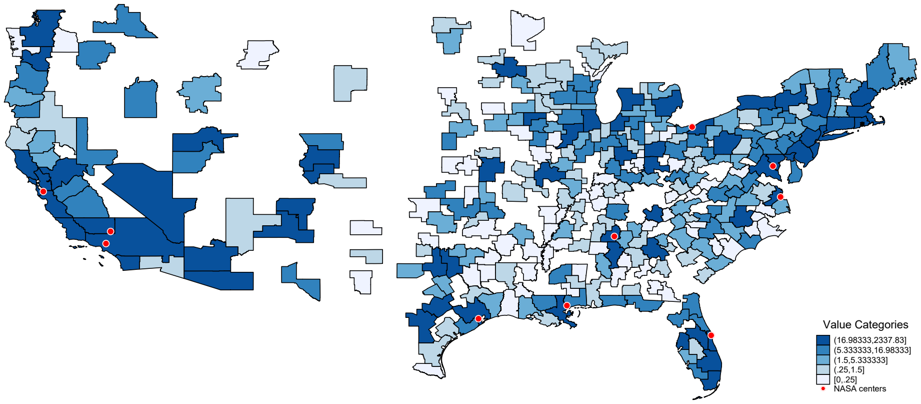
In this framework, $\beta^g_t < 1$ indicates convergence (initially high-patenting CZs grow more slowly), while $\beta^g_t > 1$ indicates divergence or persistence (initial leaders grow at faster rates). Table 4 reports results for space patents (column 1), all non-space patents (column 2), and land transportation patents (column 3). For space patents, the estimated coefficients are consistently (albeit not significantly) above one and close to those for the residual non-space sector, indicating no evidence of geographic convergence in space innovation. By contrast, land transportation exhibits substantially more convergence consistent with the broader diffusion of new vehicle technologies

Figure 13: **Total space patents by commuting zone**

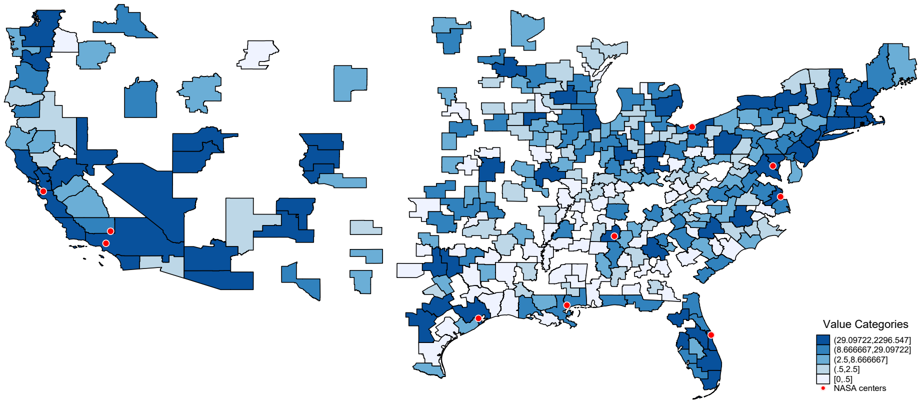
Cold War: 1975-1989



Post-Cold War: 1990-2004



New Space: 2005-2019



Notes: Total space patents by commuting zone. Only commuting zones in the contiguous United States with population of at least 100,000 in 1970 are included. Red dots indicate the location of NASA centers.

Table 4: **Persistence and convergence in the geography of space innovation**

	IHS commuting zone patents		
	Space (1)	Non-space (2)	Land (3)
	Post–Cold War (1990-2004)		
IHS commuting zone patents, Cold War (1975-1989)	1.01*** (0.03)	1.02*** (0.02)	0.83*** (0.03)
R^2	0.75	0.92	0.64
	New space (2005-2019)		
IHS commuting zone patents, Cold War (1975-1989)	1.04*** (0.03)	1.06*** (0.02)	0.93*** (0.04)
R^2	0.71	0.85	0.63
N	320	320	320

Notes: Standard errors in parenthesis. $^{***}p < 0.01$.

beyond early centers.

Overall, the evidence indicates that the geography of space innovation is remarkably stable: established hubs persist, yet concentration does not strengthen over time. This pattern suggests a balance of agglomeration forces. On the one hand, Marshallian within-industry mechanisms help sustain existing clusters. On the other hand, Jacobs-type cross-industry spillovers may facilitate diffusion. The interaction of these forces appear to yield persistence without increasing concentration, leaving the spatial structure of the space economy broadly intact even as its technologies and markets evolve.

5 Conclusion

This paper uses patent data to examine the timing and composition of space innovation, finding patterns that challenge the popular narrative attributing commercial space transformation to entrepreneurial entrants after 2005. The largest surge in space-related patenting occurred in the 1990s, coinciding with demand-side market creation through spectrum allocation, licensing regimes, and growing demand from telecommunications and GPS applications. Throughout this period and since, incumbent aerospace firms have accounted for the majority of space-related patenting, with entrants contributing a growing but still minority share concentrated in broader space technologies rather than launch vehicles. These patterns are consistent with directed technical change: incumbents direct R&D toward policy-created markets accessible from existing capabilities, while entrants later bring science-based insights into domains requiring new technological paradigms. Government's most consequential role in space innovation may lie in constructing appropriable markets rather than directly funding technological development or enabling entrepreneurial entry.

Our analysis has limitations that should be kept in mind when interpreting the results. Patents capture only a portion of innovative activity, with well-known variation in patenting propensity across technologies and firms. Software innovation, increasingly important in space applications and often central to startups, is particularly underrepresented. Moreover, our evidence is descriptive rather than causal. While the timing coincidence between policy changes and innovation surges is suggestive, we cannot isolate the effects of specific policy channels or rule out confounding factors. In particular, the broader space technologies driving many of the observed patterns may also have been influenced by contemporaneous non-space policies. Much work remains to establish causal mechanisms linking demand-side shifts to innovation outcomes and to understand how different policy instruments interact with firm capabilities and market structure.

Our findings reveal that the commercial space transformation is more closely connected to its government-led origins than narratives emphasizing entrepreneurial disruption suggest. The same regions, many of the same firms, and cumulative technological trajectories link the post-Space Race era to today's commercial expansion—suggesting that New Space and Old Space are less distinct than commonly assumed. This historical continuity echoes patterns observed in other industries undergoing commercialization. In telecommunications, airline transportation, and electricity generation, reduced government involvement reshaped market structure but did not erase the importance of incumbent capabilities or the cumulative nature of technological progress. Understanding how policy creates markets, and how different firm types respond to those markets, may offer lessons extending well beyond the space sector.

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