Defining *innovatisation*: The case of NewSpace and the changing space sector*

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Abstract: The space sector has become far more dynamic and innovative, with new actors (e.g., start-ups, venture capital) entering and the ever-growing importance of private firms. In this paper we introduce a novel concept, *innovatisation*, to understand this phenomenon. Innovatisation describes the transformation of a sector between two modes. In a mode of technological achievements (TA), only technological (not economic) performance matters, primarily for prestige purposes; in innovation, customer

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preferences, commercial opportunities, and costs become essential. Studying the economics of Apollo and the commercialization attempts of the 1980s, we show how the space sector has long featured a logic of TA. Then, analyzing recent trends, we provide quantitative empirical evidence (e.g., costs) that innovation now shapes the sector, thanks to various driving forces. The driving forces behind the innovatisation process are identified building on Jones (2022) and the disruptive innovation theory.

Keywords: Innovatisation; Innovation; Technological Achievements; NewSpace; Space economy; Entrepreneurship

1. Introduction

The global space sector has seemingly become far more dynamic and innovative. This is evidenced by new entrants, technologies, and roles of legacy institutions. Consider two historical periods: one is marked by Apollo and NASA's dominion over US space in the 1960s and 70s; the other is characterized by the recent symbolic success of the young firm SpaceX and the wave of entrepreneurship that followed. Clearly, there is a spectacular transformation in how research and technology advances are organized. Our objective is to try to understand the very nature of this transformation, to find meaning and coherence behind the observed evolutions. This objective is relevant because the representation of an increasing *commercialization* of space seems inadequate for the task of describing the current transformations. There have always been certain forms of commercialization regarding space activities (MacDonald 2018). However, the current transformations cannot be reduced to a change in the *degree* of commercialization so much as a change in the very *nature* of activities.

The goal of this paper is to propose an empirically grounded theory for what is occurring in the space sector's innovation dynamics. We call our theory *innovatisation*, and we define it as the sector's transformation from a regime of *technological achievement* (TA) to one of *innovation*.

The TA regime is not subject to the traditional rules of a market economy. In such a regime, neither consumers nor costs really count, and only technological performance matters. As the market has no influence, it offers neither the opportunities nor the constraints that entrepreneurs usually face, and innovation finds nothing to hold onto. When those have no importance, innovation cannot be the operating mode of novelty. The operating mode of novelty is therefore the technological achievement that is in a way released from the constraints of the market; it can thus unfold in a kind of space protected by the state and legitimized by non-economic objectives such as prestige or national security. Importantly, it does not mean TAs are outside of the economy, as they may have a significant economic weight, and generate some spillovers.1

In the innovation regime, commercial opportunities explode, customers' preferences enter the constraints domain, and costs become an essential determinant of project success. Consequently, innovation – as discovery of what works economically (not just technologically) – becomes the main operating mode of novelty. The transition between these two regimes is named *innovatisation* rather than *commercialization*.

To ground this approach and our hypotheses empirically, we mobilize qualitative data and descriptive statistics to document the evolution of the space sector over the past 60 years. In this paper, we focus on economic mechanisms and institutions (e.g., supply,

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1 See e.g., Kantor and Whalley (2025), Corrado et al. (2025), and Antolin-Diaz and Surico (2025), for a discussion on the spillover effects of government spending and the US space program.

demand, market structure, contracts) shaping the sector's organization; in a companion paper (Chavy-Macdonald, Cornet, and Foray 2023) we investigate the key program and system architecture decisions.2 We maintain that economic mechanisms and technological architectures (and design decisions) are clear markers of the fundamental logics behind TAs and innovations.

In Section 2, we further explain the study's context, the analytical approach (especially the innovation concept) and our methodology. In Section 3, we introduce our theoretical framework, before applying it to the space sector in Section 4. In Section 5 we provide empirical data to try to measure the degree of innovatisation in the space sector. Section 6 discusses the results and Section 7 concludes.

1. Setting the stage

Here, we set the stage reviewing the relevant literature, to establish the concept of innovation used in this field: *innovation as economic discovery*. Then, we use it to analyze the changes currently happening in the space sector. This enables us to introduce our novel concepts of *technological achievement* and *innovatisation*. We follow-up by presenting our methodology and the data.

1. Innovation as economic discovery

In 1939, Schumpeter established a clear distinction between innovation and invention: innovation would consist in any instances of "doing things differently in the realm of economic life," (Schumpeter 1939), while invention would be out of the economy, akin to the discovery of a new continent. An invention would become an innovation only when brought to the economic realm.

Building on Schumpeter's approach, Freeman and Soete (1997) adopt a similar but somewhat more restrictive definition of innovation as the commercialization of technological inventions. Kline and Rosenberg (2010) are also in line with Schumpeter, explaining that an innovation can be successful only if it meets both technical and commercial needs. Scherer (1986) is also close to this notion, arguing that innovation puts an invention into practice and exploits it commercially. This approach to innovation as a phenomenon that happens in the economy, has also been adopted in the literature dedicated to measuring innovation (OECD and Eurostat's Oslo Manual 2018).

In this paper, we build on this definition of innovation, by considering that innovation is first and foremost an economic phenomenon. It brings economic value (as profit) to

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2 We mean "architectural" engineering design and development decisions related to space technologies and their parent programs.

producers, and (as surplus) to customers.3 If a new idea brings economic value, it will penetrate the market and become an innovation; if it does not, it will not (Phelps 2013).

As a result, the innovation process leads to the adoption of an invention or new idea after it has been experimented upon within the economy and society. The innovation process does not occur in the technical sphere, but in the economic one. It is a process of discovery that reveals, from an economic viewpoint, what works and what does not. Economic discovery is, in essence, the backbone of innovation.

Therefore, while a technological invention is an engineering achievement measured by engineering performance, an innovation is an economic achievement measured by consumer surplus and profit. In this process, cost decrease is central. Thus, summarizing Ridley's (2020), innovation drives costs down so dramatically that it changes the world. We will see how true this statement is vis-à-vis the evolution of the space sector.

2. Innovation as economic discovery in the space sector

As suggested in Section 1, an astute observer can realize that the space sector is experiencing profound transformations, each driven by a specific logic: more start-ups, new markets, the big incumbents' transforming operations, greater attention to costs, etc. Our goal is to try, using the framework of innovation studies, to explain the coherence of these changes. Our central hypothesis is that innovation – defined above as *economic discovery* – has become the norm in this sector, which it was not before. The formulation of this hypothesis implies distinguishing between innovation and a novel concept we propose in this paper, that of *technological achievement* (TA), because space has always been a sector with many technological achievements. Thus, the shift from a regime producing TAs to one producing innovations represents the coherence of the various transformations that characterize space today.

A TA can be defined as a significant technological or engineering advance, made operational, with a potentially large economic impact (e.g., large expenditures, spillover effects). TAs may result e.g., from government policies, motivated by objectives not purely economic, like prestige or national security. As a result, while their economic impact may be large, they are not subject to the traditional market mechanisms ruling innovations. TAs are therefore not innovations in the sense we mean here. Importantly, they are also not *failed innovations*, which would be innovations that were introduced to the market but that failed to generate economic surplus. Finally, TAs differ also from

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3 In microeconomic analysis, consumer surplus is measured by the difference between willingness to pay and price; producer surplus or profit is measured by the difference between price and cost; social surplus is the sum of the two.

inventions by the fact that inventions are upstream from TAs. Inventions are confined to laboratories: they may become innovations if they are subject to market forces, or TAs if they are made operational but not subject to market forces, or remain inventions if they stay behind the walls of the laboratory. Figure 1 summarizes these concepts.

How do these concepts of TA and innovation set the stage for our argument? For a long time, the space sector has exhibited strong technological capacities and achievements, and while it has represented a large share of the US economy (at the peak of Apollo, the program reached over 4% of US Federal Budget),4 it did not produce much economic surplus through innovation (e.g., access to space has remained expensive for a long time). Thus it was not innovative in our sense.5 This leads us to interpret the history of the US space sector as a regime-change from a regime of TA, whereby technological advances do not translate into economic surplus, to one of innovation. This regime change is captured by the term *Innovatisation*.

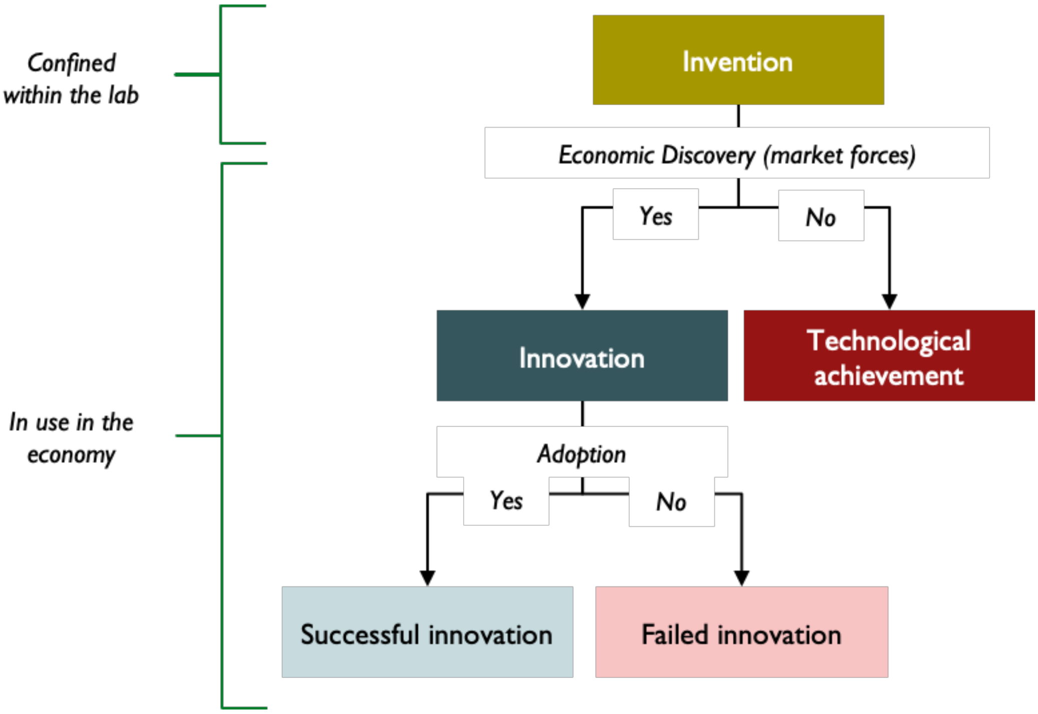

Figure 1. Disentangling invention, technological achievement and innovation. Source: Authors.

3. Methodology and data

In this paper, we aim to build a theory of innovatisation, and to provide empirical support for it. To do so, we adopt a two-step approach: first, we build on Jones' (2022)

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4 See data from The Planetary Society (2022).

5 Of course, knowledge spillovers do exist. Advanced technologies and knowledge produced in space programs feed innovation processes in various economic sectors. It would be absurd to dispute this, but the spillovers rely on true innovation activities in the other economic sectors to have value. Moreover, they come at huge opportunity costs (see also Section 4).

and the disruption theory (Christensen 1997, Henderson 2006 and Gans 2016) to establish a dynamic theoretical framework of the drivers of innovatisation. This framework is introduced in Section 3. Second, we apply this framework in a case study of the space sector to conduct a historical analysis of the major events of the past 60+ years. We also try to give qualitative elements and descriptive statistics supporting the existence of the regime shift and innovatisation. The case study is presented in Section 4. Details of the methodology, data sources & graph construction, and historical references are in Appendix A.

The changes in the space sector and NewSpace phenomenon have been investigated in the economics literature. The work most relevant to us examines space sector evolution from an economic perspective. In particular, Mazzucato and Robinson (2018), Rottner, Sage, and Ventresca (2021), and Chavy-Macdonald and Kneib (2020) made close contributions, though centered on 'ecosystems,' contrasting with our focus on innovation as economic discovery and its role in large sectoral cost decreases. Culver et al. (2007) and Weinzierl (2018) are closest in spirit to our work, discussing policy implications of the sector's evolution. Corrado et al. (2025) also takes a long-run historical view to explore spillovers, while Gaetani and Whalley (2026) also use patent data, but to determine when the sector's innovation transitioned. Our contribution complements these papers with innovatisation as a framework to analyze that evolution.

2. A simple dynamic theoretical framework

To identify and document the *innovatisation* process, i.e. the transformation from a regime of technological achievement to a regime of innovation, we draw on Jones' (2022) framework that aims at exploring the reasons behind the huge inter-sectoral variations of R&D intensity and innovation. Its rationale is that there are three generic categories of features that drive the return on innovation investments and that vary across industries. Those are: *demand,* including market size, willingness to pay for a given innovation, and buyer uncertainty; *supply*, notably the fixed costs of creating the innovation, the "scalability" costs (production, distribution), and technological opportunities; and *institutions*, including the ones helping innovators appropriate the value of innovation, the institutions supporting science and basic research, and the market structure and various regulations that can encourage or impede innovation.

Table 1 presents these features, and a useful scan of "what is good to have" for a sector to be innovative. The process of innovatisation involves the gradual shift from a situation where most of the features are unfavorable, to one where most are conducive to innovation. Major changes driving the innovatisation process in space occur at all three levels (supply, demand, and institutions, including the new role of NASA).

However, the framework proposed by Ben Jones is not a theory about how such a process can be initiated and sustained. Thus, while some features in Table 1 will be analyzed as initial drivers of the innovatisation process of the space sector (like the emergence of new technological opportunities and business opportunities), this framework does not cover all possible originators of the process. An example is the role of pioneering entrepreneurs entering the sector with new visions and values.

We therefore require a complementary approach: the disruption theory (Christensen 1997, Henderson 2006, Gans 2016) argues that in most cases successful incumbents are not able to effect major changes affecting values, culture and norms – which is what innovatisation entails.[6] Regarding the space sector, the success of incumbents in the TA age – analyzed in the next section – makes them unprepared to the regime change of the innovatisation process. From the perspective of disruption theory, the needed dynamism comes from outside the sector – incumbents that are locked-in to a system of values and norms that secured their past successes cannot find within themselves the dynamic forces of disruption. This means that outsiders – bringing a new vision and values – are important to explain early innovatisation.

Building on these two contributions, the thesis of this paper is that for a long time, determinants of returns on innovation-related investments were not favorable, so that the main logic of producing and using new engineering knowledge in the space sector was not innovation, but technological achievements. Then, the process of innovatisation started. It has two steps: first, some features started to improve through the influence of three external factors (business opportunities on the demand side, and on the supply side, technological opportunities and lowering fixed costs of entrepreneurial experimentation). This triggered the entry of entrepreneurial pioneers looking for profitable business models or exciting challenges. Indeed, an important feature of entrepreneurs is that they allocate their efforts and resources where innovations will generate further business opportunities and lever other changes in a system. We know from NewSpace[7] history that at least one pioneer made a tremendously pertinent and impactful choice. Second, these initial entrepreneurial experimentations were highly risky and uncertain but enabled a powerful positive feedback loop in cost and quality improvement, uncertainty reduction, and the positioning of NASA to support the emerging ecosystem. All these *self-reinforcing mechanisms* led to the rise of private

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[6] The concept of disruption in economics and management captures the process through which outsiders enter an existing sector to redefine established business models and activities and the underlying social values and economic principles, leading to major changes in the way the essential business function is operated.

[7] NewSpace is a term that describes some new dynamics and trends in the space sector. We do not attempt in this paper to define it, as it has been discussed at length in the literature. See for example Davidian (2020) which provides a list of newspaper and journal articles defining the concept.

innovators and investors. It was conducive also to more competition, which in turn boosts the diversity of actors and experimentation in the space innovation community.

Features that determine the return on innovation investment (*drivers*)	**Rationale**
Demand	
Market size	Obvious relationship between market size and innovation incentives; includes business opportunities
Willingness to pay	Measure of how consumers value an innovation; key determinant of price and thus of the ability of the innovator to capture a significant part of the value of the innovation
Buyer uncertainty	Consumers may have difficulty assessing whether an innovation is worth buying because information on quality is scarce or ambiguous. The opposite is when qualities of innovations are highly salient
Supply	
Fixed costs of creating new products/services	Two components – cost of launching a new firm; the R&D fixed costs
Ongoing costs of producing and distributing the innovative products/services	These are the costs determining the “scalability” of innovation
Technological (Nature) opportunities and constraints	“Exogeneous” technological trends (e.g. AI, Moore’s law) that provide new opportunities to advance technologies within a given sector
Institutions	
Institutions governing appropriability: patent, market structure, etc.	The quality of the policy framework allowing the innovator to capture the value of innovation. It includes the patent system, trade secrets, the implications of market power and firm size on appropriability, etc.
Institutions supporting basic research and transfer of knowledge	Research universities and national laboratories; the innovation ecosystem
Competition intensity and pervasiveness	Lack of competition within innovation engenders the traditional static losses of monopoly pricing and, above all, reduces the level of diversity and experimentation of the innovator’s community
Regulations	Multiple dimensions, which can go in both direction: support (environmental regulation, certification) or impediment (when influenced by incumbents to impede entry)

Table 1. Features that drive the return on innovation. Adapted from Jones (2022) by the authors.

These developments, by increasing the return to R&D investment, logically lead to more R&D expenditures and human capital (R&D inputs). In turn, this further boosts innovation, resulting in a rise in patenting (R&D output). We take a first stab at measuring these trends in Section 5.

This is what we will try to show in the next sections using space as a case study. Our phasing of the innovatisation process is shown in Figure 2 below.

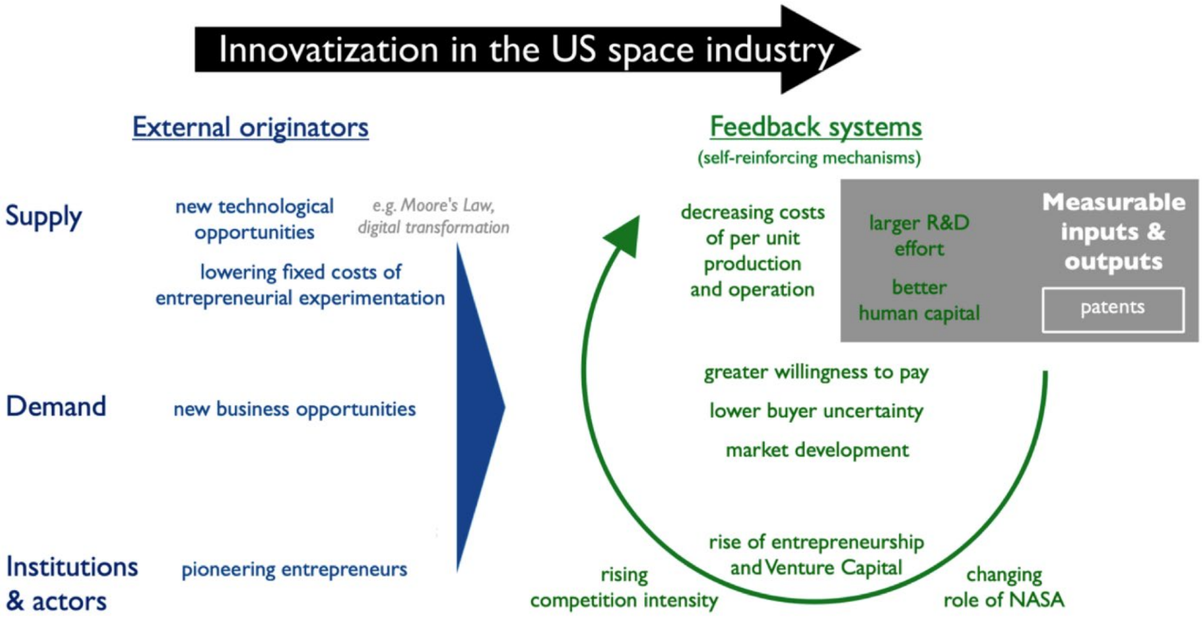

Figure 2. Synthesis of external originators, catalyst, and emerging properties underlying innovatisation of the space sector. Source: Authors.

3. An empirical analysis of the space sector

In this section, we conduct a case study of the space sector via a historical analysis informed by our framework. Looking at the evolution of the industry in the past 60 years, we can grossly distinguish three main phases: (1) Pure TA; (2) TA and economic experimentation; (3) innovatisation.[8]

1. Phase 1. Technological achievement

This first phase covers roughly NASA's first five years.[9] It spans the start of the Apollo program, with the goal to land a man on the Moon ”ahead of the Soviets“ (Kennedy et al.

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[8] The three phases roughly correspond to (1) the beginning of Apollo, (2) the end of the Apollo era up to the International Space Station era and (3) the SpaceX (NewSpace) era. Obviously, the timing is somewhat vague, so we discuss *phases* rather than *historical periods*.

[9] Admittedly, space-related activities existed before NASA's creation, but most were essentially related to military ballistic missile programs (Bromberg 2000). We consider the creation of NASA a key milestone towards the emergence of a space industry *per se*.

1962, Launius 1994).10 It is characterized by a logic of technological achievement, i.e. a sector insulated from the traditional rules of the economy and market forces driving innovation; the sector exhibits a general inattention to costs and prioritizes technological performance, to accomplish ambitious missions, motivated by prestige and national security. In other words, most of the features determining innovation returns (see Table 1) are ignored. In the next subsections, we discuss the institutions that protect technological development from the constraints of market mechanisms: the sector's market structure and NASA contracts.

Indeed, to accomplish its goal, the US government relied on mission-oriented public agencies (e.g., NASA and the DoD) to coordinate the sector by acquiring space-related R&D products and services, mainly from a few industrial partners (Mazzucato 2021, Mowery 2012). Illustrating this, Figure 3 shows that over 1963–1971, procurements from industry – many of which were R&D contracts – represented between 70% and 80% of the NASA total. Universities accounted for about 2–4%, while other agencies (e.g., DoD) and the NASA-managed Jet Propulsion Laboratory accounted for the rest.

The acquisition processes involving the industry are central. There is, thus, a need for specific institutions for coordination and incentives since market rules do not really apply in a TA logic.

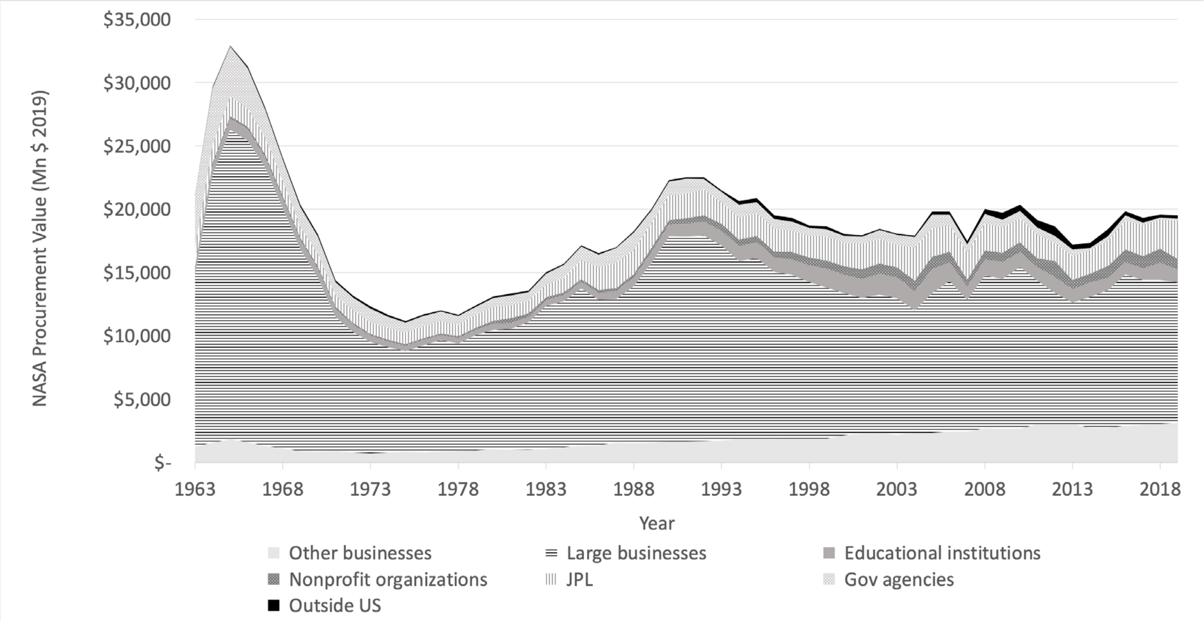

Figure 3. NASA awards by contractor type, 1963–2019. Amounts are measured in real terms (base: 2019 $). Source: NASA Procurement Report (2019).

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[10] In Apollo's case, while the prestige objective was not explicitly mentioned in public – preferring justifications like science – it was clearly referenced internally between the White House and NASA (e.g., Webb and McNamara 1961), or between Khrushchev and Kennedy (US Department of State 1961). In our companion paper (Chavy-Macdonald, Cornet, and Foray 2023), we show that preference for prestige and national security rather than costs is also visible in architectural engineering and program decisions.

1. Analysis of the market structure of the space sector during Apollo

Let us consider a market with only one buyer, one with specific technological supply requirements needed “at any cost,” facing few suppliers. The buyer assigns each supplier a specific development task without setting a price in advance. This structure – a monopsony facing an oligopoly – characterizes the Apollo market. Here, the single buyer is NASA and the reasons there are few supplier firms are twofold (Levine 1982). First, few are able to compete for major R&D contracts because of the large costs to enter and the highly specialized technical and managerial capabilities needed. Second, if a company already supplies a recurring service or item like launch vehicle stages, it is usually more expensive to seek alternate sources.

Thus, the Apollo market is structured very differently from the standard one. In a standard competitive structure with many consumers and suppliers, each supplier enters the market with a version of the technology or product at a price set by the marginal production cost. Prices reflect quality but also operational efficiency; consumers value each offer by signaling their preferences via their willingness to pay. Therefore, suppliers discover consumer preferences (e.g., quality and prices) and will try to innovate to meet them and cut costs. This process of economic discovery is undertaken by many suppliers facing many buyers, and is instrumental in informing and “disciplining” market participants on the best price–quality combinations.

Competition among sellers is thus a key mechanism that boosts economic discovery and innovation. Such competition reveals information on each supplier’s private opportunity cost for production and therefore the supplier’s technical efficiency (Adams and Adams 1972).

Economic discovery does not happen in the monopsony-oligopoly market because in such a market, only one consumer preference is made explicit, and no cost discovery occurs because the lack of competition prevents assessing each supplier’s technical efficiency. Despite its monopsony power, and even if it employs experts to check supplier offers, the buyer cannot ensure it is buying rationally; as a result of this opacity, suppliers do not focus on cost-minimizing strategies. Adams and Adams (1972), analyzing the implications of monopsony-oligopoly in the military market, argued that in such cases, the market no longer provides a benchmark for cost-performance and the buyer cannot know if it is procuring at least cost. Additionally, the large barriers to entry (e.g., large investments and specialized human capital) lead, along with the resulting stable oligopoly and low competitive pressure, to reduced incentives for firms to invest in risky innovation themselves (Szajnfarber, Richards, and Weigel 2008).

Data seems to point towards low competition during Apollo: Figure 4 shows that non-competitive awards during the Apollo era represented between 30% and 50% of the value of commercial procurements; the proportion that was *effectively* uncompetitive was likely higher. Indeed, Levine (1982) reported contemporary criticism by an MIT

Professor that "many large R&D contracts were in effect preselected and that the weightings given to proposals only amounted to '*after-the-fact* representations of general agreements... justifications for decisions, rather than causes.'" Finally, Levine noted that the space business had rather low profit margins – about 7% – making it an expensive business to stay in when faced with systematic cost overruns and technical difficulties.11 For this reason, Grumman, a key NASA contractor, withdrew from space systems after the Orbital Astronomical Observatory and Lunar Module, projects plagued by overruns and technical difficulties (Levine 1982).

Thus, the specific monopsony-oligopoly combination seems to characterize the (non-)economic logic of technological achievements, whereby both buyers and suppliers are insulated from economic experimentation and discovery. This is also reflected in the supplier contracts NASA used.

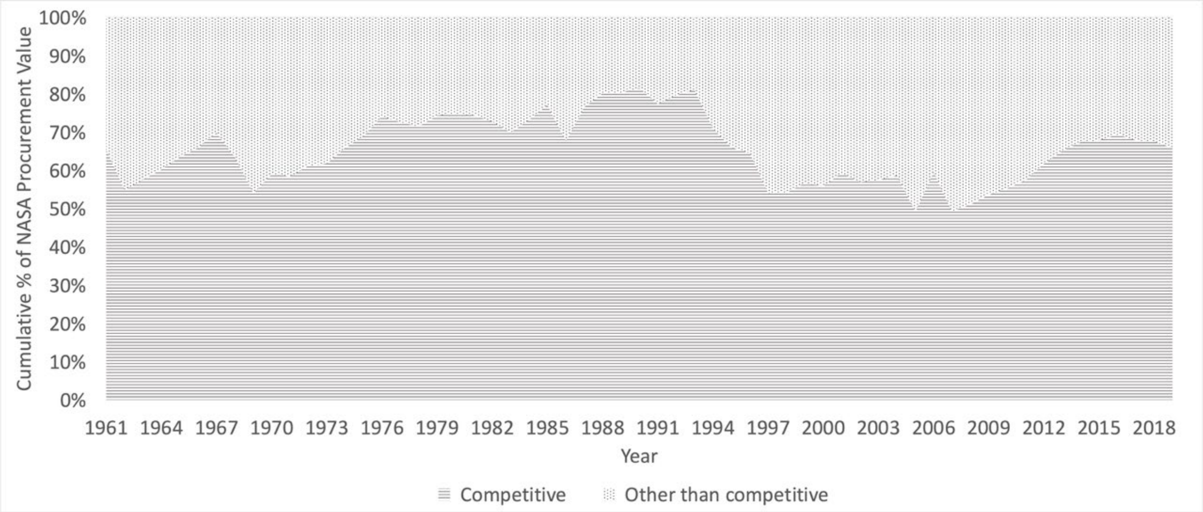

Figure 4. Competitively sourced NASA awards to firms, 1963–2019. Includes one-bid awards. *Competitive* procurements were offers selected from among more than one bidder; *Other than competitive* procurements are offers selected from either a sole responding bidder, or as a follow-on project. Source: NASA Procurement Report (2019).

2. NASA contracts

NASA contracts and their incentives, which by design embedded an inattention to costs, seemingly contributed deeply to this low-competition environment.

The contracting process for the Apollo hardware was determined – and complicated – by the nature of space products. These involve substantial R&D, high technological complexity, tight schedules, demanding reliability requirements, and very little follow-on production (Levine 1982). On Apollo, most key specifications could not be

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[11] Cost-plus fixed-fee contracts were authorized by Congress early in World War II, but profits were limited to 7% to avoid "war profiteering" (Trimble 1971). However, it seems unlikely that capping profits caps prices.

determined in advance, complicating cost estimation, and thereby pricing of NASA contracts.

Development and manufacturing contracts were negotiated procurements, meaning that NASA discussed the product characteristics with contractors, providing guidelines and specific requirements, establishing a program plan, etc. They were monitored under the Federal Acquisition Regulation (FAR) and mostly involved cost-plus-fixed-fee contracts (CPFF; Seamans 2005). Under these contracts, NASA covered companies' incurred costs – including any extras due to specification changes, cost slips, technical difficulties, and so forth – plus a fixed fee as profit. Because they can accommodate unexpected factors, such contracts are particularly useful when one cannot establish precise objectives for the work or predict costs or the required effort. Additionally, they may have been necessary to induce market entry; firms may not have been willing to bear the financial risk of investing massively in production facilities that might be abandoned after a few missions (Levine 1982).

These contracts were coveted by industry because they were worth hundreds of millions of dollars and meant guaranteed work for nearly a decade. However, they were also economically inefficient: with profits untied to performance, companies were rewarded for underbidding to get the contracts, running over cost estimates and administrative inefficiency. The contracts thus required direct NASA oversight, adding further expense.

3. Early Apollo: a TA?

The monopsony-oligopoly market structure and the CPFF contracts used by NASA during early Apollo characterize a program exempt from economic constraints and (being state-run, with objectives of prestige and national security) protected from the economy. While this mode of organization has driven notable technological progress, one cannot characterize it as innovation in our sense: it prioritizes technical performance, encouraging inattention to costs. It does not prioritize discovering what works economically. Apollo also cannot be considered mainly scientific, like CERN for example. Indeed, while science is an objective named by Apollo advocates – and it would be absurd to deny Apollo's real scientific outcomes – it remained a secondary objective, often sacrificed.12 This makes the opportunity cost of such research enormous, disproportionate compared to ”normal“ science (cf. our companion paper, Chavy-Macdonald, Cornet, and Foray 2023). As mainstream economists Bloom et al. (2019) claimed: ”Surely, the resources used in putting a man on the moon could have been directed more efficiently if the aim was solely to generate more science and innovation.”

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12 E.g. a single scientist-astronaut, Harrison Schmitt, flew on Apollo (vs. 23 pilot-astronauts in the Lunar vicinity, 11 on the surface), belatedly put on the last mission under pressure from scientists.

Then what *was* Apollo's underlying rationale? A program targeting a technological frontier at any cost, neglecting economic incentives, and not mainly science? The primary goal was neither economic nor scientific, but prestige and winning the Cold War (Webb and McNamara 1961, MacDonald 2018).13

Director David Bell's Bureau of the Budget commission already in 1962 presented to the president a report on Apollo showing that economic principles and market forces, which generally discipline and inform markets, were absent. The report reviewed current acquisition practices and explored the circumstances under which contractor operations would be an effective means to accomplish the government's goals for cost, schedule, and performance (Bell 1962). A key recommendation was to improve contract incentives, linking profits to performance (e.g., cost and schedule) to simulate market conditions. This was among the first attempts to incorporate economic considerations in technological achievements. We consider that it marks a second phase, which we now explore.

2. Phase 2: Technological achievement and economic experimentation

Contrasting with the pure technological achievement regime of Phase 1, where space was insulated from market mechanisms, Phase 2 was characterized by the introduction of economic principles into the TA regime. We investigate the use of incentive contracts following the Bell report, and the commercialization wave of the 1980s.

1. The evolution of NASA contracting policy following the Bell report

Here we analyze the evolution in contracting policy during Apollo's later stages, and its implications for innovation. We describe and assess the new incentive contract types used by NASA with suppliers.

NASA's incentive contracts

The 1962 Bell report recommended replacing CPFF (cost-plus-fixed-fee) with contracts that would align contractor incentives with NASA time, cost, and performance objectives. With CPFF, NASA bore all projects' financial and technological risks; the goal was to shift the risk burden of NASA programs via incentive provisions so that industry would also stand to lose (Levine 1982). Thus, the report advocated using fixed-price (FP), cost-plus-incentive-fee (CPIF) and cost-plus-award-fee (CPAF) contracts whenever possible.14 Fixed-price contracts have their prices fixed before work begins; they are used when the work is clear and price can be estimated. This contract type, in which

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13 Interestingly, the expression, "technological achievement" had already been used by Hecht (2001) and Nye (1994) to describe the same notion as we do in this paper, i.e. of a technological development driven by the quest for prestige.

14 We group these contracts under the general term *incentive contracts*.

contractors bear the most risk and are most incentivized to control costs, was rarely used for Apollo. With CPIF contracts, all contractor costs are reimbursed but the fee depends on predetermined time, cost, or performance targets; net profits can thus be positive or negative. With CPAF contracts, all costs are reimbursed and there is a fixed fee for acceptable performance; the contractor may also be awarded an extra fee for superior performance. After the Bell report and internal discussions begun by Administrator Webb, NASA revamped its contracting policy in 1962–1963: whenever possible, CPFFs were turned into incentive contracts (mostly CPIFs and CPAFs), which were strongly preferred for new partnerships. In 1966, NASA managed about 200 incentive contracts, up from 1 in 1961 and 6 in 1962, totaling $5.3 B (Levine 1982).15

Assessing the changes in NASA contracting policy

Incentive contracts were meant to improve contractor performance by reducing cost slips and speeding up deliveries of Apollo hardware. However, their efficiency has been debated.

On the one hand, an internal NASA task force concluded that when properly applied, incentive contracts had multiple benefits (Levine 1982). They improved deliveries on schedule and to specification, could help contain cost growth, would cost no more to administer than CPFF, needed less day-to-day contractor surveillance than CPFF, and led to better program definition. On the other hand, Levine reported, NASA personnel felt that incentives burdened them with more administration as they required more control – not less – and lengthened the procurement cycle. Additionally, they questioned the cost-reduction argument, as the increased risk sharing led contractors to ask for higher fees. By comparing firms with a large share of revenue in incentive contracts from NASA and the DoD, to similar firms that did not receive such contracts, Trimble (1971) also finds that better incentives did not improve contractors' resource management efficiency.

Similarly Roberts and Sloat (1966), studying behavioral changes following NASA's evolution towards incentive contracts, argued that while highly motivating contractors, the contracts may have created the wrong incentives, pushing firms to take shortcuts during design and production, to the detriment of larger system performance. Roberts and Sloat also noted suppliers were far more cautious about changes to the requirements as specified contractually. This meant lower flexibility for government, more need for technical negotiations, and thus limits the contracts' cost reductions. Assessing the use of schedule incentives to accelerate delivery of the Saturn V, a Government Accountability Office report yielded similar conclusions regarding their impact on cost performance (GAO 1970).

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15 The US government spent an estimated $25.8 B ($257 B in $2020 when adjusting for inflation) on Apollo over 1960–1973 (Dreier 2022); thus over 1/5th was incentive contracts.

Finally, while most of the work contracted out to industry was R&D, NASA – which bore the costs –owned the intellectual property rights (Levine 1982). This limited firms' ability to leverage new capabilities in other markets, dulling incentives somewhat.

The evidence suggests that despite efforts to simulate market conditions in a non-competitive market, incentive contracts, like CPFFs, did not promote innovation as economic discovery: instead of lowering costs and producing large social surpluses, they confirmed Apollo's TA nature. We have more evidence of this from following decades, as many reports shed light on the inefficiencies of incentive contracts in NASA programs like the International Space Station (ISS; GAO 2007) or Space Launch System (SLS; GAO 2019). Yet, these contracts led to some of the greatest technological achievements in history.

2. Technological achievement and commercialization

While the TA logic insured companies against the financial and technical risks of the huge space investments, it also limited their ability to commercialize their products or develop space markets. Also, once the Space Race was won, the sector's large state expenses became ever-less publicly acceptable. Thus, NASA objectives and processes started evolving after Apollo to encourage a larger role for the private sector in space operations – especially in Low Earth Orbit (LEO) – and to promote commercial space technology (Rumerman 1999). Following policy changes, this period saw the rise of space telecommunications, the truly commercial part of the sector, and later GPS applications.

In 1984, the Office of Commercial Programs (OCP) was created to focus on two areas: transfer of technology and commercial use of space. The former aimed to leverage the private sector to commercialize technologies for which NASA owned the Intellectual Property (IP), but was met with limited enthusiasm from NASA researchers (Bush 1996). The latter focused on stimulating company participation in R&D programs, and on developing new markets for NASA services. The OCP's mandate included facilitating access to NASA resources and facilities and encouraging private investment independent of NASA funding (Rumerman 1999). For example, the Small Business Innovation Research (SBIR) program had specific lines of financing to support breakthrough technologies aligned to agency objectives with commercial potential. However, the 1986 Challenger disaster triggered a dramatic policy shift, limiting Space Shuttle use for private payloads and more generally commercial activity in LEO (Mazzucato and Robinson 2018). The sector thus remained highly centralized around NASA, and dominated by larger firms.

Though NASA and the DoD tried pulling innovation from smaller firms, the Challenger disaster shattered nascent enthusiasm for LEO commercialization. Additionally, the aerospace and defense industry consolidation of the 1990s, following slashed defense spending, cemented incumbents' position. By the 2000s, over 50 mergers and acquisitions had effectively remodeled the sector into an oligopoly of the "Big 5" aerospace and defense players: Boeing, Lockheed Martin, Raytheon, Northrop Grumman and General Dynamics (Cornell 2011). Cornell emphasized three consequences: (1) less "discretionary" R&D expenditures, not linked to a specific project but more likely to generate unexpected discoveries of broad interest; (2) a stronger oligopoly making it harder for smaller, more agile competitors (thus fostering an ecosystem where technological innovation was not optimized); (3) an overreliance on a few large firms with expensive bureaucracies and multiple product focuses.

Thus, the commercialization focus did not interrupt the technological achievement logic of Apollo. Indeed, the main features determining innovation returns (see Table 1) are unchanged – except for the satcom market and later GPS, where early signs of innovatisation are visible. The focus on commercialization simply reflected concern about large public space expenditures and their returns, showing a willingness to experiment with new economic models but remaining in the TA logic. An important retort is that TAs create knowledge spillovers and have a large weight in the economy (Bloom et al. 2019). Yet spillovers are rather an *ex-post* legitimation of a TA program produced at a very high opportunity cost, rather than an *ex-ante* mechanism to generate economic value.

3. Phase 3: Innovatisation

The third phase, starting at the turn of the XXIst century with the emergence of NewSpace, is characterized by an *innovatisation* of the space sector. Innovatisation describes a sectoral transition from a logic of technological achievement to one of innovation. The latter describes a sector where interactions between economic agents are ruled by market mechanisms, and where innovation, the discovery process of whether new products or services work economically, is the main operating mode for technological progress.

To understand the arrival of economic discovery into space, we use the framework of Section 3. We provide qualitative assessments and quantitative measures showing how the determinants to the return on R&D investments have evolved, helping explain the start of the innovatisation process.

1. External originators

The space sector's transformation is plausibly triggered by initial changes coming from outside. We describe them below.

Supply – New technological opportunities

The sector is characterized by new tech opportunities, which can be seen at two levels: as *enablers – thanks in particular to Moore's law - and as attractors.*

First, Moore's law, which enabled significant gains in productivity growth in many sectors of the economy via the IT revolution (Thompson et al. 2022), also has likely had a strong impact on space. Satellites, which are a minimum of 60-80% electronics and software by cost (see standard cost models e.g., Wertz et al. 2011, Ch. 11), were heavily impacted (Sweeting 2018). For example, advances in the past two decades brought a 1000× decrease in energy required per compute operation (and far smaller satellite) (Butash et al. 2021). Recently, computation-intensive big data and artificial intelligence (AI) have "spun in" to space (McKinsey & WEF 2022; see also Appendix C). This likely pushed the use of AI on Earth Observation (EO) satellites, enabling data consumption and using value-added applications directly in space vs. on the ground, slashing downlink bandwidth needs and EO costs.

Secondly, technological opportunities attract investments; Popp et al. (2020) show that venture capital puts a premium on energy firms that include high-tech innovations. Branstetter et al. (2019) show similar patterns in automotive manufacturing and parts, aerospace and defense, medical devices, and pharmaceuticals: across 229 publicly listed companies in those 4 industries, they found that firms using more software generate more patents per R&D dollar, and their R&D is better valued.

Supply – Entrepreneurial experimentation and decreasing fixed costs of creating new products and services

A likely immediate and obvious effect of new tech opportunities and exogenous improvements in electronics is a greatly decreased cost of *creating new space products and services.*16 These costs have two parts: the industry-agnostic costs of creating business processes; and the sector-specific costs of R&D, technological experimentation and product development.

The falling costs associated with the creation of business and development processes is a broad phenomenon characterizing many sectors, particularly those most using the internet. For example, Nanda and Rhodes-Kropf (2016) show that recent technological changes like open-source software and cloud computing have significantly lowered the cost of launching a business. Similarly, Varian (2019) explains how outsourcing and standardization of business processes (e.g., cloud accounting) help democratize entry by enabling start-ups to focus on core competencies, and buy other services as they scale.

But the cost of technological experimentation can also be sector specific. In space, such costs are slashed by the rise of smaller satellites and cheaper launches. They are also likely lowered by ever-more software that (a) accelerates R&D cycles; (b) increasingly replaces hardware as a proportion of space artefacts' value, cutting upgrade and reuse

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16 Note that experimentation and production/operations costs are often difficult to disentangle in space.

costs; and (c) forms new (cheaper-to-develop) products and services. The latter feature growing downstream segments that market satellite data.

Table 2 shows some of the probable impact of electronics miniaturization on satellite cost; it shows typical power and cost ranges for satellite mass categories. Fitting a given capability in smaller mass and power budgets allows shifting to a smaller, and thus lower-cost satellite (Table 2). Appendix C gives examples of specific components that have greatly improved, and the impact on key satellite functionality. These were often imported from other industries: "the hallmark of the modern small satellite is the adoption of up-to-date consumer technologies" (Sweeting 2018) – like smartphones.

Rough ranges	**Mass (kg)**	**Power (W)**	**Cost (M$)**
Small/large satellite	500–8000+	500–10 k	100–500
Minisatellite	100–500	30–500	5–150
Microsatellite	10–100	< 80	1–40
Nanosatellite *(cube)*	1–10	< 20	0.05–10

Table 2. Miniaturization: Small satellite mass class nomenclature, with associated rough power and cost ranges. Lower mass & power components (see Appendix C) allow shifting to smaller satellites, at far lower cost. 'CubeSats' are usually nanosats. Ranges are rough author syntheses; mass ranges are mostly standard (e.g., Sweeting 2018), power and cost use Saing (2020), Bearden (2000).

Figure 5 charts the decreasing costs of entrepreneurial experimentation, estimated by the minimal costs of building and deploying commercial satellites. Thus, we see costs to experiment on a new venture: building one satellite (dark points) to test technical feasibility, or a full constellation to test the market (circles). In lighter tone, we also see commercial R&D satellites, i.e. earlier technical experimentation, often far cheaper but distantly linked to revenue. Overall, Figure 5 suggests dramatically dropping experimentation costs of all kinds (100× or more), for both telecom and Earth observation commercial satellites, driven by the small-satellite revolution (Sweeting 2018).

Key events of the (small) satellite sector are shown on Figure 5's x-axis (see Appendix A for details). Two deserve special mention: the creation of the 'P-POD' standard launch interface (CubeSat dispenser), which drove an explosion in nanosatellites (Sweeting 2018): "the true enabling technology for this class of mission" (Swartwout 2013); and the 2007 iPhone launch, which arguably drove the electronics components miniaturization wave that also then enabled small satellites (see also Appendix C).

Figure 5 indicates finally that minimum experimentation cost for commercial-grade satellites is likely now in the few hundred thousand range, or a few million/tens of million for a commercial constellation. Historically, hundreds of millions of dollars were needed for large commercial satellites. Academic CubeSats can be flown for US $50'000–300'000. There has also been an increase to 10+ small satellite launch opportunities per year, and this led to a design-build-test-fly cycle of ~1 year, "which spurred rapid development of key spacecraft technologies, such as imaging systems and accurate three-axis attitude control" (de Carvalho et al. 2020).

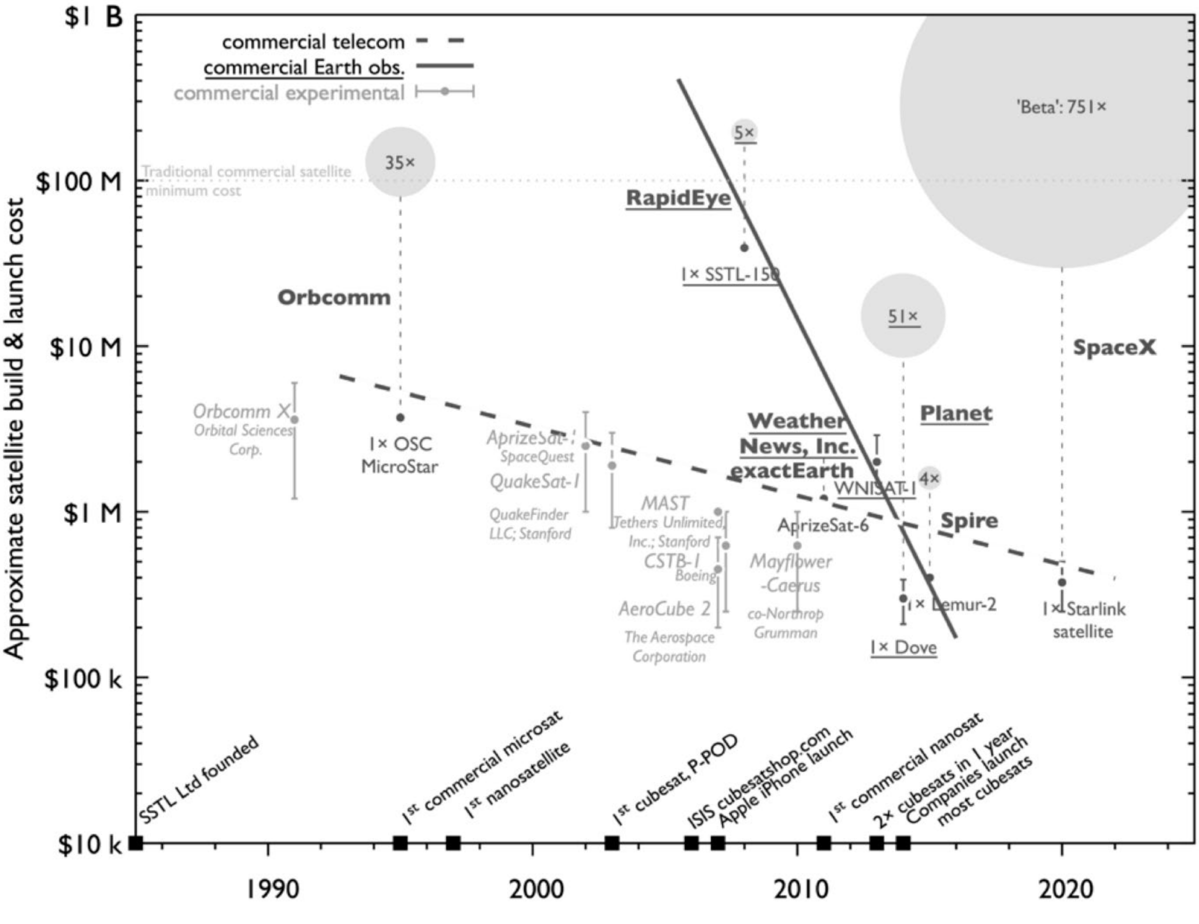

Figure 5. Experimentation costs: minimum costs to build commercial satellites. Revenue-generating telecom and Earth observation are shown separately (in dark); experimental precursors in lighter color. These estimate minimum costs of experimentation: prototyping (light), technical (dark dots), and economic. Most small commercial satellites operate in constellations, shown as numbered circles above – the minimum cost to test economic viability. Key events are shown on the x-axis. Error bars show uncertainty; Source: Authors' own computations; data in Appendix A.

Demand – Market size and the emergence of business opportunities

The promise of a large market is a key driver for entrepreneurs seeking commercial opportunities (Jones 2022), and can be seen in the space sector, where nascent commercial development culture goes hand-in-hand with the promise of untapped markets and opportunities. For example, a rising tide of connectivity demand accompanying the IT revolution helped trigger many investments in telecom, including satellite telecom. Indeed, international internet bandwidth went from < 1 Tbit/s in 2001 to 185 Tbit/s in early 2016 (ITU 2016, 2011), and all infrastructure had to scale accordingly. Similarly, the success of GPS applications in the 90s has underscored demand for satellite systems. Finally, Gaetani and Whalley (2026) argue that the 1990s feature an increase in space patenting activities, “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.”

Institutions & actors – Pioneering entrepreneurs

A key initial driver to trigger a virtuous cycle of innovatisation is intuitively pioneering entrepreneurs. Indeed well-resourced, experienced, determined entrepreneurs are a scarce resource. Many have been active in space in recent decades; some decisively so. Figure 6 shows a steady stream of entrepreneurs trying the space business since the 1980s, and usually failing (notably Gary Hudson, Walt Anderson, John Gibson). Focusing on space transportation, launch, and tourism, there were 53 “substantial” entrepreneurial ventures from 1980-2010, a list compiled by cross-listing several others – see Appendix A. These 53 represent virtually all US companies in this segment, founded in that period, with at least $10M raised or revenue. Here, we call “well-resourced” those firms with access to over $100M (2010 $); there were 15 in these 31 years. Yet, why did some succeed whilst others failed? Insufficient resources were likely a key factor, with 10 of the 15 well-resourced attempts enjoying at least partial success, vs. 14 out of the 38 poorer. Overall, the success rate is just under half.

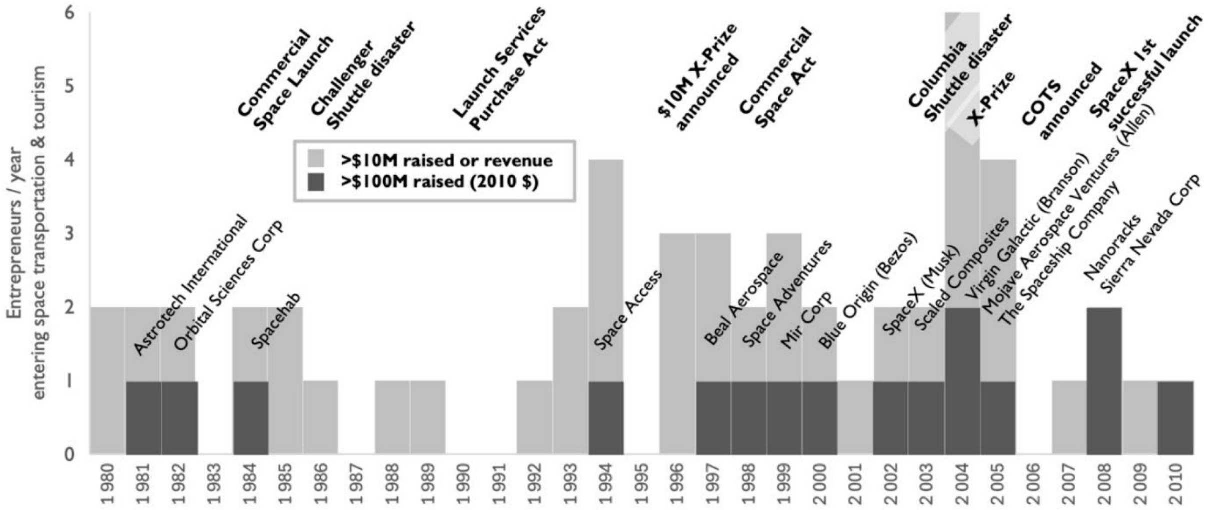

Figure 6. Pioneer US entrepreneurs entering space transportation & tourism, "major" ventures only. There is a fairly constant pace of entrepreneurs trying a space business since 1980, except for the post-Challenger disaster years, and an increase in the late 90s and early 2000s. In addition to improving tech conditions (especially for electronics and software) it is noteworthy that Peter Diamandis' $10M Ansari X-Prize, announced in 1996 and awarded in 2004 to Mojave Aerospace Ventures, generated significant attention for this business. The X-Prize and Musk/SpaceX are often credited with signaling that innovation in this segment is feasible (e.g., Culver et al., 2007). Methodology in Appendix A.

SpaceX is the runaway success story of these. One of its outstanding characteristics is its 'outsider' approach (e.g. Berger 2021): (i) avoiding traditional aerospace suppliers (its motivation for being vertically integrated); (ii) avoiding hiring many experienced industry staff except a few key VPs, but rather molding (top) new graduates; (iii) leadership coming as much from automotive or IT as aerospace;17 (iv) introducing IT practices like "fail-fast" development, more transparent pricing, and elite engineering talent-hunting. SpaceX, with its disruptive approach, eventually produced extraordinary results, documented below.

Yet why did Musk come to enter space, why focus on launchers, and how did he disrupt them? Musk came as a user/client, initially wanting to buy a launch for his more modest Mars Oasis project, but finding a bottleneck. His decision to focus on this segment has been a key event in the history of space innovatisation. As Baumol argues (1990), a country or industry does not just need to have a critical mass of ''entrepreneurs'' (there is always a certain number) – the point is to have entrepreneurs allocating resources in the relevant areas – areas where innovation strongly boosts productivity and performance. For Baumol, *productive* entrepreneurs are needed (*versus* non-productive and destructive); this is precisely what Musk did. Finally, the outsider approach naturally came from his diagnosis that the problem was not only the current launchers, but the providers, governments, and their interrelations (Musk, circa 2002: "I began to understand why things were so expensive.

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17 Of 14 recent VPs and executives, only 5 come primarily from aerospace, with 5 from automotive & manufacturing (Beltran 2023).

I looked at the horses NASA had [...] like Boeing and Lockheed Martin [...] Those horses are lame.", Berger 2021).

With its disruptive approach to rocket development, SpaceX has therefore significantly challenged existing industry practices, creating a new era in space launch: BryceTech (2016) reports from interviews with major investors that "SpaceX has really opened the doors. Space used to be the domain of NASA and large military contractors, and SpaceX showed that it is possible to build a purely commercial enterprise doing launches. They have out-executed some of the more traditional folks. That gave permission to a whole bunch of other folks to think about the problem."18

But SpaceX's shattering of industry patterns was also a result of legal action. The pre-Musk "rules of the game" did not permit new entrants to meaningfully compete for government launch business (Beal 2000), although successive Acts in 1984, 1990, and 1998 nudged towards "opening" launchers, and changing entrepreneurial conditions. Through lawsuits, technical demonstrations, and lobbying Musk changed things abruptly. Indeed, other entrepreneurial attempts in launchers that did not change "the rules" (towards competition, away from government capture and subsidy) proved unproductive. Andy Beal, who invested twice as much as Musk, said upon failure in 2000, "There will never be a private launch industry as long as NASA and the U.S. government choose and subsidize launch systems" (referring to the soon-to-be ULA monopoly). By contrast insiders like Boeing and Lockheed Martin were focused on fierce competition via legal action and espionage to win more share of the government market, having been ousted from the international market due to their uncompetitive cost (Berger et al. 2021). Essentially, they sought rents on their close relationship with government.

2. Feedback systems: from pioneering entrepreneurs to positive feedbacks

The first entrepreneurial experimentations seemingly generated a first wave of innovation with significant cost decreases and opening of new market opportunities. This plausibly increased returns to R&D investments, as well as boosting demand and reducing uncertainty, thereby starting a virtuous feedback cycle of R&D investments and innovation in space (see Figure 2). Below, we provide qualitative and quantitative indicators supporting this narrative.

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18 It is also important to note that SpaceX also received significant support – expertise, financing, access to infrastructures – from the government, especially NASA. However, as we show in Section 4.c.ii, the help provided by NASA was of a very different nature compared to previous programs. The agency used a co-financing mechanism – not traditional cost-plus contracts, where all costs are refunded – and forcing companies to have "skin in the game" by investing their own capital.

The space sector has also recently seen a massive decrease in recurring costs of production and operation – e.g., the decrease induced by scaling up innovation. This decrease has two likely components: the classical mechanisms of improving production and operation costs – including technology standardization, large batch numbers, many quasi-identical experiments, and learning by doing; and the increasing share of software in the total value of space systems. Software and digital technologies are well-known factors for low-cost scalability. We detail these two components below.

Supply – Decreasing costs of producing, operating and scaling

Regarding the first component, by producing more (similar) products, these mechanisms can lead to technological learning and thus cost reductions. This is the classical, well-documented “learning curve" that secures business returns and economic viability long-term (e.g., Ulrich & Eppinger 2012). However, it should never be taken for granted: e.g., with nuclear technologies, substantial cost reductions do not materialize when system designs continually change (Grubler 2010).

We suggest learning by doing and learning curves are key factors, e.g., via the shorter (one-year) development cycles of CubeSats. Similarly, with the shift to satellite constellations, larger batch numbers allow learning. Tracing precise learning curves is challenging due to confidentiality, but other examples seem apparent.

Both SpaceX’s launchers and Starlink satellites feature major iterations and learning. SpaceX went from the Falcon 1 launcher (5 launched, for 180 kg to LEO) to Falcon 9 (v1.0-v1.2 Block 5), which was upgraded to have a reusable lower stage. Figure 7 shows an apparent learning curve for the Falcon 9 launches, with Falcon 1 and Heavy shown for reference, although they are not strictly comparable. SpaceX’s costs and the true capacity of the Falcon 9 vs. time are not publicly known; Figure 7 approximates these (SpaceX 2023).

In addition to cost decreases via learning, and consistent with Cornell (2011), H. Jones (2018) argues that SpaceX successfully lowered costs by focusing on simplifying design and a new industrial culture. This includes (e.g.) boosting production and launch rates, also shifting production towards automation and fewer parts; a small, highly motivated, young workforce; vertical integration and in-house development; modern management with fewer layers and leaner infrastructure; and a commercial development culture. Illustrating this, NASA estimated using their standard NAFCOM cost model, that developing the Falcon 9 in-house would have cost NASA $1’383-$3’977 M, depending on the approach. The verified total SpaceX expenditure on the development was $443 M; this used a fixed-price contract (Rasky 2015; NASA 2011b). The reasons for this remarkable cost-savings are not fully established, but likely involve the "outsider approach”’ described above, and the powerful feedbacks from the proliferating trials, learning by doing, and cost improvements (see Figure 2).

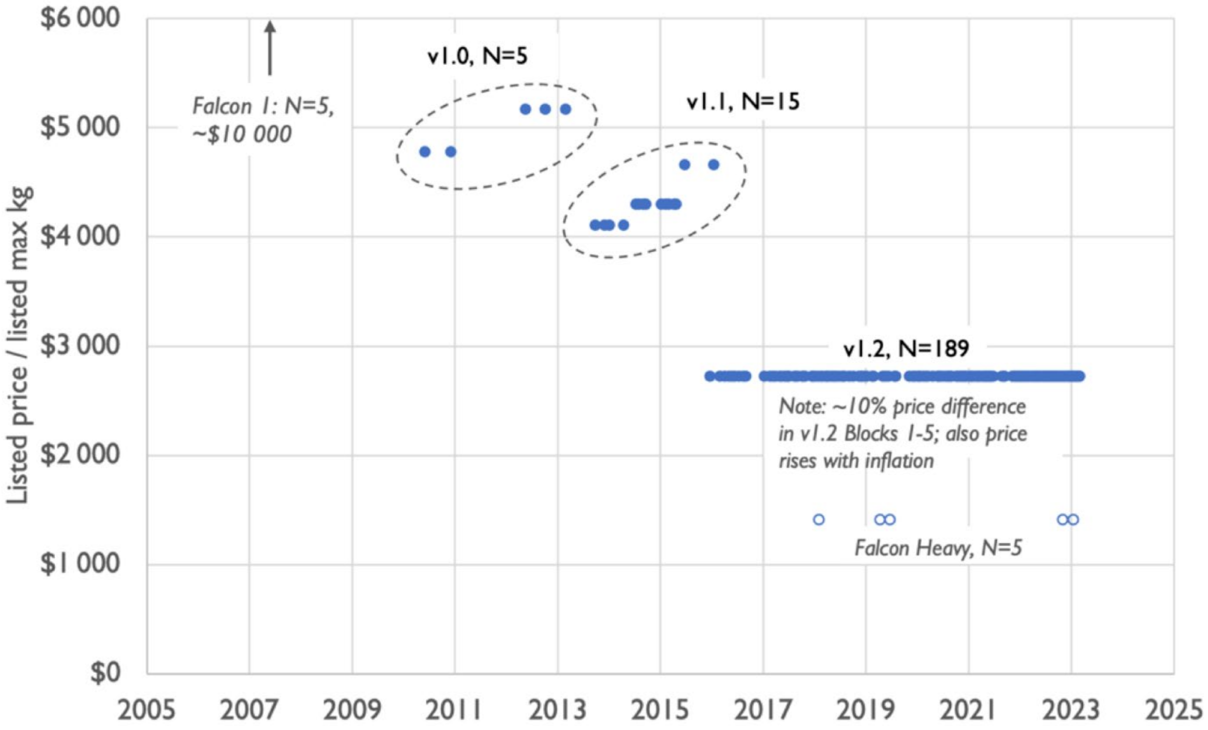

Figure 7. Falcon learning curve: SpaceX's 219 launch attempts as of March 7th, 2023, at their *listed* prices and max capacities, to a reference LEO orbit (SpaceX 2023). The 209 Falcon 9 launches dominate; learning is strongly suggested by decreasing prices vs. time. All SpaceX vehicles except Starship used the Merlin engine (which was heavily upgraded from version 1A (2006) to 1D (2013; see Chavy-Macdonald, Cornet, and Foray 2023); engines are typically ~60% of rockets' cost.) Finally, Starship launches may cost in the low millions for up to 150 tons of payload (The Economist, 2022). Source: authors' computations.

Another firm, Planet, continuously iterates its Dove satellites, with 15 builds in 6 years (a 3-to-6-month design lifecycle) over 500 launched (Harrison 2022). Its founder Will Marshall said in 2023 that they achieved a 15× improvement in performance per unit cost over the company's lifetime (Hoffmann 2024), substantially upgrading its satellites while cost-cutting. OneWeb reached the point of building two 150-kg satellites per day for its planned 648 units, aiming for $0.5 M apiece, but reportedly only attaining $1M (Henry 2020; Daehnick et al. 2020). Spire also claims continuously improved sensors and software on its 120-strong constellation (Nguyen et al. 2022). These practices enable continuous testing and learning, key to long-term cost reduction. With Falcon, the beginning of reuse (and return of material) brings invaluable, unprecedented data on component durability (Clapp 2022). By contrast in the TA regime batch numbers were low, prototypes costly, and test data scarce.

Table 3 illustrates the significant cost decrease in the launch and satellite segments: launch costs of the Falcon 9 are almost 4× lower than the prior market leader, Ariane 5 (developed under a TA regime). This is likely due to learning effects. Falcon 9's costs continue to drop, while ridesharing also brings far easier space access for tiny satellites. Similarly, according to McKinsey and WEF (2022) interviews with 100 space leaders, "technological advances in software, miniaturization, off-the-shelf components, and reusable launch vehicles have combined to reduce the cost of reaching and operating in space."[19]

Costs	**~1995**	**~2020**
Access to space *(launch, LEO)*	~$10'200 *(Ariane 5G, CSIS)*	~$2'600 /kg *(Falcon 9, CSIS)*
Satellite platforms	~$55'000/kg *(typical)*	< $7'000/kg *(OneWeb, McKinsey)*
Satellite imagery *(optical, high resolution: < 1m^2)*	>\$30/km^2 (2002) *(Fraser 2003)*	< \$15/km^2 *Low resolution:* \$1/km^2
Satellite telecom capacity *(CAPEX)*	~$1000/Mbps/month	~$10/Mbps/month *(McKinsey)*

Table 3. Comparison of the evolution of key cost indicators between around 1995 and 2020. (Sources are in the table.)

Supply – Software and scalability

The second enabler of scalability is the rising share of software content in space systems. Similarly, in the related field of aviation almost a third of the Boeing 777's development cost was likely for software (Ulrich & Eppinger 2012, Long 2008).

In satellites, successive standard cost estimation models show the ever-rising role of software. Flight software can cost 10-20% of the satellite platform in the USCM8 model (larger, older satellites), but 20-50% in SSCM (smaller, newer satellites) (Wertz et al. 2011).[20] Thus both macro-trends and decreasing satellite size push cost towards residing in software, which is more scalable.

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[19] For more details of Table 3, see Appendix C.

[20] The Unmanned Space Vehicle Cost Model (USCM) was sponsored by the US Air Force and based on 44 mostly institutional satellites from the 1970s to 1990s, in the 300 kg – 7.4 tonne range; the Small Satellite Cost Model (SSCM) is sponsored by the US DoD, NASA, and The Aerospace Corporation, and is based on 53 satellites starting from the 1990s, in the 20 – 400 kg range (mostly under 100 kg). SSCM19 is still used today, after 8 updates.

Software is not just a higher proportion of cost, but also of value: there is strong empirical evidence for the growing importance of software for successful innovation in aerospace (Branstetter et al. 2019). The share of software patents in aerospace & defense firms' portfolios has risen from 7% in 1981 to over 20% in 2005, making aerospace innovation more software-intensive than automotive or medical devices. This also agrees with consultants that emphasize the growing role of software-heavy "downstream" services, largely navigation and satellite television, worth 87% of space sector revenues in 2019, and growing at 8.5% (vs. 2.5% in manufacturing, 2.8% in launch; Tanghe 2023).

Demand – Market development

New markets are emerging, resulting in NewSpace companies covering many space industry segments (Weinzierl 2018): access to space (e.g., SpaceX), remote sensing (e.g., Planet), satellite telecom (e.g., OneWeb), space data and analytics (e.g., Orbital Insight), and lunar mining (e.g., ispace). Space tourism (e.g., Axiom), a market seemingly being unlocked by better, cheaper access to space, is an example new business opportunity. It is now being fiercely competed over by NewSpace firms like Blue Origin, SpaceX, and Virgin Galactic, and may reach about $400 M in the next decade (Weinzierl et al. 2022).

Generally, growth prospects seem huge. A study by Crane et al. (2020) compares recent projections of space economy growth in 2017–2018 by UBS, Morgan Stanley, the US Chamber of Commerce, Bank of America, and Goldman Sachs. These range from ~$1 trillion to over $3 trillion revenue by 2040; when transparent, they are driven by rising demand for internet services from space. At 4–10% annual growth, space may grow far faster than the rest of the economy, projected at 2.8% (US: 1.9%) over 2020–2040 (OECD, 2018). Thus, investment bankers and analysts speak of a "space of opportunity."

Demand – Greater willingness to pay

Buyers' willingness to pay for innovation shapes innovators' addressable market (Table 1, Jones 2022), and is another potentially key driver in space in recent years. We present three examples.

First, Starlink – SpaceX's satellite constellation, providing high-speed internet access worldwide – is revealing. Despite a relatively high price ($90/month and initial hardware for $599)21 many consumers have proven willing to pay for reliable internet available everywhere. Indeed in March 2023, SpaceX announced on Twitter that it had

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21 Pricing information taken from SpaceX's website as of July 2023, for a consumer living in New York, USA.

reached 1.5 M subscribers. Competitors are also investing massively in broadband constellations, with Amazon's Leo (3'236 satellites planned) and OneWeb (648).22

Second, space tourism firms have been able to collect deposits, despite lacking regular operations. Recently, companies like Virgin Galactic or Blue Origin have aimed to broaden this market from professional astronauts and multi-millionaires to anyone able to pay $450'000 for a suborbital hop. As of Dec. 31st 2025, Virgin had $79 M in deposits on >$220 M in total tickets sold, for 700 tourists.[22]

Third, the case of Planet suggests that a company with an innovative business model can develop markets and "discover" willingness to pay at the lower end of the market. The firm was created in 2010 to provide Earth Observation imagery more frequently, at lower resolution, and more affordably. This was possible via a constellation of mass-produced nanosatellites, compared to the larger satellites of traditional providers – e.g., Maxar/WorldView – producing high-resolution, expensive imagery (Technology Strategy Board 2014, slide 5). With Planet's first "public" customers in 2014, it managed to sell lower-resolution imagery that was more frequently updated, and thus demonstrated a path to commercially viability for nanosatellites with smaller optical systems. In 2026 it had over 1000 customers, with 2/3 institutional, for $308 M of revenue and positive EBITDA (Planet Labs 2026).

Demand – Lower buyer's uncertainty

The decreasing uncertainty of buyers about the benefits of innovative products and services offered by new players can also play a major role, as it accelerates new technology adoption (Jones 2022). This is certainly observable in space, i.e. the boom of commercial launch vehicles and nanosatellites.

Rocket development has long been the business of governments and their contractors. Building a new, reliable rocket outside the traditional NASA procurement model was thought impossible, especially since the failed attempts of the 80s and 90s (Berger 2021). Thus, SpaceX had difficulty finding lead customers for its commercially-developed Falcon 1 launcher, and after 3 failures, its 4th launch went without any payload. Its initial launches were for DARPA, then NASA; the Falcon 1 only had 1 commercially-contracted launch, of 5 total (Wikipedia 2024, Falcon 1). The Falcon 9, SpaceX's next rocket, also had only 2 commercial orders by the time of the NASA COTS award in August 2006 (SpaceX 2023). Orders began arriving after the NASA CRS contract in Dec. 2008 - for 12 launches - and especially after the 1st successful Falcon 9 launch in June 2010 (again without payload). The first commercial mission with a private customer flew only in Sept. 2013 – by then the order book had 41 launches, and

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22 According to Amazon (2026) and Eutelsat (2026) websites, and Virgin Galactic 2025 annual report.

it has only grown. During this whole period, SpaceX kept prices constant, while the "waiting time" for launch lengthened with the orders (decreasing the service's attractiveness); yet sales picked up. Thus, perceived reliability was likely an important factor, driving lower buyer uncertainty. Access to space is no longer an extraordinary event, but a reliable and routinized operation.

Although for Sweeting (2018) small satellites started being useful around the year 2000, nanosatellites and CubeSats – the smallest launched *en masse* – were still "an early curiosity with limited utility." They were seen mostly as training tools (Jayaram & Swartwout 2010), without commercial use (Carvalho 2020). As shown on Figure 5, the 1st nanosat was launched in 1997, and the first CubeSat in 2003, yet the first commercial nanosat is launched in 2011, and significant numbers only in 2013-2015 (Figure 5's colored points under $10M are mostly nanosats). Then in 2014, Planet demonstrated that a constellation of CubeSats could form an Earth Observation business. Currently, over 95 firms worldwide offer turnkey platforms and "mission services" (entire missions) of CubeSats and nanosats (Kulu 2024); AAC Clyde Space and GomSpace, two of the largest suppliers of this segment, report millions in revenue and tens of millions in backlog. Many commercial constellation firms also mainly use CubeSats (Kulu 2024): over 45 worldwide in Earth Observation, weather etc., 63 in communications, 22 in communications/transponder monitoring, and 4 in Quantum Key Distribution. These firms are likely buying CubeSats now due to the lower uncertainty on their utility.

Institutions & actors – New roles for NASA

NASA's new role accompanies and reinforces innovatisation, and its contracting philosophy has evolved towards using more innovative public-private partnerships (PPPs),23 triggering deep changes in the space ecosystem (Mazzucato and Robinson 2018). This transformation of NASA's role has three fundamental components.

First, it now acts more like an investor, supporting innovative firms with funding. For instance, NASA takes a role similar to a VC investing in start-ups, aiming to develop a competitive space industry. While initiatives like the SBIR program (which invests seed money into companies with breakthrough technologies) have existed since the 1980s and 90s, this role was expanded with the successful Commercial Orbital Transportation Services (COTS) program.

Initiated in 2005, COTS had two goals. The first was to provide a replacement for the Space Shuttle after the 2003 Columbia disaster. The second was to create a "broader, more competitive industry that could serve societal and NASA needs at a cost less than

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[23] Here we refer to NASA, but similar evolutions can be seen for the DoD, another key space actor. PPPs contrast with traditional procurements using fixed-price contracts, and use various mechanisms and degrees of involvement of each party. For a description of space PPPs and a review of the current literature, see Kim (2023).

was presently the case under traditional practices dependent on a few huge companies" (Lambright 2015). As Lambright explained, the COTS program was an innovative PPP, moving away from traditional cost-plus procurement: it aimed to develop new capabilities (here cargo delivery to LEO and the ISS), rather than hardware answering agency-specific needs. The fixed contract amount ensured companies had skin in the game – since they needed to complement it with their own funds – and the PPP setup allowed them to innovate freely with their own designs (e.g., through less oversight but milestone-dependent financing). Importantly, they retained ownership of intellectual property. The goal was to boost companies' incentives to innovate by improving appropriability of research: with IP rights, they could capture more of the innovation's value through commercialization and acquiring customers beyond NASA.

In the COTS program, companies defined their own business models and milestones, as they would with VCs. NASA would provide financing in stages as milestones were reached. With COTS' success, two firms – SpaceX and Orbital – demonstrated the ability to deliver cargo to the ISS. By investing only $800 M, the agency enabled the emergence of two space transportation service providers who together invested about $1B (Lambright 2015). The COTS program was initially seen as a back-up solution, but its success and the later cancellation of the Constellation program by the Obama Administration made COTS the de facto solution for US access to space. This is why the Commercial Crew Program used the same model in 2010 to develop crew transportation capabilities.

The second interesting shift in NASA's role is it becoming a customer of space services. Thus, instead of buying and operating launch vehicles like the Space Shuttle, it started buying transportation services on a competitive basis (Lambright 2015). For example, in 2008, the agency competitively procured several fixed-price flights to the ISS. The procurement, Commercial Resupply Services-1 (CRS-1), was open to all, but eventually won by SpaceX and Orbital – the same firms that were already working with NASA under COTS. SpaceX was awarded 12 trips for $1.6 B and Orbital eight trips for $1.9 B. From sole buyer of very specific technologies using cost-plus contracts, NASA became just another customer, buying relatively generic products or services at fixed prices: a radically new philosophy for the agency. Figure 8 illustrates this via the evolution of NASA procurement award type between 1993 and 2019. Fixed-price contracts totaled about 30% of NASA procurement in 2019 but less than 10% in 1993.

NASA becoming a customer potentially has spectacular implications for innovation: first, it acts as anchor customer, helping kick-off companies' commercial cases; second, it acts as a "stamp of approval" for the market, helping firms expand their customer bases. In turn, this creates a market structure that is far more favorable to innovation, as the development of interactions between a wide range of producers and customers reveals useful economic information – i.e. producer marginal cost and customer preferences. Finally, NASA also acts as a partner and facilitator, supporting companies via PPPs. This ranges from tech transfer to free or reimbursable access to world-class experts, and to facilities, like launch pads and ground stations, worth billions (MacDonald et al. 2014). For example, Nanoracks, a provider of brokerage services to use the US National Lab aboard the ISS, has a non-reimbursable SAA with NASA that gives it access to the ISS at no cost (Mazzucato and Robinson 2018). This access, which includes launch, is easily worth tens of millions of dollars. Similarly, after interviewing space ecosystem members, BryceTech (2016) emphasized NASA's key role as a technical resource. By encouraging staff entrepreneurship and participation in commercial ventures, or its former leaders in consulting or joining company boards, NASA supports expertise transfer to the wider ecosystem.

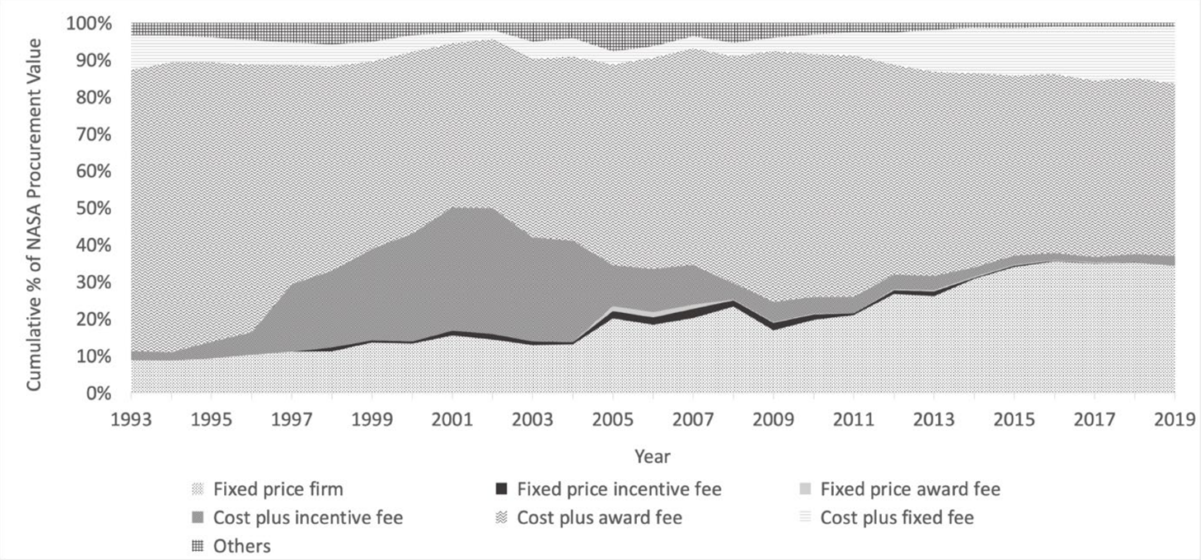

Figure 8. Share of NASA procurements awarded to firms by contract type. Source: NASA Procurement Report (2019).

The somewhat unplanned shift in NASA's role is remarkable, from cost-plus-contract project manager towards "normal" customer, then becoming an investor and partner to industry. Moreover, the agency is still seen as a development leader for large space missions involving high-risk technology development (BryceTech 2016). For Lambright (2015), the commercialization of LEO allows NASA to redirect its resources to deep space exploration.

Institutions & actors – Entrepreneurship

A second wave of entrepreneurship came at the end of the 2000s, likely building on the favorable conditions created by the pioneering entrepreneurs. These companies leveraged the interest of private capital due to the first successes of the pioneers, to develop innovative business models and address space markets with disruptive solutions (Vernile 2018). Figure 9 illustrates this rise with the number of financed start-ups by founding year.24

While the rise of entrepreneurship is a trend observed in other deep tech sectors (Dealroom et al. 2023) its possible role in space is remarkable with respect to changing culture and organization – challenging the Big 5 oligopoly. Indeed, Cornell (2011) argued that to be competitive, NewSpace firms take advantage of being everything the Big 5 are not: (i) small, specialized around a core mission or competence; (ii) young, with a workforce trained on working with (e.g.) nanosatellites and able to think outside the box; (iii) hierarchically "flat," with minimal bureaucracy; (iv) laser-focused on cost reductions; (v) endowed with an entrepreneurial profit-seeking culture and higher risk tolerance.

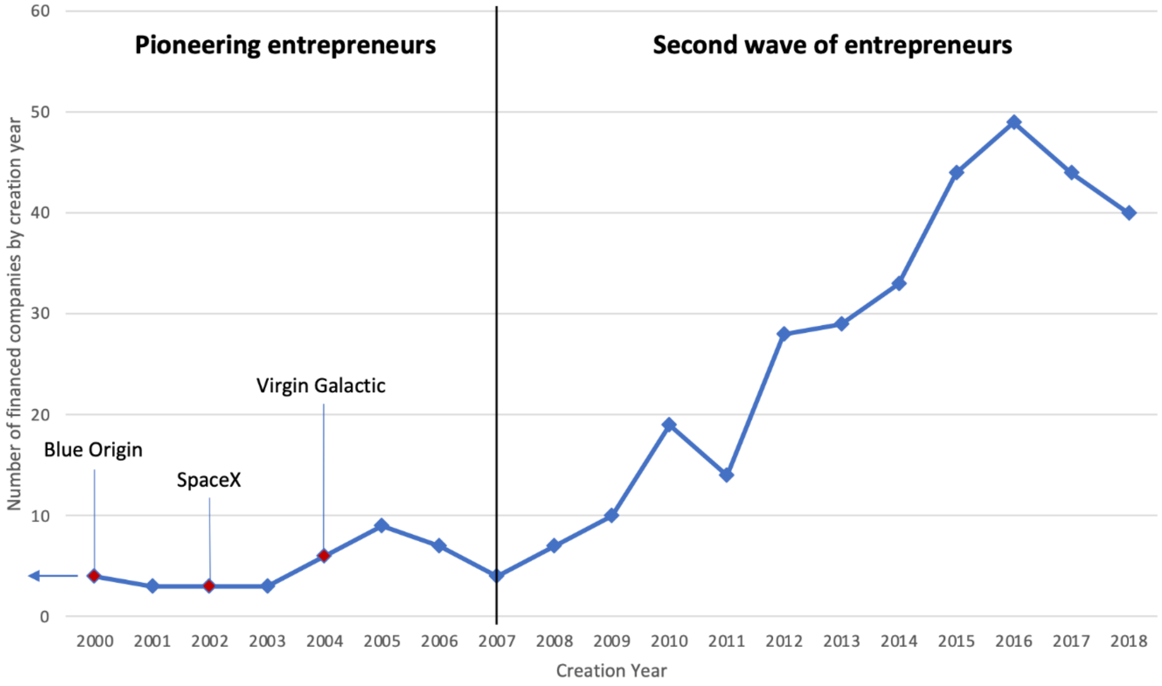

Figure 9. Global Angel- and VC-backed space start-ups by founding year during 2000–2018. Source: Adapted from BryceTech (2021).

Institutions & actors – The rise of Venture Capital

Along with rising entrepreneurship, the amount of private funds poured into the industry, notably through VC, is impressive. Among the main beneficiaries are companies operating in LEO (Lerner, et al. 2016). Reports from BryceTech (2016, 2022)

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[24] Financed start-ups, as defined by BryceTech (2021), have announced at least one angel or VC investment. Thus, the number of firms in later years may be underestimated. The study's scope was global, but most firms were headquartered in the US.

indicate that globally, $9 B of VC financed space firms in 2021, up from $186 M over 2000–2005. In total, $52.5 B was invested globally in space between 2000 and 2021, mostly in the US (BryceTech 2022). This may be due to the emergence of new business models and markets and the promise of lucrative investment opportunities. The phenomenon may also be reinforced by the lower experimentation costs, allowing VCs to finance more firms or earlier experiments (see Subsection 4.c.i.). Funds are then better able to identify the companies that work best, leading to a disproportionate increase in innovation (Ewens et al. 2018).

Recent years also saw the arrival of another source of capital: special-purpose acquisition companies (SPACs). This financial engineering tool aims to facilitate start-ups' access to financial markets while offering retail investors the opportunity to gain exposure to space businesses.[25] However, the SPAC market cooled significantly in 2022 (Rob et. al. 2022), stressing the riskiness of such investments.

While rising SPAC and VC funds show a trend common to the rest of the economy (e.g., US VC investments have increased by 113% between 2019 and 2021, vs. +128% for the global space industry; BryceTech 2022), it suggests a sort of normalization of the space sector. It signals that the sector is entering a more economically viable phase, with private investors directly entering space, resulting in less dependence on government and ending its monopsony.

Private investments in space start-ups therefore reflect a potentially large increase in R&D input.

Institutions & actors – Market structure: toward competition

From the Monopsony-Oligopoly of Phases 1 and 2, the market structure of the space sector has evolved towards a more competitive state, likely pushed by the rise of entrepreneurship from pioneering entrepreneurs (see Subsection 4.c.i). This has an important potential impact on innovation, as the greater competition from start-ups may have completely disrupted the sector, bringing a new entrepreneurial culture and business models based on commercialization and innovation. This increases the level of diversity and experimentation in the system. Obviously, the evolution of the competitive landscape forces legacy companies to adapt, which we discuss here.

The apparent transformation of the competitive landscape and resulting evolution of legacy industry is well illustrated by Boeing and its development of a new capsule for human spaceflight – the *Starliner CST-100* – within the Commercial Crew Program, a funded SAA. In total, Boeing received $4.82 B for the capsule (NASA 2019). As with the

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[25] Essentially, SPACs enable firms to become publicly traded by bypassing the traditional initial public offering (IPO) process. They work as follows: a "blank-check company" has no specific purpose except as an indicator of the sector it wishes to invest in; it raises money on the stock market and then uses it to buy another firm. The bought firm thus becomes publicly traded through the blank-check company.

COTS program, the bidding process was competitive, and the financing amount fixed, subject to defining a business plan and successfully reaching predetermined milestones. This is consistent with the new NASA contracting philosophy detailed above, which uses fixed-price contracts to leverage private capital by forcing companies to co-invest, innovate, and find commercial applications beyond government. Another interesting example is the National Team, whereby legacy firms Lockheed Martin and Northrop Grumman joined a team led by NewSpace company Blue Origin to compete to develop the Human Landing System – a Moon landing demonstrator for the Artemis III mission. The contract followed the same principles as COTS and Commercial Crew.

Yet while these two examples show legacy aerospace firms trying to adapt to this new environment and philosophy, they also illustrate their difficulties and dependence on government contracts. Indeed SpaceX received only $3.14 B from NASA to develop its capsule; Boeing got $4.82 B (NASA 2019). Yet Boeing has had several schedule slips during the capsule's development, and has taken over $2 B in losses on it (Wikipedia 2026). Boeing finally flew a crewed flight in June 2024 (originally planned for 2017), but it had a severe malfunction; SpaceX achieved the milestone in 2020. Similarly, the National Team lost to SpaceX as NASA expressed concerns about its proposal, including limitations to its commercial approach (Lueders 2021).26 The agency stressed the lack of evidence on how costs would be reduced and how the technology would apply to markets beyond Artemis (Lueders 2021).

4. Measuring innovatisation

In Section 4.c, we argue that the space sector has entered the innovatisation process, by providing evidence on changes to the factors driving returns on R&D investments (see Figure 2). If the returns on R&D investments rise, innovatisation should lead to more R&D inputs and outputs. We take a first stab at measuring this below.

1. R&D input

Larger R&D expenses

Sections 4.a and b. showed that industry has always been a partner in key space R&D projects. However, during Phases 1 & 2, most R&D was funded by NASA procurements. Privately funded R&D was limited and mostly aimed at obtaining those large procurements (Guastaferro 1992). This extreme reliance on public funding puts a hard ceiling on sectoral development, especially at a time of large public debts. The innovatisation of space can potentially shatter this ceiling because it is characterized by a big boost in R&D efforts from the private sector, complementing and de-emphasizing

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[26] NASA initially intended to select two of the three proposals received, but later chose only one – SpaceX – due to budget constraints.

public funding. Such innovatisation can be visible in two emerging R&D financing sources: NewSpace firms (backed by private capital like VCs), and non-space companies.

According to McKinsey (Brukardt et al. 2021), the share of public spending in US space-related R&D, which was over 90% of the total (~$9.5 B) in 2010, dropped to about 70% (of $18 B) in 2020. The report suggests this is due to an R&D surge from US NewSpace firms which, boosted by the rise of entrepreneurship and VC (see Section 4.c.ii), invested almost $6 B in 2020, vs. less than $1 B in 2010.

The rise in space R&D spending can also come from non-space companies that want to reap the benefits of the rapid development of space technologies and their applications to other sectors. For example, Google and Microsoft (Rottner, Sage, and Ventresca 2021) acquired space start-ups and invested considerable internal resources in space-related R&D. These companies' motivations were based on the abundance of data generated, including by new technologies (e.g., nanosatellites), and on the firms' ability to build synergies between the IT and space sectors (Vernile 2018). For instance, in 2014 Google bought Skybox, a satellite imaging company that could (e.g.) help keep Google Maps up-to-date and improve internet access and disaster relief (Gail 2014); Apple considered creating its own satellite constellation to give its devices internet access anywhere in the world (Weinzierl et al. 2022). Weinzierl et al. argue that all companies should have a space strategy to boost their value proposition. They cite the pharmaceutical industry: e.g., Merck sends payloads to the ISS to study the development of crystals in drugs, and to improve drug manufacturing and storage.

Increase in human capital

Along with more R&D spending, the space industry's newfound dynamism has been accompanied by apparent growth in human capital. This can be explained by (1) a more attractive sector, and (2) evolving space tech education programs in universities.

First, the sector has likely become far more attractive to talent in recent years. A 2025 survey by the firm Universum names the top five most attractive companies for recent US engineering graduates: Lockheed Martin, SpaceX, NASA, Boeing, and Northrop Grumman.[27] While such surveys must be taken with caution, the attractiveness of aerospace is striking, with 6 of the top 10 spots. The 2009 survey yielded a top five of NASA, Lockheed Martin, Boeing, Google, and General Electric; space had three of the top ten spots.[28] SpaceX had 1st place in 2022, and 2nd place ever since. It and other NewSpace companies demonstrate cultures based on entrepreneurship, fast experimentation, and flat hierarchies (Berger 2021). These companies' cultures may,

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[27] The survey sample was over 33'000 US students; engineering was a subsample (Universum 2025).

[28] Year 1 of the survey had 60'930 responding students of all fields from 341 US universities (Universum 2009).

along with their impact, be key to explaining young graduates' regained interest. Supporting this idea, Zurbuchen (cited in Berger 2021) said:

> I recently performed an analysis of the very best students in my space engineering programs over the past decade, based on their scholarly, leadership and entrepreneurial performance at Michigan. To my amazement, I found that of my top 10 students, five work at SpaceX. No other company or lab has attracted more than two of these top students. I also noticed that SpaceX recruited only two of them directly from the university. The others were drawn to the company after some years of experience elsewhere—joining SpaceX despite lower salaries and longer work hours. Why do they leave successful jobs in big companies to join a risky space startup? A former student told me, "This is a place where I am the limiting factor, not my work environment." At SpaceX, he considers himself to be in an entrepreneurial environment in which great young people collaborate to do amazing things. He never felt like this in his previous job with an aerospace company.

This example illustrates the cultural changes brought by NewSpace firms. SpaceX attracts the best engineers – not only to the company, but also doping the sector.

The second potential explanation for a boost in sectoral human capital is that universities' roles are evolving. In earlier decades, university space activities were essentially research; e.g., MIT created the Apollo navigation and guidance systems. However, universities then expanded their role in a sector marked by a wave of retirements and technological change like tiny satellites.

Jayaram and Swartwout (2010) explained the contribution of the development of the CubeSat standard, and the creation of DoD and NASA programs supporting hands-on education, such as the AFRL University Nanosat, CanSat, and CubeSat programs. These shifts have likely contributed to (1) the multiplication of space education university programs and (2) higher quality engineers entering space. In particular, the CubeSat was created by two professors for educational needs. It was intended to be a satellite that could be developed (a) in only 2 years, (b) at very low cost, and (c) weighing very little. In the past 10 years, on average 16 US university nanosatellites and CubeSats have been launched per year (Kulu 2024). We estimate that on average about 56 students are trained per nanosatellite, over its 3-year cycle (Cornet et al. 2023, N=26 satellites). Thus, conservatively 900 students are trained each year on nanosatellites – that go to space.[29] The 900+ students/year can be compared to an average workforce of 40'000 US satellite engineers (Cornet et al. 2023);[30] ~2% of the US workforce retires every year, or about 800 engineers. As for quality, Jayaram and Swartwout (2010) relate anecdotally that an aerospace VP strongly prefers hiring graduates from these hands-on programs.

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[29] Apart from the many nanosatellites that are built but not launched, students and trainees are also utilized, albeit less, on Institute or Agency nanosatellites (not counted here). Likewise, larger university (training) satellites are not counted, nor are CanSats (of which thousands likely exist without having been launched).

[30] The 2019 Satellite Industry Association estimate of 90,000 employees in design, development and manufacturing in the satellite industry, combined with the SSPI (Space & Satellite Professionals International) (2016) estimate of 30-50% engineers working in space companies.

2. R&D outputs – Patents

Figure 10 shows US space-related patents by filing year, from 1975 to 2019. We note a gradual rise, a possible "bump" in the late 90s, and especially a sharp peak starting around 2015. The late-90s "bump" is visible especially in the *Transmission*, *Transmission of Digital Information*, and *Cosmonautics* technology categories; this might be largely attributable to the dot-com bubble, and its effect on space (the first wave of satellite constellations: Iridium, Globalstar, Orbcomm, etc.). The later peak is accounted for by *the Radio Direction-Finding and Radio Navigation* tech category – likely GPS/GNSS in smartphones, and related tech. Thus, we see the rising importance of tech categories related to space applications – GPS, telecom – vs. "pure" space (*Cosmonautics*). This is consistent with a shift towards innovation, and market applications.

Overall, Figure 10 does show an increase in US patenting in the 2010s (perhaps earlier); this is consistent with the feedback systems phase (Figure 2).

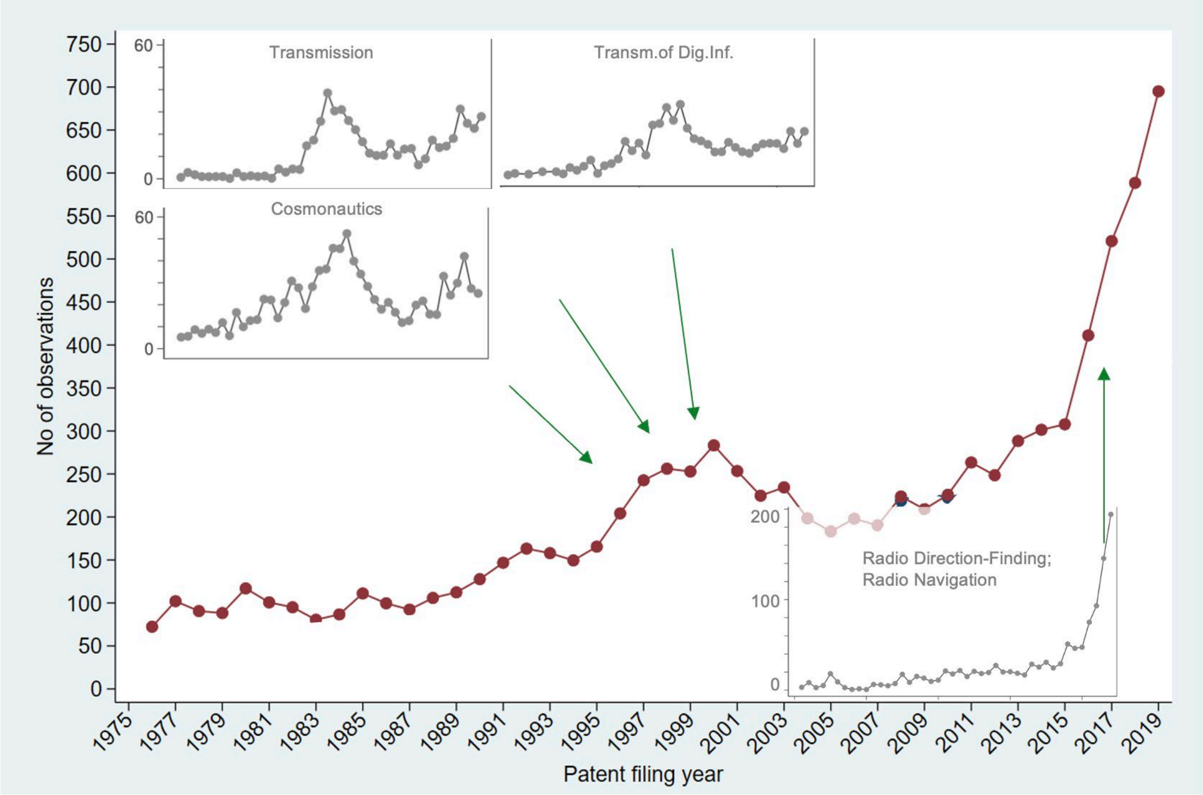

Figure 10. Space-related patents by patent filing year 1975-2019. The indicated peak is largely caused by the Radio Direction-Finding / Radio Navigation technology categories. Source: Authors, in Cornet et al. (2023), Patstat 2021; see Appendix A.

5. Policy implications

With space's new market forces come market failures. We investigate four cases: business model complementarities and coordination issues, increasing returns and the risk of concentration, negative externalities from space debris (and space governance more broadly), and start-up financing.

Coordination failures arise when several business models are interdependent and must therefore be developed simultaneously. As Weinzierl (2018) explained, such market failures occur in the space sector, where many business models make sense only when others already exist. For example, LEO in-orbit servicing strongly depends on the presence of LEO constellations. For Weinzierl, "individually, each of these technologies has only a limited payoff. […] Realized together, however, they would form a self-sustaining system with enormous profit potential." Carefully crafted public policy may help with complementarities. For example, NASA has started the NextSTEP program, providing a single framework to establish a wide range of (SAA-like) public-private partnerships to boost the commercial development of deep space exploration capabilities (e.g., for Artemis). Each potential capability is subject to a call for proposals, and PPPs are to be linked to NextSTEP's "appendix topics." For example, Appendix A is on habitation systems, and Appendix H on the Human Landing System (the Artemis lander; see Section 4.c.ii). As NASA identifies needs, new appendices (and eventually PPPs) are added.

Another market failure arises when economic activities are subject to increasing marginal returns. Then, no unregulated market outcome is also economically efficient. Under perfect competition, production and operations cannot take advantage of the increasing returns, so costs are not minimized. If a monopoly emerges, the monopolist may be able to exploit the increasing returns, but is likely to create social inefficiency via above-marginal-cost pricing strategies. The risks of this potential market failure are emphasized by SpaceX's recent successes with its semi-reusable Falcon 9 rocket and Starlink constellation. As the low-cost launcher gets very many satellites to orbit, the synergies between these two SpaceX businesses generate increasing returns, leading to a dominant position for the firm in both launch and satellite internet markets (The Economist, 2023).

A third market failure is negative externalities, arising when an economic agent's activity generates costs for other parties which it does not internalize. Space is a global commons, an open access resource, suffering potentially from the tragedy of the commons (Weinzierl 2018). Clearly the growing number of objects in orbit, whether satellite constellations or debris (defunct satellites, parts, or smaller collision fragments) is a negative externality, as orbits (especially LEO) become congested and, eventually, access to space is threatened. This issue has fostered significant interest in the literature, e.g. Macauley 2015. Weinzierl (2018) mentioned various mechanisms suggested in the economic literature, like setting a Pigouvian price on debris to try to mitigate the externality. However, he suggested that the lack of governance in space and the current legal framework (with e.g., no property rights) make their implementation very difficult.

Another form of market failure is likely to cause inefficient resource allocation in R&D and innovation, especially for small firms needing access to capital. It involves the fact that research and other innovation inputs only produce knowledge with uncertainty. As observed by Bryan and Williams (2021), in many business contexts uncertainty does not harm economic efficiency if risks can be suitably hedged. But Arrow (1962) noted that the uncertainty of research and innovation is combined with asymmetric information as the principal cannot observe the effort of the agents. This means innovation involves uncertainty that cannot be fully hedged because success depends on inventors' unobservable effort. Because of unhedged uncertainty, it may be hard for small firms to raise funding. Moreover, start-ups have no collateral for banks in return for debt funding. There is a gap between the rate of return required by an innovator investing their own funds and the higher rate needed by external investors on capital markets. Some innovations, that pass the private return hurdle and "normal" interest rate, will not be funded because the cost of external capital is too high. One aim for VC is to fix this market failure; this is now being achieved in space. But VC is limited in scope, and not for all projects. Existing complement or substitute are government subsidies for early-stage projects, such as NASA SBIR program (Lerner 1996). Other ideas explored in the literature are financial engineering (e.g., megafunds and securitization) to finance long-term risky projects (Hull, Lo, and Stein 2019).

6. Conclusion

In this paper, we aimed to analyze the spectacular transformation of the space sector using a new framework. The framework allowed us to capture a gradual shift from a regime of technological achievement to one of innovation. We call this process innovatisation.

Building on Jones (2022), we define innovatisation as a gradual shift from a situation where most of the features determining innovation returns are unfavorable, to one where conditions become conducive to innovation. We showed how this process is unfolding in the space sector.

In the first phase, space developments like Apollo were insulated from market constraints. The sector was molded by government and motivated by geopolitics, national prestige and security – not business. This is reflected in the sector's institutions and mechanisms: contracts were highly specified and regulated, leaving little room for contractor creativity (Lambright 2015), and markets had a monopsony-oligopoly structure. This brought about an inattention to costs; R&D, conducted by a few large incumbents, mostly addressed specifications of a single customer – the state, via NASA and the DoD. Pronounced centralization and control left the model highly dependent on government policy. Thus, such programs were often subject to cost and schedule slips (Szajnfarber et al. 2008), inefficient pricing strategies (Toman and Macauley 1989), and lack of innovation (Cornell 2011), yielding incremental technological improvements and spillovers at a high opportunity cost.

We propose naming such a logic "technological achievement:" like for Apollo, it involves massive R&D efforts and is executed by a few organizations exempt from economic tests. For the reasons above, TAs are not innovations. Nor are they science, because seeking scientific knowledge is usually not the main objective; science is often sacrificed, as it was for Apollo, to "higher objectives" like national prestige or national security (see our companion paper Chavy-Macdonald, Cornet, and Foray 2023). The concept of TA thus identifies a third regime for advancing knowledge and technologies – one that does not fall under either science or innovation. It is not really identified in the literature (with few exceptions), even though it mobilizes enormous resources. It can also be successful on its own terms, as for Apollo.

After the TA period, the sector moved to Phase 2, a transition where some economic experimentations were made but the TA logic remained, before entering Phase 3: innovatisation. Our hypothesis is that innovation in space increased due to rising returns on innovation, occurring in two steps. First, external factors started the process (technological opportunities, disruptive entrepreneurs, decreased fixed costs of creating new business), leading to more favorable return conditions. Second, this allowed the sector to begin a powerful positive feedback cycle (driven by lower costs, willingness to pay, decreased uncertainty, change in institutions, entrepreneurship).

The transition documented here is exceptional, and perhaps even unique, in history. Because interest in commercialization and economic spillovers emerged early in the sector's history and did not really change its fundamental modes of operation, we believe that such an exceptional transformation cannot be captured by a simple argument about commercialization. Instead, we think the concept of innovatisation, though new to the innovation economics literature, is better suited to capture the logic underlying the changes analyzed here. Innovatisation causes great upheavals and simultaneously is a resource multiplier and generator of new opportunities. All the actors of the prior TA regime – accustomed to certain routines – have come to face new constraints, challenges, and methods of management and governance. A careful and detailed analysis of the space sector's innovatisation is essential for a better understanding of how public policy must be reinvented to face these transformations.

It is beyond the scope of this paper to measure the impact on social welfare of the transformations brought by innovatisation. However, the massive decrease in space-sector costs brings significant benefits to society, and so does the emergence of new businesses and services. Measuring their impact on social welfare is a promising area for future work. We assume that welfare effects will depend on (i) the ability of new institutional mechanisms to reduce the various market failures, especially the tragedy of the commons associated to space debris; and (ii) the nature of space activity: for example, the prospect for welfare gain is rather clear for internet connectivity satellites, less so for space tourism. Indeed, the framework and findings developed in this paper open the door to further empirical research in various directions. First, more empirical analysis on the innovatisation of the space sector is needed and will be part of our future work. Second, it may be fruitful to extend the concept of innovatisation to other sectors. One obvious case might be nuclear technologies, which will provide a different perspective on a process of similar nature. Finally, it may be useful to further apply our framework to studies of the current challenges facing the European space sector and its central actor, ESA. One hypothesis to be rigorously tested is that the European sector has not yet reached innovatisation and is still operating in the second phase this paper identified. The second phase would feature many performance and competitiveness issues, and the extraordinary power of innovation and entrepreneurship in the US space sector will likely produce a large performance and competitiveness gap vis-à-vis its European counterpart. To transcend the gap, we must understand it.

7. Appendix

1. Methodology

1. Methodological note on the approach

For data, we rely on both published sources and proprietary databases (e.g., Pitchbook, Patstat). We also rely on e.g., pricing data published on company's website. For more information on how our data series and graphs are built, we provide methodological notes in Appendix A. Published sources notably consist in news and industry magazine articles (as found, e.g., on SpaceNews), and official documentation such as NASA Procurement Reports and Government Accountability Office (GAO) analyses.

We also rely extensively on books and research articles that stand as reputed historical analyses of the space sector. Books include works by Levine (1982), Launius (1994), Bromberg (2000), Seamans (2005) and Berger (2021). We briefly present them and their authors in Appendix B. In the academic literature on space sector history, we rely on MacDonald (2018), who relates a long-term economic history of US space; Lambright (2015) who describes in detail how the COTS program came to fruition; and Cornell (2011), who discusses five turning points of the US space industry from the past 20 years. Finally, the changes in the space sector have been investigated in the economics literature looking at the NewSpace phenomenon. The work most relevant to us examines space sector evolution from an economic perspective. In particular, Mazzucato and Robinson (2018), Rottner, Sage, and Ventresca (2021), and Chavy-Macdonald and Kneib (2020) made close contributions, though centered on 'ecosystems,' contrasting with our focus on innovation as economic discovery and its role in large sectoral cost decreases. Culver et al. (2007) and Weinzierl (2018) are closest in spirit to our work, discussing policy implications of the sector's evolution. Our contribution complements these papers with innovatisation as a framework to analyze that evolution.

2. Methodological note on selected figures

1. **Figure 5 on experimentation costs**: If not cited directly, most costs were estimated very roughly (with large uncertainties shown), using similar-sized analogues (de Carvalho et al. 2020) or cost models such as SSCM (Wertz et al. 2011).

Datapoint	Source
Orbcomm X	Krebs, Gunter D. 2023. "Gunther's Space Page." Accessed September 10, 2023. https://space.skyrocket.de/index.html
Orbcomm	Krebs 2023; Funding Universe. n.d. "Orbital Sciences Corporation History." Source: International Directory of Company Histories, Vol. 22. St. James Press, 1998. Accessed September

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QuakeSat 1, MAST, CSTB-1, AeroCube 2	Krebs 2023
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Mayflower-Caerus	Krebs 2023
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Planet	Holm, Rachel. 2015. "A Look Back: Planet's Progress in 2014." Blog on corporate website. Planet Pulse - Planet Labs. January 11, 2015. https://www.planet.com/pulse/a-look-back-planets-progress-in-2014/ McKinsey and WEF 2022
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Events on the x-axis of Figure 5: Surrey Satellite Technology Ltd (SSTL) became a pioneer of small satellite systems (Sweeting 2018). For Swartwout, ‘the true innovation of CubeSats is the P-POD launch interface’ because it decoupled development, integration, and verification of the spacecraft from that of the launch vehicle. The ISIS CubeSat shop (a spin-off of Delft University of Technology, followed by GomSpace’s shop in 2007) has been a ‘one-stop webshop for CubeSats and nanosats’ parts (de Carvalho et al. 2020), a marketplace greatly facilitating the task of novice teams and thus decreasing experimentation costs. The year 2013 saw a doubling of on-orbit CubeSats, which by 2014 were mostly company-launched, not academic or agency-launched).

2. **Figure 6 on pioneering entrepreneurs**: the list was compiled by cross-listing several others:

1. Famous firms, as compiled by e.g., MacDonald 2018, Culver et al. 2007, Berger 2021
2. Jonathan’s Space Report list of entities (in principle every company successfully launching to orbit should be captured here) https://www.planet4589.org/space/gcat/web/orgs/index.html
3. Astronautix, notably this site http://www.astronautix.com/x/x-prize.html
4. Several Wikipedia pages, notably https://en.wikipedia.org/wiki/List_of_private_spaceflight_companies and https://en.wikipedia.org/wiki/Ansari_X_Prize
5. https://www.faa.gov/about/office_org/headquarters_offices/ast/media/suborbital_report.pdf - a very relevant report
6. https://www.orbireport.com/startup/ - and other assorted lists
7. https://www.spaceprojects.com/companies/
8. https://forum.nasaspaceflight.com/index.php?topic=10012.0

Each candidate firm was then checked for size / accomplishments using Wikipedia, a news search, the company website using archive.org, crunchbase and pitchbook, industry news sites like spacenews, spacedaily, etc. until explicit information on their revenue or funds raised was found. In a few cases of uncertainty (between \$5 M and \$10 M acquired), we erred on the side of inclusion.

1. **Figure 10 on patents**: as documented in Cornet et al. (2023), following the methodology of Collette et al. (2018), we aim at identifying patent applications resulting from the US and EU space sector innovation R&D (or more in general, innovation) activities. Thus, we apply a patent text search strategy based on the occurrence of any specific space related keywords in patents abstracts. The list of keywords was provided by the Canadian Intellectual Property Office (list used in Collette et al., 2018), and it was produced by patent examiners working in technology areas where space related patents are more prevalent. Drawing from the 2021 version of the PATSTAT database, we download the abstract of all the patents that have been filed at the United States Patent and Trademark Office (USPTO) as well as in the different European patent offices during the period 1976 to 2019. By applying our text-based search strategy we select just those patents containing one or more "space sector" keywords in their abstract. The final sample resulting from this procedure is made up of 14,792 patents, with a significance prevalence of patents filed in the US.

9. Key books and their authors

Levine was a historian who wrote the NASA History Series' book *Managing NASA in the Apollo Era* (1984). It is an extensive study of the organization of the agency during the Apollo years, in which the author describes NASA's organizational structure and key policy decisions that shaped the agency for decades (e.g., procurement and budgetary processes).

Bromberg was a historian of modern physical science and technology, later specialized in aerospace. She received a NASA-funded grant in the 90s, to study the relationships between NASA and the space industry in the fifty years following the Second World War. This led to the book *NASA and the Space Industry* in 1999.

Launius was the former chief historian of NASA, retiring in 2016. He wrote prolifically on the history of NASA and the space sector. Here we refer to a retrospective analysis on the Apollo project he conducted in 1994, where he presents a short narrative account; we also used his excellent 2006 review of Apollo books.

Seamans was a Professor of Aeronautical Engineering at MIT, and Associate and then Deputy Administrator of NASA during Apollo. He was later Secretary of the Air Force. He was “General Manager” of NASA, and part of the famous *Triad* that took the major decisions of Apollo, with NASA Administrator Webb and Deputy Administrator Dryden. His book *Project Apollo: The Tough Decisions* (2005) gives insider insights on the program’s decision process.

Berger is a meteorologist and science journalist for Ars Technica. His book *Liftoff: Elon Musk and the Desperate Early Days that Launched SpaceX* (2021) describes the beginnings of SpaceX and its success factors in detail, based on extensive interviews of the key people.

10. Example component cost reductions

Here we show examples of specific space components that have greatly increased their capability per unit mass and power in the past 20 years. Between the periods 2000-2004 and 2017-2022, processor speeds improved ~20× per unit power, GPS receivers improved ~10× in accuracy for <¼ the mass, and gyroscopes ~10× the accuracy at 1/10th the power. The result of the latter two is that nanosatellites in 2022 routinely reach 10× the pointing accuracy that only mini- or microsatellites managed in 2000, enabling them to perform Earth Observation and nearly all telecom missions.

Indeed, in the early 2000s mini- and microsatellites achieved typical required pointing accuracy for telecom, and in some cases for Earth observation (EO). By the 2010s (with WNISAT-1 and CANX-3), thanks to new components, even many nanosatellites could meet EO requirements. This meant far cheaper satellites (see Table 2) could deliver useful services, often utilizing consumer electronics but also better imaging sensors, buses, and so forth.

Table C.1 (data from de Carvalho et al. 2020, Frost et al. 2014 and Weston et al. 2023) shows how two technical metrics have greatly improved in small satellites: processor speed and pointing accuracy (the latter is key for Earth observation as well as telecom). This is equivalent to cost decrease (smaller components are often cheaper; less mass and wattage diminishes requirements on the rest of the satellite), and results from better components (de Carvalho et al. 2020), most of which are exogenous improvements due to Moore’s Law. Table C.1 shows a 2017 AMD microprocessor, new GPS receiver and gyroscope – yielding ~10× improvements in miniaturization and performance (not to mention cost) – coming from consumer electronics and now used in small satellites (Weston et al. 2023).

Also from Table C.1, using the 2004-released LEON3 microprocessor, a satellite likely needs 9–10 W minimum power for image processing and autonomy. Table 2 shows this is very unlikely to fit in a nanosatellite power budget; it may even be unlikely in the largest microsatellites (processors are a small percentage of the overall power budget). By contrast, using the 2017 AMD non-space chip, power ceases to be a bottleneck for intense processing tasks, even for nanosatellites.

	Past	Current	Requirements
Processor speed *MIPS: million instructions per second* *W: watt of power*	0.006 MIPS/W *(1971: Intel 4004)* 0.2 MIPS/W *(1980: MIL-STD-1750A)* ~15 MIPS/W *(2004: LEON 3FT-RTAX)*	390 MIPS/W *(2017: AMD EPYC)*	Small C&C: 1 MIPS Typical C&DH: ~30 MIPS Image processing, Autonomy: 100 MIPS
Pointing accuracy *°: Pointing error*	> 0.1° / > 0.03° *(2000: Most / Best micro- or minisat)*	≤ 0.01° *(2022: Many nanosats, etc.)*	Smallest spacecraft: 0.1° EO: 0.03° *– Envisat* Telecom: 0.2° *-ITU-R S.1064-1*
GPS receiver *Accuracy, mass*	10 m, 160 g *(pre-2002: SpaceQuest GPS-12-V1)*	1.2 m, 31 g *(2022: NovaTel OEM719)*	*Part of pointing accuracy*
Gyroscope *Bias stability, angle random walk, power*	≤ 1°/h, ≤ 0.1°/√h, 2.5 W *(pre-2001: LITEF µFORS-1)*	≤ 0.1°/h, ≤ 0.01°/√h, 0.2 W *(~2021: Silicon Sensing Systems CRH03 (OEM))*	*Part of pointing accuracy*

Table C.1. Satellite component miniaturization: Improving satellite processor speed and pointing accuracy over the last 20 years. Both metrics are driven by parts availability (processors, GPS, gyroscopes). NovaTel, AMD, and Silicon Sensing Systems are general electronics suppliers, not space-specific; their components are ~10× better. Requirements for processor speed are for typical tasks (e.g., basic Command and Control (C&C), or typical Command and Data Handling (C&DH)). Requirements for pointing accuracy shows the current International Telecommunications Union guidelines for telecom satellites, and an example of an expensive Earth Observation satellite from 2003, *Envisat.* Data from de Carvalho et al. (2020), Frost et al. (2014) and Weston et al. (2023).

11. Cost reductions

As for satellite platforms (Table 3), a 2020 McKinsey study reported that several firms claimed to be producing telecom satellites at costs substantially lower than the prevailing $50’000–$60’000/kg: e.g., Inmarsat, OneWeb (which has since gone bankrupt), and SpaceX (Daehnick et al. 2020). Importantly, these are commercial-ready satellites, not mere tech demonstrations. OneWeb likely achieved a cost as low as $7’000/kg, while SpaceX may be aiming for $2’000/kg with its 12’000 near-term satellites (3–4× as many as those now in orbit; Daehnick et al. 2020). Several firms have also reported far lower ground terminal costs. Another recently identified trend is the emergence of new specialized suppliers, targeting cost reduction through mass production (Denis et al. 2020); this has had a considerable impact on the industry (de

Carvalho et al. 2020). This shift towards a constellations model, underpinned by mass production, also impacts scalability. Although upfront costs, including production investment, can be onerous, once production lines are set up, continuous satellite production makes scalability easy. Constellations also appear to be a shift to more “winner-takes-all” markets, vs. traditional satellites that have lower start-up costs, but lower scalability.

Services to other sectors (e.g., satellite imagery and telecom) have also seen accelerated cost-cutting; see Table 3 (Serra and Northern Sky Research 2018). Imagery features both price cuts and new availability at high temporal resolution (several identical images/day). In telecom, high-throughput satellite (HTS) technology, cheaper manufacturing and launches, and software-defined satellites led CAPEX/Mbps/month to drop by about 10× (from $1000 to $100) from the early 1990s to 2015, and by another 10× ($100 to $10) from 2015 to 2020. The current trend is a 50% decrease in HTS unit costs every 5 years, and this should continue with very high-throughput satellite tech and LEO constellations (Serra and Northern Sky Research 2018).

12. Index of Acronyms

AI: Artificial Intelligence

AFRL: Air-Force Research Laboratory

ASEE: American Society for Engineering Education

B: Billion

C&C: Command & Control

C&DH: Command & Data Handling

CERN: European Organization for Nuclear Research

COTS: Commercial Orbital Transportation Services

CPAF: Cost-plus award fee

CPFF: Cost-plus fixed fee

CPIF: Cost-plus incentive fee

CRS: Commercial Resupply Services

CSIS: Center for Strategic and International Studies

DoD: Department of Defense

EO: Earth Observation

FAR: Federal Acquisition Regulation

FP: Fixed-price

GAO: Government Accountability Office

GDP: Gross Domestic Product

GPS: Global Positioning System

HTS: High Throughput Satellite

IP: Intellectual Property

IPO: Initial Public Offering

ISIS: Innovative Solutions in Space BV (now renamed ISISPACE)

ISS: International Space Station

IT: Information Technology

ITU: International Telecommunications Union

K: Kilo (Thousand)

LEO: Low Earth Orbit

M: Million

Mbps: megabits per second

MIT: Massachusetts Institute of Technology

MIPS: million instructions per second

NAA: North American Aviation

NAFCOM: NASA-Air Force Cost Model

NASA: National Aeronautics and Space Administration

NRO: National Reconnaissance Office

OCP: Office of Commercial Programs

OECD: Organization for Economic Cooperation and Development

PPP: Public Private Partnerships

R&D: Research and Development

SAA: Space Act Agreements

SBIR: Small Business Innovation Research

SIA: Satellite Industry Association

SLS: Space Launch System

SPAC: Special Purpose Acquisition Company

SSCM: Small Satellite Cost Model

SSTL: Surrey Satellite Technology Ltd

TA: Technological Achievement

ULA: United Launch Alliance

USCM: Unmanned Space Vehicle Cost Model

VC: Venture Capital

VHTS: Very High Throughput Satellite

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