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CH-9000 St.Gallen
Tel +41(71)224-2525
Fax +41(71)224-2536
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Defining *innovatisation*: The case of NewSpace and the changing space sector*

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Benoit Cornet,†‡ Marc-André Chavy-Macdonald,§ Dominique Foray**

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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), neither consumers nor costs really count, nor again science, but only technological performance; in innovation, customer preferences, commercial opportunities, and costs become essential. Studying the economics of Apollo and the commercialisation attempts of the 1980s, we show how the space sector has long featured a logic of TA. Then, analysing recent trends, we provide quantitative empirical evidence (e.g., costs) that innovation now shapes the sector: building on Jones (2022), we identify the driving forces behind the innovatisation of the space sector, forces that are further supported by the rise of entrepreneurship and venture capital; we then discuss the emergence of two properties of the space sector, with the rise of R&D inputs (expenditures and human capital) as a result of these changes.

Keywords: Innovatization; Innovation; Technological Achievements; Public private partnerships; NewSpace

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† Corresponding author.

‡ Center for Aviation & Space Competence (CFAC-HSG). Address: CFAC-HSG, Office 3-240, Dufourstrasse 40a, 9000 St. Gallen. E-mail: benoit.cornet@unisg.ch.

§ Center for Aviation & Space Competence (CFAC-HSG). Address: CFAC-HSG, Office 3-240, Dufourstrasse 40a, 9000 St. Gallen. E-mail: marc.chavy-macdonald@unisg.ch.

** College of Management of Technology (CDM-EPFL). Address: CDM-EPFL, 1015 Lausanne. E-mail: dominique.foray@epfl.ch.

Dufourstrasse 40a
CH-9000 St.Gallen
Tel +41(71)224-2525
Fax +41(71)224-2536
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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 characterised 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 organised. 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 notion of a commercialisation of space seems inadequate for the task of describing the current transformations. There have always been certain forms of commercialisation regarding space activities (MacDonald 2018). However, the current transformations cannot be reduced to a change in the *degree* of commercialisation 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 define it as the sector's transformation from a mode of *technological achievement* (TA) to one of *innovation*. Based on our analysis of the sector's evolution over the past 60 years, we aim to characterise both regimes. This paper focuses on US space innovation, which largely drives NewSpace as well as global space innovation in general.

Our approach will be first to characterise the old regime as one situated outside the economy – which we thus term a TA regime: one where, in short, the economy has no influence; neither consumers nor costs really count, and only technological performance matters. As the economy has no influence, it offers neither the opportunities nor the constraints that entrepreneurs usually face, and innovation finds nothing to hold onto. Innovation fundamentally defines itself in relation to consumers (and, more widely, customers) and costs. When these 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 economy; it can thus unfold in a kind of space protected by the state and legitimised by non-economic objectives such as prestige.

The new regime is that of innovation: 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 regimes is named *innovatisation* rather than *commercialisation*.

To ground this approach and our hypotheses empirically, we use original methods aiming to analyse the space sector along two fundamental dimensions, each explored in a separate paper. In this paper, we look at the economic mechanisms and institutions (e.g. supply, demand, market structure, contracts) shaping the sector's organisation; in a companion paper (Chavy-Macdonald, Cornet, and Foray 2023) we investigate the key programme and system architecture decisions.[1] We maintain that

[1] We mean 'architectural' engineering design and development decisions related to space technologies and their parent programs.

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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 Sections 3, 4 and 5 we study the innovatisation of the space sector via its evolution in three phases. The first phase, pure TA, is exemplified by the early days of the Apollo programme. TA and economic experimentation mark a second phase, with the introduction of contract incentives and attempts to commercialise. And, with the ongoing transformation of the sector and emergence of NewSpace, innovatisation stands as the third phase. Across Sections 3, 4 and 5 we investigate the changes in economic mechanisms, institutions and actors that determine a totally new ecosystem. Finally, Section 6 concludes.

2. Setting the stage

Here we set the stage by defining the concept of innovation we use in this paper: that of innovation as economic discovery. Then, we present our methodology and outline the data and relevant literature. Finally, we introduce our phased analytical approach.

a. Innovation as economic discovery

As we suggested in Section 1, any astute observer can realise that the space sector is experiencing profound transformations, each of them driven by a specific logic: start-ups, new markets, the big incumbents' transforming operations, greater attention to costs, and so forth. Our goal is to try, using the analytical framework of innovation economics, to explain the coherence of these changes. Our central hypothesis is that innovation – which we define hereunder – has become the norm in this sector, something it was not before. The formulation of this hypothesis implies distinguishing between innovation and technological achievement because, obviously, space has always been a sector with plenty of technological achievements. The shift from a TA regime to an innovation regime represents this element of coherence, linking the various transformations that characterise space today. To understand it, we need to spend more time on the concept of innovation we use in this paper.

Innovation is an economic phenomenon because it fundamentally aims to bring economic value (as surplus) to customers and (as profits) to producers.[2] If a new idea brings economic value, it will penetrate the market and become an innovation; if it does not, it will not become an innovation. The innovation process leads to the adoption of an invention or new idea after it has been experimented upon within the economy and society.

As a result, 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 – the backbone or essence of innovation – is undertaken to answer many

[2] 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.

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questions arising when introducing a new product, service or business model on the market. How will it perform? This is not only a technological, but also an economic question. Will high performance be attained only at prohibitively high cost? That would make adoption almost impossible. How rapidly is performance likely to improve, and the cost of production to decline? How appropriable is the value of the product for the innovating firm? In other words, how likely is the innovator to capture a significant part of the new value generated? And how likely is a regulator or court to destroy expected profits through new requirements or a judicial ruling? How soon will a new, superior product come along?

Answering these questions via the process of economic experimentation and discovery generates economic knowledge: 'if an invention at the proof-of-concept stage went on to be developed and adopted, thus becoming an innovation, it did create economic knowledge' (Phelps 2013). If economic discovery shows that the new product fits consumer preferences, and that sufficient performance can be attained at tolerable cost, then the new product or service will be adopted on a large scale, generating economic and social value as transformational benefits accrue to much of society.

It is therefore a question of seeing whether a new idea – and its substantiation as a product, process or business model – will be adopted by customers, and what will be the costs and profits. Even if the technology works, it must be adopted by the market to become an innovation (Phelps 2013). While a technological invention is an engineering achievement measured by engineering performance, an innovation is an economic achievement measured by consumer surplus and possibly profits. A decrease in costs associated with certain activities – a fundamental source of increased consumer surplus – is an essential part of innovation. Thus Ridley (2020) argues that innovation changes the world, thanks to the massive decrease in costs it generates. We will see how true this statement is vis-à-vis the new state of the art in the space sector.

Fully adopted, innovation brings significant economic and social value, and it leads to considerable structural transformations. This means that a new technology will not produce such value, nor will it lead to such transformations, unless it has been adopted and generalised, thereby becoming an innovation. There are, on the one hand, spectacular technological advances that translate into very little economic value; these cannot be called innovations. On the other hand, a new way of organising an economic activity (e.g., a new business model) can be viewed as a great innovation even if it uses very little technology.

How does this radical concept of innovation set the stage for our argument? For a long time, the space sector may have exhibited strong technological capacities and achievements but did not produce much economic value through innovation and, therefore, was not innovative in the sense we suggest here.[3] It is this concept of innovation that underpins our approach and leads us to interpret the history of the US space sector as a regime-change from a regime of TA, whereby technological advances do

[3] 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).

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not translate into economic value – which determines many characteristics of technologies, organisation, governance, or performance – to a regime of Innovation. This regime change is captured by the term *Innovatisation*.

b. Empirical strategy

Our underlying empirical hypothesis is that both regimes, TA and innovation, can express their key features and specific logics at two levels of decision-making. The business decisions or economic mechanisms and institutions are for example about demand, supply, market structure, contracts and governance practices ruling the principal-agent relationships between buyers (NASA and the Department of Defense (DoD)) and suppliers (space firms). Development decisions concern 'architectural' engineering, and programme and associated organisation design. Our goal is thus to capture the specific logics of TA versus innovation by analysing (a) the mechanisms ruling the relationships between space market participants (this paper), and (b) the decisions underlying the major technical systems and programmes (Chavy-Macdonald, Cornet, and Foray 2023).[4]

For data, we essentially rely on published sources. These 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 that stand as reputed historical analyses of the space sector, including works by Levine (1982), Launius (1994), Bromberg (2000), Seamans (2005) and Berger (2021). We briefly present them and their authors in Appendix A.

Additionally, the changes in the space sector have been investigated in the academic literature looking at the NewSpace phenomenon.[5] 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 centred 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 also close to our work, discussing policy implications of the sector's evolution. Our paper complements these papers with innovatisation as a theoretical framework to analyse that evolution.

Also relevant is the literature on space sector history. For instance, MacDonald (2018) related a long-term economic history of US space; Lambright (2015) described in detail how the COTS programme came to fruition, and Cornell (2011) discussed five turning points of the US space industry from the past 20 years. We build on these studies to understand sectoral evolution, and to establish our theoretical framework.

[4] In our companion paper (Chavy-Macdonald, Cornet, and Foray 2023), we notably look at 33 key decisions of the Apollo technology architecture, the programme itself and the developing organisations. The goal is to investigate in detail the key decisions of Apollo and subsequent programmes, revealing their true nature as TAs.

[5] *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.

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Finally, the difference between innovation and commercialisation regarding NewSpace has been investigated in the literature (e.g., Davidian 2020). Our work directly contributes a theoretical framework drawn from innovation economics.

c. Phasing

Looking at the evolution of the space sector in the past 60 years, we can grossly distinguish three main phases: (1) Pure TA; (2) TA and economic experimentation; (3) innovatisation.[6]

That evolution is driven by several interdependent, mutually reinforcing drivers, as shown in Figure 1: supply-side drivers correspond to new technological opportunities, decreasing fixed costs of creating new products and services, and decreasing costs of producing, distributing and scaling; demand-side drivers correspond to market size and the emergence of business opportunities, greater willingness to pay, and lower (buyer's) uncertainty; and institutional drivers correspond to the new role of NASA and a market structure featuring more competition.

The development of drivers favorable to innovation naturally leads to an increase in the inputs to R&D – especially R&D expenditures and human capital, which are thus "emerging properties" – being poured into the sector. We argue that a significant share of this increase in R&D inputs is due to the rise of entrepreneurship, which acts as catalyser, by attracting private capital which is massively invested in R&D, and by recruiting a new generation of highly talented and well-trained engineers. In turn these emerging properties further boost innovation.

Our analysis is split in three parts to describe successively each of these three phases

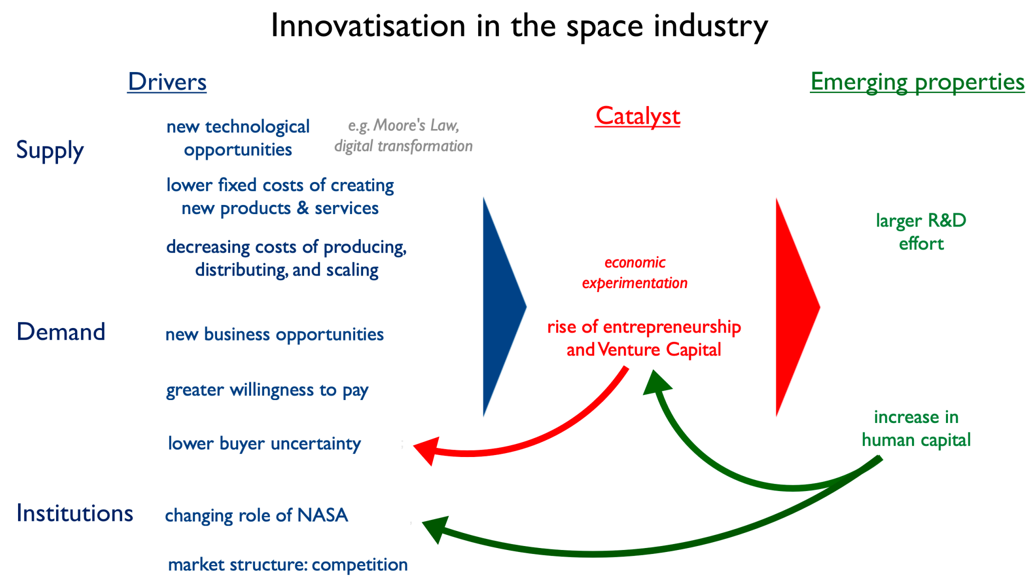

Figure 1. Synthesis of drivers, catalyst, and emerging properties underlying innovatisation of the space sector.

[6] 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*.

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3. Technological achievement

This first phase covers roughly NASA's first five years.[7] It is characterised by a logic of technological achievement. This describes a sector insulated from the traditional rules of the economy and market forces driving innovation – the sector exhibits a general inattention to costs and sets a priority on technological performance, to accomplish ambitious missions, motivated by prestige and national security. 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. 1962, Launius 1994).[8]

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 industry but also from universities and other laboratories. Illustrating this, Figure 2 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.

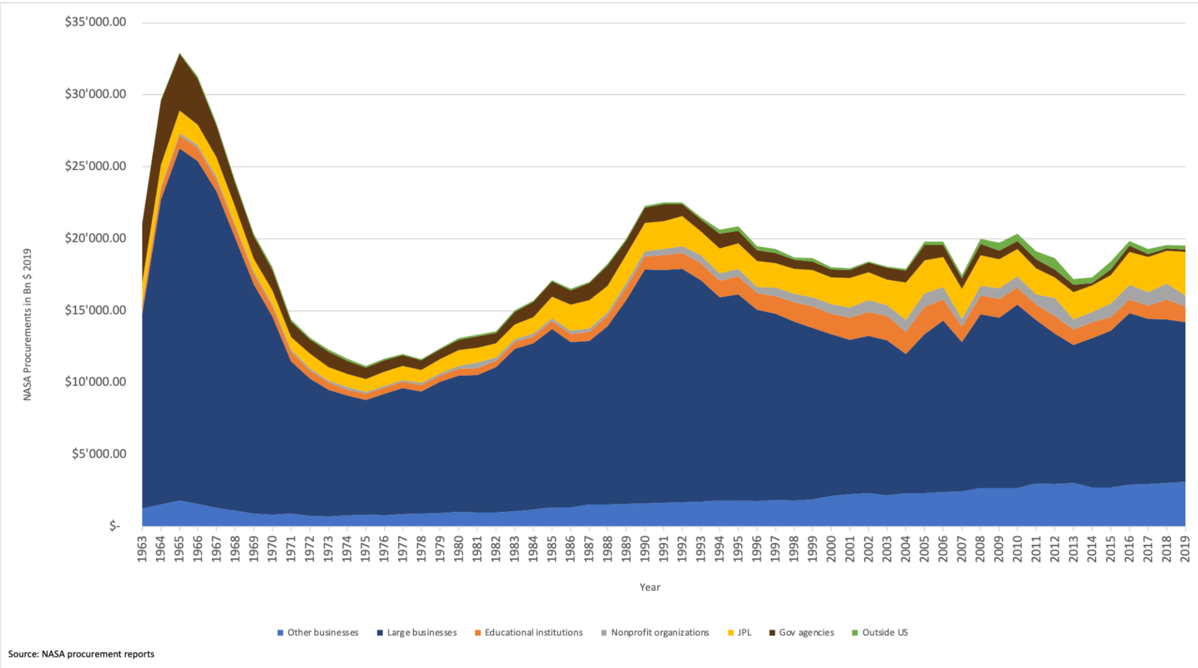

Figure 2. NASA awards by contractor type, 1963–2019 (NASA Procurement Report 2019).

[7] Admittedly, space-related activities existed before NASA's birth, but they 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*.

[8] 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 inattention to costs is also visible in architectural engineering and program decisions.

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Because the sector at the time was entirely driven by NASA and its moon-landing objective, in this section, we shed light on the logic of technological achievement during Apollo's early days by analysing the mechanisms ruling government-industry relationships, namely the sector's market structure and NASA contracts.

a. 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 – characterises the Apollo market. Here, the single buyer is NASA and the reasons there are few supplier firms are twofold. First, few are able to compete for major R&D contracts because of the large costs to enter and the highly specialised 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 (Levine 1982).

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 which is largely set by the marginal production cost. Prices reflect quality but also operational efficiency; consumers value each offer by signalling 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 it is an instrumental process in informing and 'disciplining' market participants on the best price–quality combination.

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 potential technical efficiency. Despite its monopsony power, and even if it employs experts to check supplier offers, the buyer cannot ensure it is buying rationally; because of this opacity, suppliers do not focus on cost-minimising strategies. Adams and Adams (1972), analysing 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 specialised 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 tends to support the low-competition hypothesis during Apollo: Figure 3 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.[9] 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).

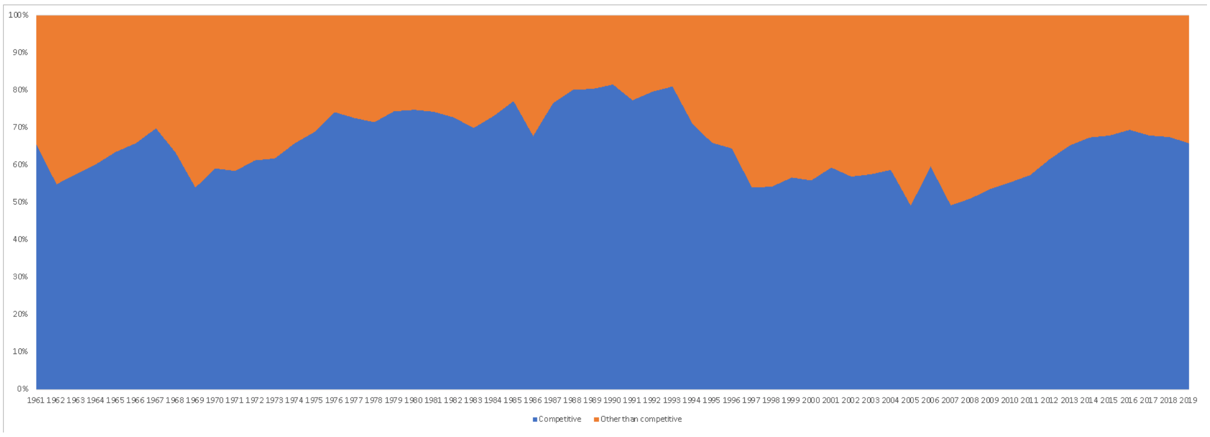

Figure 3. Competitively sourced NASA awards to firms, 1963–2019 (NASA Procurement Report 2019). Includes one-bid awards. *Competitive* procurements were offers selected from more than one offeror; *Other than competitive* procurements are offers selected from either a single offeror, or a follow-on project.

The low-competition hypothesis is also supported by evidence of organisational and technical inadequacies at the contractor level, especially at Apollo's start. As reported by Levine (1982), in 1964, Seamans – *de facto* manager of the Apollo program – thought that key reasons for schedule and cost slips were contractors' organisation in terms of (e.g.) supply chain management, quickly expanding engineering teams and workforce quality, management and oversight of large-scale projects. Their organisation was not structurally sufficient for the tasks they needed to fulfil, even though the required effort was enormous as the industry was asked to simultaneously develop a launch vehicle, three spacecraft modules and ground support equipment (Levine 1982). The most telling example was North American Aviation (NAA), the prime for the command and service modules as well as the Saturn V S-II stage and, via its Rocketdyne Division, prime for the F-1 and J-2 engines (Levine 1982).[10] Bromberg (2000) described how NAA's engineering drawings were behind schedule, the command module was overweight, and subcontractors were late about delivering poorly engineered systems.

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

[10] Levine (1982) gives other examples of large NASA and DoD R&D programs plagued by cost overruns and slippage in 1962–1964: the Centaur launch vehicle (with General Dynamics as prime), the RL-10 engine (Pratt and Whitney), Gemini (McDonnell), and the Saturn S-IV and S-IVB (Douglas).

Thus, the particular combination of monopsony and oligopoly characterises 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 contracts NASA used for its suppliers.

b. NASA contracts

NASA contracts and their incentives contributed thoroughly to this low-competition environment. By design, they embedded an inattention to costs.

The contracting process for the development and manufacturing of the hardware to be used during Apollo 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 determined in advance, making it difficult to estimate costs, and thereby pricing NASA contracts became complicated.

Development and manufacturing contracts were negotiated procurements, meaning that NASA discussed the product characteristics with contractors, providing guidelines and specific requirements, establishing a programme 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 a specifications change, cost slip, technical difficulty, 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 level. 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 from performance, companies were rewarded for underbidding to get the contracts, for running over cost estimates, and for administrative inefficiency as they boosted their revenues and profits. The contracts thus required direct NASA oversight, adding further expenses.

c. Synthesis: What is a technological achievement?

The monopsony-oligopoly market structure and the CPFF contracts used by NASA during early Apollo characterise a programme exempt from economic constraints and (being state-run, with objectives of prestige and national security) protected from the economy. While this mode of organisation has driven notable technological progress, one cannot characterise it as innovation in the sense we mean; it gives priority to technical performance, promoting inattention to costs. It does not prioritise discovering what works economically. Apollo also cannot be considered mainly scientific, like CERN for example. Indeed, while science is an objective stressed by Apollo advocates – and it would be absurd to deny its real scientific outcomes – science itself remained a secondary objective, often

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sacrificed. This makes the opportunity cost of such research enormous, disproportionate to what 'normal' science would cost (cf. our companion paper, Chavy-Macdonald, Cornet, and Foray 2023). As mainstream economists Bloom et al. (2019) writing on innovation policy 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'.

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

Director David Bell's Bureau of the Budget commission, as early as 1962, presented to the president a report on results of work showing that economic principles and market forces, which generally discipline and inform market participants, were absent. The report reviewed current acquisition practices of the federal government, and explored the circumstances under which contractor operations were effective means to accomplish the government's goals for cost, schedule, and performance (Bell 1962). A key recommendation was to reshape the contracting system to give industry better incentives; linking profits to performance in contract provisions (e.g., for cost and schedule) to simulate market conditions. This was among the first experiments aiming to incorporate economic considerations in technological achievements. We consider that it marks a second phase, and we now explore how well it did and what impact it had on innovation.

4. Phase 2: Technological achievement and economic experimentation

Contrasting with the pure technological achievement regime of Phase 1, where space was insulated from economic constraints, Phase 2 was characterised by the introduction of economic principles into the TA regime. In particular, we investigate two key events: the use of incentive contracts following the Bell report, and the commercialisation wave of the 1980s.

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

Here we analyse NASA's evolution in contracting policy during Apollo's later stages, and its implications for innovation. We describe the new contract types used by the agency with private firms, and then we assess their role in light of the incentives they provided.

i. NASA's incentive contracts

The 1962 Bell report recommended replacing CPFF with contracts that would align contractor incentives with NASA's time, cost, and performance objectives. With CPFF, NASA bore all projects' financial and technological risks; the goal then was to shift the risk burden of NASA programmes by introducing incentive provisions such that industry would also stand to lose (Levine 1982). Thus, the report suggested using fixed-price (FP), cost-plus-incentive-fee (CPIF) and cost-plus-award-fee (CPAF)

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CH-9000 St.Gallen
Tel +41(71)224-2525
Fax +41(71)224-2536
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contracts whenever possible.[11] 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 contractors bear the most risk and are most incentivised to control costs, was rarely used for Apollo. With CPIF contracts, all contractor costs are reimbursed but the fee depends on predetermined targets concerning time, cost, or performance; net profits can therefore be positive or negative. With CPAF contracts, all incurred costs are reimbursed and there is a fixed fee for acceptable performance and, in addition, the contractor may 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 systematically favoured for new partnerships. In 1966, NASA managed about 200 incentive contracts, up from one in 1961 and six in 1962, totalling $5.3 B (Levine 1982).[12]

ii. Assessing the changes in NASA contracting policy

Incentive contracts were meant to improve contractor performance by reducing cost slips and speeding up the delivery 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 programme 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 receiving a large share of revenue in the form of incentive contracts from NASA and the DoD to similar firms that did not receive such contracts, Trimble (1971) also finds that changing towards an incentive environment did not improve contractors' resource management efficiency.

Consistent with these criticisms, Roberts and Sloat (1966), looking at government and contractor behavioural changes following the evolution of NASA policy towards incentive contracts, argued that while highly motivating contractors, the contracts may have created the wrong incentives. They may have pushed firms to take shortcuts during design and production, shortcuts which could be detrimental to the performance of the larger system. Roberts and Sloat also explained that contractors became far more cautious about changes to the requirements as specified contractually. This resulted in lower technical flexibility for the government, more need for technical negotiations, and thus limits the effect of these contracts on cost reductions. Assessing the use of schedule incentives to accelerate delivery of the Saturn V, a Government Accountability Office report yielded similar conclusions regarding the impact of these contracts on cost performance (GAO 1970).

[11] We group these contracts under the general term *incentive contracts*.

[12] The US government spent an estimated $25.8 B on Apollo over 1960–1973 (Dreier 2022); thus, at least one-fifth was incentive contracts.

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CH-9000 St.Gallen
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Finally, while most of the work contracted out to industry was R&D, it is NASA – which bore the costs – that owned intellectual property rights (Levine 1982). This limited firms' ability to leverage new capabilities by seeking other markets.

The evidence suggests that despite efforts to simulate market conditions in a non-competitive market, incentive contracts, like CPFFs, did not create conditions favouring 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 the following decades, as many reports shed light on the inefficiencies surrounding the use of incentive contracts in NASA programmes like the International Space Station (ISS; GAO 2007) or the Space Launch System (SLS; GAO 2019). Yet, these contracts led to major developments, even to some of the greatest technological achievements in History.

b. Technological achievement and commercialisation

While the TA logic insured companies against the financial and technical risks linked to the huge investments needed in space, it also limited their ability to commercialise their products or develop space markets. Additionally, once the Space Race was won, the sector's state-run nature made the large expenses less and less acceptable to the public. 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).

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 commercialise NASA technologies via technology transfer since NASA owned the Intellectual Property (IP) from its R&D. The latter focused on stimulating company participation in R&D programmes, 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) programme, which targets small innovative firms, 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 centralised around NASA, dominated by large aerospace companies.

Though NASA and the DoD tried pulling innovation from smaller firms, the Challenger disaster shattered nascent enthusiasm for LEO commercialisation. Additionally, the aerospace and defence industry consolidation of the 1990s, following slashed defence spending, cemented the incumbents' position. By the 2000s, over 50 mergers and acquisitions had effectively remodelled the sector into an oligopoly of the 'Big 5' aerospace and defence players: Boeing, Lockheed Martin, Raytheon, Northrop Grumman and General Dynamics (Cornell 2011). Cornell emphasised three consequences: (1) A reduction in 'discretionary' R&D expenditures – the R&D not linked to a specific project, more likely to generate unexpected discoveries of broad interest; (2) A stronger oligopoly making it harder for smaller, more agile companies to compete (thereby fostering an industry ecosystem where

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CH-9000 St.Gallen
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technological innovation was not optimised); (3) An overreliance on a few large firms with expensive bureaucracies and multiple product focuses.

Thus, the focus on commercialisation did not interrupt the technological achievement logic of early Apollo. It simply reflected more concerns about large public space expenditures and their return for society and showed a willingness to experiment with new economic models yet remained in the TA logic. The first retort to these concerns is that, especially because they create knowledge spillovers, TAs stimulate the economy. But spillovers must be managed and optimised – the *raison d'être* of the OCP. Yet because the sector seems still *de facto* directed by NASA and *insensitive to costs* – in spite of stated objectives – knowledge spillovers engender large opportunity costs, limiting their impact.

5. Innovatisation

The third phase, which we consider as starting after the turn of the 21st century with the emergence of NewSpace, is characterised by an *innovatisation* of the space sector. Innovatisation describes a transition phase for the sector, from a logic of technological achievement to one of innovation. The latter describes a sector where interactions among economic agents are ruled by market mechanisms, and where innovation, which designates the discovery process of whether the new products or services work economically, is the main operating mode for technological progress.

To understand this transition and what triggered the arrival of innovation as economic discovery into the space sector, we adopt a four-step approach. First, we introduce and adapt a framework developed by Jones (2022), to identify the so-called *drivers* of innovation. Second, we show how these drivers have changed over time in the space sector, becoming at some points so significant that they boosted innovation, triggering the innovatisation process. Third, we discuss how entrepreneurship and venture capital have supported this transition as catalysers. Fourth, we provide evidence of the rise of innovation in the sector by showing increases in inputs to innovation – R&D expenditures and human capital, which we call *emerging properties*. We end the section by shedding light on some of the resulting policy issues.

a. Framework

Jones (2022) presents a 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 features that drive the return on innovation investment and that vary across industries – what we call drivers in this paper. 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) of the innovation, and Nature's opportunities; and *institutions*, which include the ones helping innovators to appropriate the value of innovation, the institutions supporting science and basic research, and the market structure. Table 1 presents each of these drivers and their rationale.

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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 to assess 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 (marketing) 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) which provide new opportunities of innovation 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 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
Regulations	Multiple dimensions, which 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 (2023) by the authors.

Because they drive the return on innovation, a positive change in these features should result in the rise of private innovators and investors, and ultimately in an increase in the inputs to innovation (e.g. R&D expenditures, human capital). This is what we show in the next three subsections, applying this framework to the specific conditions of the space sector.[13]

b. Drivers of innovatisation in the space industry

The space sector's transformations are driven by initial changes on the demand and supply sides, and in terms of institutions. These changes mutually reinforce each other (see Figure 1), and the transformations' causes and effects are deeply intertwined.[14]

i. Supply side

New technological opportunities

The sector is characterised by new tech opportunities, which can be seen at two levels: first as an *enabler* - Moore's Law and exogenous tech progress. In Silicon Valley - home of many NewSpace firms - Moore's Law is called "the most important graph in human history," and considered to be a key source of productivity growth, via the IT revolution (Thompson et al. 2022). Indeed, consistent with literature on the impact of IT, recent econometric analysis by Thompson et al. (2022) finds that improving computing power, specifically, explains half or more of all performance improvements across three domains (weather prediction, protein folding, oil exploration) suggesting computing and Moore's Law are "a central driver of progress across many areas over decades". Satellites are minimum 60-80% electronics and software by cost, according to standard cost models (Wertz et al. 2011),[15] and thus heavily impacted (Sweeting 2018). Accordingly, industry leaders say the current "second attempt" at small satellite constellations is enabled by two extra decades of Moore's Law, yielding a 1000× decrease in energy required per compute operation (and far smaller satellite) (Butash et al. 2021). The first try, in the 1990s, failed – often imputed to the high fixed costs of deploying many satellites (Sweeting 2018). Recently, computation-intensive big data and artificial intelligence are 'spinning in' to space (McKinsey & WEF 2022; see also Appendix B); AI on EO satellites enables consuming data and deploying value-added applications in space rather than on the ground, thus slashing downlink bandwidth needs, and EO costs. It seems likely that satellites is an area where "computing power has been overwhelmingly important as a source of gains in performance" (Thompson et al. 2022).

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[13] Obviously, Jones' framework offers some flexibility in the analysis of these drivers, as each sector would respond differently, each of them playing a different, more or less important role. In this paper, we build on this flexibility by adapting the framework to the specificities of the space sector.

[14] The order of the drivers does not imply a hierarchy between them.

[15] Cost models SSCM and USCM8 (see Footnote 26 of Wertz et al. 2011) example calculations in Tables 11-34, 11-35, 11-37, 11-38, excluding costs from the following subsystems: structure, thermal, propulsion, integration assembly & test, and ADCS (partly, shown as range).

Secondly, tech opportunities are an *attractor*: high tech can attract investments. Empirical evidence indicates that start-ups classified as high-tech enterprises are more likely to raise funds. Popp et al. (2020) showed that venture capital puts a premium on energy firms that include high-tech innovations. Branstetter et al. (2019) showed similar patterns in automotive manufacturing and parts, aerospace and defence, medical devices, and pharmaceuticals. Across 229 publicly listed companies in those four industries, Branstetter et al. found that firms using more software generate more patents per R&D dollar, and their R&D is better valued by equity markets.

Decreasing fixed costs of creating new products and services

The most 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* (see Fig. 1).[16] In turn, the rise of entrepreneurship and innovation is facilitated by these lower "experimentation" costs. 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 cost associated with the creation of business and development processes is a broad phenomenon characterising many sectors, particularly those most benefitting from the internet (Nanda and Rhodes-Kropf 2016). Nanda and Rhodes-Kropf highlighted the effect of recent technological changes (e.g., the internet, open-source software and cloud computing) on the falling costs of launching a business. They explain that Initial experiments which would have cost $5 million a decade ago, can be conducted now under $50'000. The new start-ups today do not buy Sun servers, Cisco networking gear, Oracle databases and EMC storage systems; they are paying significantly less (between 100× and 1000×) today per unit of compute, of storage, and networking.

Similarly, Varian (2018) described how start-ups can outsource many business processes, from hiring employees to cloud computing, software management, accounting, customer relations, team communication or user support. By choosing standardised processes, start-ups can focus on their core competences and buy the services they need as they scale. This effect helps democratise entry and allows for more audacious and costly projects.

Conversely, the cost of technological experimentation can be specific to the sector. In space, such costs are slashed by the rise of smaller satellites and cheaper launches. They are also slashed 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 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 impact of electronics miniaturisation 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).

[16] Note that experimentation and production/operations costs are somewhat difficult to disentangle in the space sector. We attempt to make this distinction in this paper, whenever possible.

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Fax +41(71)224-2536
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Appendix B shows 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 (Appendix B), 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. 'The hallmark of the modern small satellite is the adoption of up-to-date consumer technologies' (Sweeting 2018), though the satellite may also include better imaging sensors, buses, and so forth.

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. Miniaturisation: Small satellite mass class nomenclature, with associated rough power and cost ranges. Lower mass & power components (see Appendix B) 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).

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Fax +41(71)224-2536
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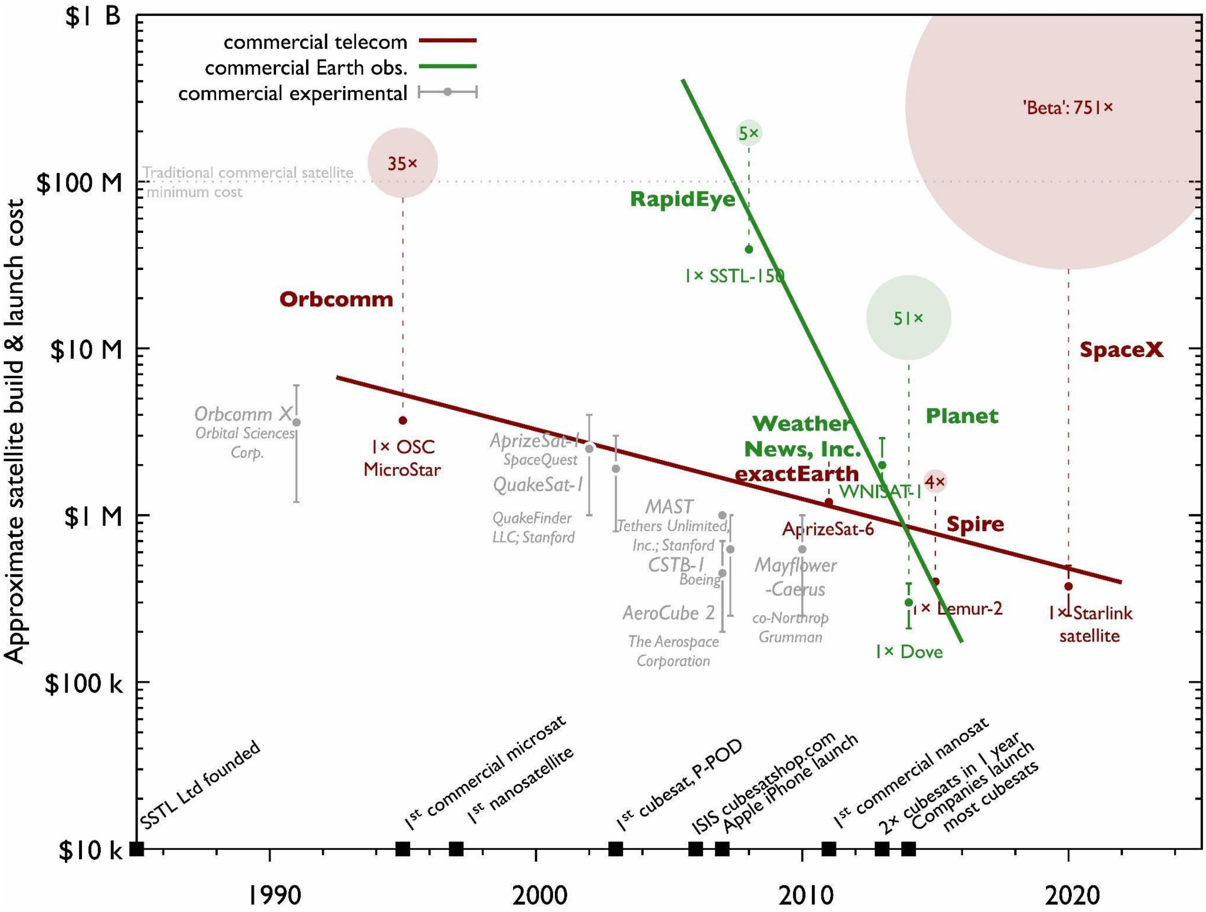

Figure 4. Experimentation costs: minimum costs of commercial satellites. Purely experimental projects are shown in grey; operations-grade (revenue-generating) telecom and Earth observation in red and green. These lowest-cost commercial cases estimate minimum costs of experimentation: early technical (grey), later technical (red and green dots), and economic. Most commercial small satellites operate in constellations (circles – minimum cost to test viable operations). Note the drop by 1–2 orders of magnitude since the 1990s. Key events are shown on the x-axis. Error bars show uncertainty; data in Appendix C.

Building on this new component availability, Figure 4 charts the decreasing costs of entrepreneurial experimentation as captured by building and deploying commercial satellites. The lowest-cost deployments of commercial satellites are shown (red or green points); for commercial operations these typically need a more costly constellation (circles). Thus, we see costs to experiment on both technical and commercial parts of a new venture: one satellite to test technical feasibility, a full constellation to test the market. In grey, we also see commercial R&D satellites – earlier technical experimentation, often far cheaper but distantly linked to revenue. Overall, Figure 4 shows dramatically dropping experimentation costs of all kinds (100× or more), for both telecom and Earth observation commercial satellites.

Key events impacting the (small) satellite sector are shown on Figure 4's x-axis: Surrey Satellite Technology Ltd (SSTL) became a pioneer of small satellite systems (Sweeting 2018). The 'P-POD' standard launch interface (CubeSat dispenser) drove an explosion in nanosatellites (Sweeting 2018), 'the true enabling technology for this class of mission' (Swartwout 2013). Indeed for Swartwout, 'the true innovation of CubeSats is the P-POD launch interface' because it decoupled development,

Dufourstrasse 40a
CH-9000 St.Gallen
Tel +41(71)224-2525
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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 2007 iPhone launch symbolises the miniaturisation enabling small satellites; 2013 saw a doubling of on-orbit CubeSats, which by 2014 were mostly company-launched, not academic or agency-launched).

Figure 4 indicates that minimum experimentation cost for commercial-grade satellites is lately in the few hundred thousand range, or a few million / tens of million for a commercial constellation. This compares to the hundreds of millions of dollars historically needed for large commercial satellites. Academic CubeSats can be flown for US $50'000–300'000. There has also been an increase to 10+ 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).

Decreasing costs of producing, distributing, and scaling

The space sector has also recently seen a massive decrease in recurring costs of production and distribution – e.g. the decrease of all costs induced by the scalability of innovation. This decrease has two components: the classical mechanisms of improving production and operation costs – including technology standardisation, large batch numbers, and many quasi-identical experiments; and the increasing share of software in the total value of space systems. Software and other digital technologies are, indeed, key factors for low-cost scalability. These two components are presented below.

Regarding the first component, by producing more (and similar) artefacts and products, these mechanisms can potentially lead to technological learning and then to cost reductions. This is the classical, well-documented 'learning curve' that secures business returns and economic viability in the long run (e.g., Ulrich & Eppinger 2012). However, as with nuclear technologies, substantial cost reductions do not materialise when system designs and architectures continually change (Grubler 2010).

Learning by doing and learning curves have been identified as key factors, via shorter (one-year) development cycles, for CubeSats. Similarly, with the shift to constellations, growing batch numbers allows learning. Although tracing precise learning curves is challenging due to cost data confidentiality, other cases seem to show them.

SpaceX has both launchers and Starlink satellites that feature major iterations and learning. In launchers, SpaceX went from the Falcon 1 (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 6 shows a rough 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 5 shows the listed price over the listed maximum capacity to a reference orbit, taken at the time of each launch (SpaceX 2023). The Falcon Heavy is basically three Falcon 9 cores strapped together, for far more capacity. The Merlin engine was developed with the Falcon 1; used for all but Starship, it was also upgraded considerably from the 1A (2006) to 1D (2013; see Table 3, bottom). Finally, according to *The Economist* (2022), it is hoped Starship launches will cost in the low millions for up to 150 tonnes of payload.

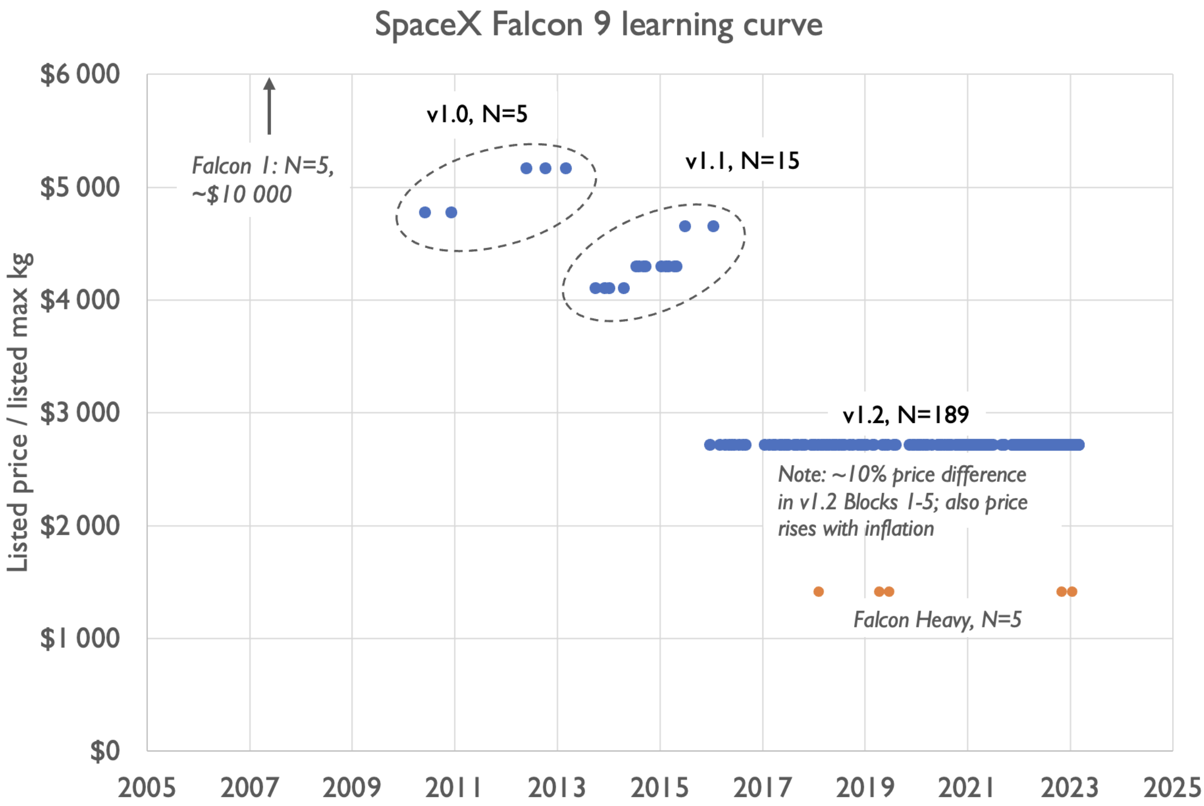

Figure 5. SpaceX's 219 launch attempts of as of March 3rd, 2022, at their listed prices and max capacities, to a reference LEO orbit (SpaceX 2023). The 209 Falcon 9 launches dominate; we see learning evidenced by decreasing prices vs. time. All SpaceX vehicles except Starship used versions of the Merlin engine; engines are typically ~60% of a rocket's cost.

In addition to decreases in costs via learning, and consistent with Cornell (2011), Jones (2018) argues that SpaceX was successful in lowering costs via a focus on simplifying design and new industrial culture. This includes (e.g.) boosting production and launch rates, changing production methods 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.

As for other firms, Planet continuously iterates its Dove satellites, with 15 builds in 6 years (suggesting a 3-to-6-month design lifecycle) over its 500 launched. Through the different cycles, the company substantially upgraded the satellites while likely cost-cutting (Harrison 2022). OneWeb reached the point of building two 150-kg satellites per day for its planned batch of 648, 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 allow continuous testing and learning, key to long-term cost reduction. With Falcon, the beginning of reuse (and return of material) has brought invaluable, unprecedented data on component durability

(Clapp 2022). By contrast, batch numbers were low in the TA regime, where prototypes were costly and test data scarce.

Comparing launch costs of the Falcon 9 with the prior market leader, Ariane 5 (developed under a TA regime), a huge gap – almost a 4× decrease – emerges as a result of learning effects (see Table 3). Falcon 9's costs continue to drop, and the oft-used Space Shuttle was ~5× more expensive per kilogram than Ariane 5 (NASA claims marginal cost was ~2×; additionally, the Shuttle had 'extras' like seven passengers and significant downmass, which should be considered when making such comparisons). There is also far better access to space for smaller satellites, with ridesharing and similar markets recently created.

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: < 1m²)*	>$30/km² (2002) *(Fraser 2003)*	< $15/km² *Low resolution:* $1/km²
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.)

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 specialised 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

Dufourstrasse 40a
CH-9000 St.Gallen
Tel +41(71)224-2525
Fax +41(71)224-2536
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every 5 years, and this should continue with very high-throughput satellite tech and LEO constellations (Serra and Northern Sky Research 2018).

According to McKinsey and WEF's (2022) interviews with 100 leaders from private and public institutions, 'technological advances in software, miniaturisation, off-the-shelf components, and reusable launch vehicles have combined to reduce the cost of reaching and operating in space.' Miniaturised and non-space components were discussed around Table 2. Though obviously key to cost decreases, often new component availability triggers a process of testing, learning, and integrating them into new designs before costs can drop. This process may be needed for non-radiation-hardened consumer electronics. Because using them in a design brings risks, electronics miniaturisation often slashes experimentation costs, and large cost cuts emerge later.

Looking at Table 3, it seems the space sector has finally entered a moment of potentially world-changing decreases in costs due to innovations – as described by Ridley (2020), cited in our introduction.

Software and scalability

The second component of cheaper scalability is an increase in space systems' software content. This is part of the rise of software-intensive systems, including in automotive and aviation; e.g. the Boeing 777 was thought to cost $3B to develop (Ulrich & Eppinger 2012), of which $800M for software development (Long 2008).[17]

As for satellites, successive standard cost estimation models show a high, and rising importance of software. Flight software for example missions in USCM8 might cost 10-20% of the satellite bus (for larger, older satellites) to 20-50% in SSCM (smaller, newer satellites) (Wertz et al. 2011)[18]. Thus both time and decreasing satellite size push towards cost residing in software, which is relatively scalable.

Software captures not just a higher proportion of cost, but also of value: there is strong statistical 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' portfolio has risen from 7% in 1981 to over 20% in 2005, making aerospace innovation more software intensive than automotive or medical devices. The sample of firms accounted for 73% of global production in aerospace & defense. This is in agreement with industry consultant analyses, that also emphasize the growing importance, relatively, 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 and 2.8% in manufacturing and launch, respectively; Tanghe 2023).

[17] We were unable to verify Long's reference; however, $800M is broadly consistent with the verified figure of 2.5M lines of code, using standard cost models like COCOMO (Wertz et al. 2011).

[18] 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.

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ii. Demand side

On the demand side, three intertwined changes seem relevant: an increase in market size with the emergence of business opportunities; a larger consumers' willingness to pay for innovative products and services; and a decrease in (buyers') uncertainty .

Market size and the emergence of business opportunities

The promise of a large market is an important driver for entrepreneurs looking for commercial opportunities (Jones 2022). This is what we see in the space sector, where the nascent commercial development culture goes hand-in-hand with the promise of untapped markets and business opportunities.

NewSpace companies cover all segments of the space industry (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 beyond LEO like lunar mining (e.g., ispace). Space tourism (e.g., Axiom), a market unlocked by better, easier, cheaper access to space, is an example of new business opportunity. It is currently the object of fierce competition among several NewSpace firms including Blue Origin, SpaceX and Virgin Galactic; it is projected to reach about $400 M in the next decade (Weinzierl et al. 2022). More generally, space sector 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, and use of, internet services from space. At 4–10% annual growth, the space sector should grow much faster than the rest of the economy, as OECD (2018) long-term forecasts indicate the world's (respectively US) real GDP should grow at an average annual rate of 2.8% (1.9%) over 2020–2040. This is why investment banks and market analysts call the sector a 'space of opportunity.'

Greater willingness to pay

Consumers' willingness to pay is another important driver of innovation, as it provides potential innovators with an addressable market that may allow them to generate returns on their investments (Jones 2022). Recent years have showcased an increasing consumers' willingness to pay for space related products and services. Here, we present three key examples.

First, the case of Starlink – SpaceX's satellite constellation, providing high-speed internet access across the globe – is particularly revealing. Despite a relatively high price ($90/month for service and an initial hardware purchase of $599) [19] many consumers have proved willing to pay for reliable internet available everywhere. Indeed, in March 2023, SpaceX announced on twitter that it had reached 1.5 M subscribers. The company aims to capture a share of the $1 trillion worldwide internet connectivity market (Pultarova 2023), currently dominated by ground-based tech, fiber and 5G. The large addressable market and the scalability of satellites compared to ground-based infrastructure – constellations can theoretically serve anyone on the globe – attract significant investments. As of July

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

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2023, SpaceX had 4'487 operational satellites (Pultarova 2023), about half the global total or ~8'200 (ESA 2023), with plans for tens of thousands more. Competitors are also investing massively in broadband constellations, with Amazon's Kuiper (3'236 satellites planned) and OneWeb (648).[20]

Second, space tourism also yields interesting insights: while space travel has long been possible for only a select few professional astronauts and very determined multi-millionaires, recent years have seen the emergence of companies aiming at a broader space tourism market – through orbital and suborbital flights (e.g. Virgin Galactic, Blue Origin, SpaceX, Axiom Space). Ticket prices now range from $450'000 for a suborbital flight with Virgin Galactic – relatively "easy", a few minutes of weightlessness at the lower edge of space – to e.g. $50-75 M for a trip to the ISS or with SpaceX to orbit (Colglazier & Ahrens, 2023). As of Dec. 31st 2022, Virgin had collected deposits worth $103 M, on $310 M of tickets sold, for 800 future astronauts. While sustainability of the market remains to be proven, the fact that several firms have backlogs (e.g. Blue Origin, Axiom) shows that some customers are willing to pay for the experience, triggering investment and competition.

Third, the case of Planet is also interesting. It shows that a company with an innovative business model can develop markets and "discover" more willingness to pay. The firm was created in 2010 to provide Earth Observation imagery more frequently but at lower resolution, and thus 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 (Satellite Applications Catapult 2014, slide 5). At the time of Planet's first "public" customers in 2014, it managed to sell lower-resolution imagery (3-5 m instead of 1 m) that was more frequently updated (Satellite Applications Catapult 2014, slide 5), and thus made it possible for nanosatellites and their smaller optical systems to be commercially viable. In 2021 it had over 850 customers (>25 buying above $1M), with over 60% institutional (defence & intelligence, or civil government) and 59% North American, generating $130 M of revenue, and $48 M gross profit (Marshall et al. 2022).

Lower buyer's uncertainty

The decreasing uncertainty of buyers about the reliability and performance of innovative products and services offered by new players also plays a major role, as it has a direct impact on new technology adoption (Jones 2022). This is certainly happening in the space sector, as shown by the boom of commercial launch vehicles and nanosatellites.

Rocket launches have long been the prerogative of governments and government-sponsored companies, due to their large costs and risks. Building a new and reliable rocket outside the traditional NASA procurement model was considered impossible, a belief further supported by the failed attempts of the 1980s (Berger 2021). However, the success of early NewSpace venture SpaceX completely shifted the narrative (Cornell 2011). The company conducted its first successful launch (Falcon 1) in late 2008, an important milestone for the industry. It showed that a private firm with no legacy knowledge and hardware could develop a working, reliable and competitive launcher using

[20] According to information available on Amazon (2023) and OneWeb (2023) websites.

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CH-9000 St.Gallen
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Fax +41(71)224-2536
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private capital.[21] Indeed, industry consultants BryceTech (2016) report 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 outexecuted some of the more traditional folks. That gave permission to a whole bunch of other folks to think about the problem." Consequently, as rocketry was no longer "too hard" for them, capital poured into nascent space companies, especially launch firms. In 2022, more than 100 small launch vehicles projects were in different stages of planning or development, according to BryceTech (2022). While the report notes that many of them will not materialize and that the maturing market will eventually run into a shakeout, such a boom emphasises the large uncertainty reduction regarding entrepreneurs' ability to master such technology.

Although small satellites began to be useful around the year 2000 (Sweeting 2018), nanosatellites and CubeSats – the smallest to be launched *en masse* – continued to be "an early curiosity with limited utility". They were seen principally as training tools (Jayaram & Swartwout 2010), without commercial use (Carvalho 2020). As shown on Figure 4, 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 (Fig. 4's coloured points well under $10M are nanosats, except MicroStar and Starlink). There were commercially-paid tech demonstration and R&D nanosats through the 2000s (grey dots, Fig. 4), but no serious attempt to generate revenue – meanwhile, universities launched dozens. Universities' improvements and demonstrations and the continuing march of Moore's Law decreased uncertainty about the technology's utility. Then finally, Planet showed it was possible for a constellation of CubeSats to be the basis for an Earth Observation business. This triggered interest from Silicon Valley capital as tech investors recognized the potential of satellite data for information-centric business applications, and the relatively low cost and ease of the CubeSat platform (BryceTech 2020). Thus the decrease in uncertainty around the tech led to thousands of firms built around nanosats (Kulu 2023).

iii. Institutions

Institutions have been important for the rise of innovation in the sector. Here, we discuss the impact of NASA's new roles, and the transformation of the market structure of the sector toward more competition.

New roles for NASA

NASA's new role accompanies and reinforces innovatisation.[22] Its contracting philosophy has evolved, notably due to the use of the 1958 Space Act for setting up a wide variety of public-private

[21] Of course, SpaceX also received significant support – expertise, financing, access to infrastructures – from the government, especially from NASA. However, as we show in section 5.b.iii, the help provided by NASA was of a very different nature compared to previous programmes. The agency notably implemented a co-financing mechanism, moving away from traditional cost-plus contracts – where all costs are refunded – and forcing companies to have "skin in the game" by investing their own capital.

[22] Here we refer to NASA, but similar evolutions can be seen for the DoD, also a key actor in the sector.

partnerships (PPP).[23] This has triggered deep changes in the space ecosystem (Mazzucato and Robinson 2018) and thus the agency's role, transforming it in at least three fundamental ways.

First, it now acts more like an investor, supporting innovative firms via funding. NASA as an investor characterises a situation in which NASA takes a role akin to that of a VC investing in start-ups, with the aim to develop a competitive space industry. While smaller initiatives like the SBIR programme (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) programme.

Initiated in 2005, COTS had two goals. The first was that it should provide a replacement for the Space Shuttle after the 2003 Columbia disaster. The second was that it should create a 'broader, more competitive industry that would serve societal and NASA needs at a cost less than 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 the traditional procurement model based on cost-plus FAR contracts: it aimed at developing new capabilities (in this case, 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 – as they needed to complement that amount with their own money; and the design of the PPP was such that they could innovate freely with their own designs (e.g., through lower amount of oversight but milestone dependent financing). Importantly, they retained ownership of intellectual property, which they could leverage through commercialisation. The goal here was to increase companies' incentives to innovate by increasing appropriability of research: by retaining IP rights, they could capture a larger share of the innovation's value through commercialisation and the acquisition of new customers beyond NASA.

For the COTS programme, companies defined their own business models and milestones, like they would for a VC firm. For its part, NASA would provide financing in stages as said milestones were reached. With this programme's success, two companies – SpaceX and Orbital – demonstrated the ability to deliver cargo to the ISS. With an investment of 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 programme by the Obama Administration made COTS the de

[23] Under certain conditions, the Space Act provides the agency with a far more flexible legal framework for implementing partnerships with private industry than the Federal Acquisition Regulation governing public procurements. In a *Practitioner's Guide to Space Act Agreements,* Schuman (2008), Attorney-Advisor at NASA Goddard, described the three possible types of Space Act agreements (SAA): reimbursable, non-reimbursable and funded agreements. Reimbursable SAAs are a type of partnership wherein NASA's costs (associated with the use of its facilities, personnel or equipment), which benefit primarily the agreement partner, are reimbursed totally or in part by that partner. Reimbursable SAAs are used when NASA has unique goods, services, or facilities that can be made available to another party in a way that is consistent with NASA's mission. Non-reimbursable SAAs involve NASA and one or more partners in a mutually beneficial activity that furthers a NASA mission. In this type of partnership, each party bears the cost of its participation and there is no exchange of funds. Funded SAAs consist in NASA transferring appropriated funds to a domestic partner for the purpose of accomplishing a NASA mission or to facilitate the development of a generic capability. This type of agreement was used for the Commercial Orbital Transportation Services (COTS) programme.

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CH-9000 St.Gallen
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facto solution for US access to space. This is why the Commercial Crew Programme (CCP) used the same model for the development of crew transportation capabilities in 2010.

The second interesting shift in NASA's role is that it has become 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. 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 it was eventually won by SpaceX and Orbital – the same two 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 contracts of the cost-plus type, NASA became one customer among others, buying relatively generic products or services at fixed prices. Figure 6 illustrates this by showing the evolution of NASA procurements by award type between 1993 and 2019. Fixed-price contracts totalled about 30% of NASA procurement in 2019 whereas they had accounted for less than 10% in 1993.

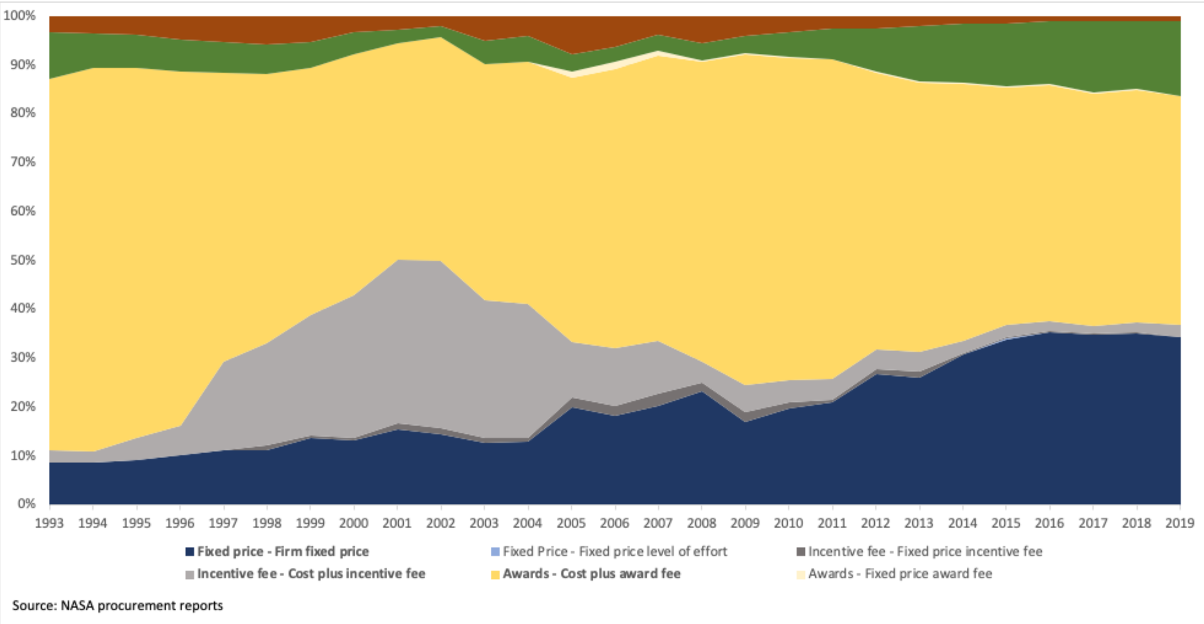

Figure 6. Value of NASA procurements awarded to firms by contract type (NASA Procurement Report 2019).

NASA becoming a customer has spectacular implications for innovation: first, it acts as anchor customer, enabling to kick-off companies' commercial case; second, it acts as a "stamp of approval" for other customers, enabling the company to expand its customer base. In turn, this creates a market structure that is much more favourable 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 using PPPs. This ranges from tech transfer to free or reimbursable access to world-class experts, and to facilities including launch pads and ground stations worth billions (MacDonald et al. 2014). For example, Nanoracks, a provider of brokerage services to use ISS labs, has a non-reimbursable SAA with NASA, which notably gives it

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access to the ISS at no cost (Mazzucato and Robinson 2018). This access is worth at least tens of millions of dollars. Similarly, after interviewing space ecosystem members, BryceTech (2016) emphasised NASA's key role as a technical resource. By encouraging its staff and board membership's entrepreneurship and participation in commercial ventures, or by encouraging its former leaders to provide consulting services, NASA supports the transfer of expertise to the wider ecosystem.

The somewhat unplanned shift in NASA's role is remarkable, both in the ecosystem and in its contracting policy. The latter evolved from a focus on fulfilling specific technological requirements – with costs which were by nature less predictable and thus fully reimbursed – towards a new logic with fixed prices and providing incentives for firms to innovate and to reduce costs. NASA's role then evolved to become an investor, customer, and partner in the industry. Moreover, the agency is still seen as a development leader for large space missions which involve high-risk technology development (BryceTech 2016). For Lambright (2015), the commercialisation of LEO allows NASA to redirect its resources to deep space exploration.

Market structure: toward competition

From the Monopsony-Oligopoly of phases 1 and 2, the market structure of the space sector has slowly evolved toward a more competitive state, pushed by the rise of entrepreneurship (see section 5.c.i). This has an important impact on innovation, as the increased competition from start-ups completely disrupted the sector, bringing a new entrepreneurial culture and business models based on commercialisation and innovation. Obviously, the evolution of the competitive landscape forced legacy companies to adapt, which we discuss in this section.

The evolution of the competitive landscape and the resulting evolution of the legacy industry is perfectly illustrated by Boeing and the development of its new capsule for human spaceflight – the *Starliner CST-100* – within the CCP, a funded Space Act agreement. In total, the company received $4.82 B for the capsule (NASA 2019). As with the 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 in Section 5.b.iii, a philosophy which uses fixed-price contracts to leverage private capital by forcing companies to invest themselves, innovate, and find commercial applications beyond government markets. 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 (HLS) – a Moon landing demonstrator for the Artemis III mission. The contract followed the same principles as COTS and the Commercial Crew Program.

Yet while these two examples show legacy aerospace firms trying to adapt to this new environment and philosophy, they also illustrate their difficulties in doing so and their dependence on government contracts. Indeed, SpaceX received only $3.14 B from NASA to develop its capsule; Boeing received $4.82 B (NASA 2019). Yet Boeing has had several schedule slips during the capsule's development, requiring it to pay $900 M in penalties (Foust 2022). As of this writing, Boeing has yet to demonstrate a crewed flight, whereas SpaceX achieved the milestone in 2020 (*sans* penalties). Similarly, the National Team lost to SpaceX as NASA expressed concerns about its proposal, including limitations to

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CH-9000 St.Gallen
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its commercial approach (Lueders 2021).[24] The agency stressed the lack of evidence on how costs would be reduced and how the technology would apply to other markets beyond Artemis (Lueders 2021).

c. Entrepreneurship and Venture capital as catalyst of the innovatisation process

Underlying the evolution of the drivers mentioned in the previous subsection, is the major role played by new entrants, and in particular start-ups. Entrepreneurs supported by venture capitalist were an important catalyser of all of these changes. Indeed, NewSpace start-ups took advantage of the favourable conditions created by the evolution of the drivers presented in section 5.b, by raising large amount of private capital to invest in R&D and attract a new generation of talented and well-trained engineers. In this section, we provide empirical evidence of the rise of entrepreurship and venture capital in the space sector.[25]

i. The rise of entrepreneurship

The 2000s were characterised by entrepreneurship and the emergence of NewSpace companies: start-ups that leverage private capital to develop innovative business models and address new or existing space markets with disruptive solutions (Vernile 2018). Figure 7 illustrates this rise of entrepreneurship, showing the number of financed start-ups by founding year.[26] Two periods are visible. In the first half of the 2000s, we see a few foundations realised by wealthy individuals (e.g., Jeff Bezos, Elon Musk, Richard Branson) investing their personal wealth into space ventures. This first period of successful new firms was key to sectoral development, signalling to entrepreneurs and venture capitalists that it was possible to create a successful venture in space (Vernile 2018), and triggering a second, larger wave of start-ups.

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

[25] In section 5.d. we provide empirical evidence of the two emerging properties of the space sector, emphasising in more details the pivotal role played by entrepreneurs and venture capital.

[26] 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.

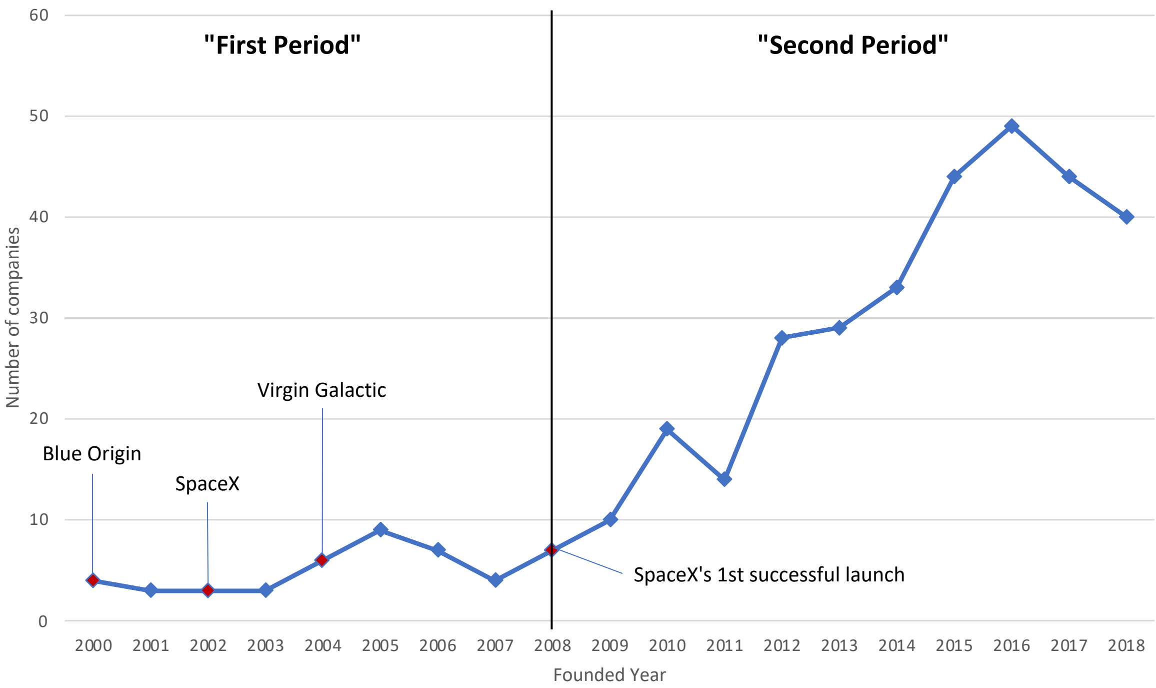

Figure 7. Global Angel- and VC-backed space start-ups by founding year during 2000–2018. Adapted from BryceTech (2021).

While the rise of entrepreneurship is a trend observed in other deep tech sectors (Dealroom et al. 2023) its impact in space is remarkable when it comes to changing culture and organisation – challenging the Big 5 oligopoly. Emphasising this point, Cornell (2011) argued that in order to be competitive, NewSpace companies take advantage of being everything the Big 5 are not. NewSpace companies are: (i) small, specialised 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 a higher risk tolerance.

Berger (2021) provided another interesting example of the cultural revolution, in SpaceX:

> On August 20, 2010 Thomas H. Zurbuchen, professor of space science and aerospace engineering at the University of Michigan [later becoming associate administrator at NASA] wrote in *Aviation Week* journal: 'On June 4, Falcon 9 achieved orbit, and I won a number of bets. In most cases, the people I bet against were predicting failure for reasons related to SpaceX's lack of experience and heritage hardware. The young crew at the heart of SpaceX, and their leader, Elon Musk, sure don't look like their peers at Lockheed Martin, Boeing or Orbital Sciences! They do lack experience and definitely lack heritage hardware. Yet, I won my bets because I strongly believe there are things more important than experience and heritage, such as an entrepreneurial culture and talent. And this is where SpaceX is currently head and shoulders above its competitors.'

In the launcher and transportation segment, SpaceX exemplifies the results of the new entrepreneurial culture. NASA estimated that developing the Falcon 9 would have cost $3'977 M based on its traditional environment and culture, and $1'383 M with a more commercial approach (using the NASA-Air Force Cost Model, NAFCOM). The estimated SpaceX expenditure using a fixed-price contract totalled $443 M (NASA 2011b). The reasons for this decrease have yet to be clearly identified (NASA 2011a), but preliminary investigations suggest vertical integration, organisation design and work methods from IT and accelerated information flows, as well as strong incentives and leadership, may be factors (Rasky 2015).

ii. The rise of Venture Capital

Along with the rise of entrepreneurship, the amount of private funds poured into the industry, notably through VC, is remarkable. Among the main beneficiaries are companies operating in LEO (Lerner, et al. 2016). Reports from BryceTech (2016, 2022) indicate that globally, $9 B of venture capital 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 decrease in experimentation costs, as lower costs enable VCs to finance more firms or earlier experiments. 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 rise 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 business.[27] 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), this trend marks a sort of normalisation of the space sector. It signals that the sector is entering a more economically viable phase, with private investors directly entering the space economy, resulting in less dependence on government and ending its monopsony.

As these resources are invested by start-ups for the development of innovative products, the increase in R&D input potential has therefore become enormous, driven by business opportunities rather than political or national security objectives.

d. Emerging properties

In Section 5.b, we presented initial changes – which we called drivers – kickstarting the innovatisation of the space sector. Indeed, over time, these changes created conditions favourable to innovation, which resulted in a increase in R&D inputs – R&D expenditures and human capital – boosted by the rise of entrepreneurship and venture capital (5.c). This resulted in two emerging properties of the space sector, which we describe below.

[27] 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.

Dufourstrasse 40a
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Larger R&D effort

Sections 3 & 4 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 shatters this ceiling because it is characterised by a big boost in R&D efforts – notably via expenditures – from the private sector as it complements and de-emphasises public funding. Such innovatisation is visible in two emerging R&D financing sources: NewSpace firms (backed by private capital, e.g., VCs), and non-space companies.

According to a recent McKinsey report (Brukardt et al. 2021), the share of public spending in US space-related R&D, which was more than 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 venture capital (see Section 5.a), invested almost $6 B in 2020 whereas they had invested less than $1 B in 2010.

The rise in R&D spending in space also comes from non-space companies, firms that are neither aerospace nor NewSpace companies but 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 by both new technologies (e.g., nanosatellites) and legacy technologies, and on the companies' 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 provide its devices with internet access anywhere in the world (Weinzierl et al. 2022). Weinzierl et al. (2022) argue that all companies should have a space strategy to boost their value proposition. They cite the pharmaceutical industry, which uses space for research: 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 growth in human capital. This can be explained by both (1) a more attractive sector and (2) evolving space tech education programmes in universities.

First, the sector has become significantly more attractive to talent in recent years. A 2022 survey conducted by the firm Universum names the top five most attractive companies for recent US engineering graduates: SpaceX, Tesla, NASA, Boeing, and Lockheed Martin.[28] While such surveys must be taken with caution, the attractiveness of space is striking, with four of the top five spots and six of

[28] The survey sample was 49'197 students from 317 US universities; engineering was a subsample (Universum 2022).

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the top ten. The 2009 survey yielded a top five of NASA, Lockheed Martin, Boeing, Google, and General Electric; space had three of the top ten spots.[29] SpaceX stood out as the single most attractive firm in 2022, beating Moon-landing NASA. SpaceX and other NewSpace companies demonstrate cultures based on entrepreneurship, fast experimentation, and flat hierarchies. These companies' cultures may, 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 shows the cultural changes brought by NewSpace firms. SpaceX attracts the best engineers – not only to the company but also to the sector.

The second explanation for a boost in sectoral human capital is that universities' roles are evolving and expanding. In earlier decades, universities were focused on research; for example, MIT created the Apollo navigation and guidance systems. However, universities then expanded their role in an environment marked by a wave of retirements in aerospace and the technological change of tiny satellites.

Jayaram and Swartwout (2010) explained the contribution due to the development of the CubeSat standard and the creation of DoD and NASA programmes supporting hands-on education, such as the AFRL University Nanosat, CanSat, and CubeSat programmes. These shifts have contributed to (1) the multiplication of space education university programmes and (2) an increase in the quality of 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 5 years, on average 23 US university nanosatellites and CubeSats have been launched per year (Kulu 2023). Universities self-reported an average of 34 students involved in each of ten nanosat programmes over a 3-year cycle (National Academies of Sciences, Engineering, and Medicine et al. 2016, Table 3.1; personal communication from David Voss to Thomas Zurbuchen, January 2016). Assuming this corresponds to ten launches, almost 800 students are trained each year on nanosatellites – and they launch their satellites.[30] This account concerning nanosats does not count the many nanosatellites which are built but never launched; likewise, larger university satellites are not counted, nor are CanSats (of which thousands likely exist without having been launched). The 800 students per year can be compared to an average workforce of 20'800 in

[29] Year 1 of the survey had 60'930 responding students of all fields from 341 US universities (Universum 2009).
[30] A conservative assumption: seven were either launched or are scheduled to (Kulu 2023).

satellite manufacturing over 2012–2017 (BryceTech and SIA 2017).[31] In 2021, 7'100 students graduated from US aerospace engineering programmes (ASEE 2022), but aviation dwarfs space: only ~20–25% of engineers in the satellite industry are trained in aerospace programmes (SSPI and Korn Ferry 2016). As for the increase in quality, Jayaram and Swartwout (2010) related anecdotal evidence from hands-on programmes. For example, an aerospace VP said: 'Two of your students [from nanosatellite programmes] beat out dozens of other students from supposedly "bigger name" schools'. The VP continued: 'One didn't just beat out candidates for our post-grad internship, he got himself bumped out of that category into the permanent-hire category at a time I had no intention of hiring permanent new graduates. And it wasn't even close.' Graduate numbers and quality aside, universities have also nurtured many graduate-led space spin-offs.

e. Policy challenges

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'. 'Realised together, however,' Wenzierl continued, '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 programme, 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, Appendix D concerns in-situ resource utilisation, and Appendix H focuses the Human Landing System (the Artemis lander; see Section 5.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. In that case, no unregulated market outcome is also economically efficient. If perfect competition is imposed, production and operations cannot take advantage of the increasing returns, so costs are not minimised. If a monopoly emerges, the monopolist may be able to exploit the increasing returns, but they are likely to generate social inefficiency via above-marginal-cost pricing strategies. The inherent risks of this potential market failure are emphasised by SpaceX's recent successes with its semi-reusable Falcon 9 rocket and Starlink constellation. As the low-cost launcher allows a great many satellites to orbit, the synergies between these two SpaceX businesses generate increasing returns which lead to a dominant position for the company in both launch and satellite internet markets (The

[31] The last period available. Over 10× are employed in the 'satellite industry' (incl. services, launchers, ground stations; BryceTech and SIA 2017). However, both figures count all staff, not just engineers; ~2% of the US workforce retires every year.

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Economist, 2023). Recent events in Ukraine emphasise strategic benefits for the US, but they also emphasise the risks posed by such a concentration of power: Elon Musk threatened in October 2022 to cut access to Starlink. Counters to such market failures are, like the role of public policy, unclear; they may warrant future research.

A third market failure is negative externalities, arising when an economic agent's activity generates costs for other parties which it does not internalise. Clearly the rising number of objects in orbit, whether satellite constellations or debris (defunct satellites, parts, or smaller collision fragments) is a negative externality as Earth orbits (especially LEO) become congested and, eventually, access to space becomes 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, Weinzierl suggested that the lack of governance in space and the current legal framework (with, e.g., no property rights) could make their implementation 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 which 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 will not be funded because even when they pass the private return hurdle and 'normal' interest rate, the cost of external capital is too high. One aim for VC is to fix this market failure, and this aim is now being achieved in the space sector. But VC supply is limited in scope; it is not for all industries and projects. A possible complement or substitute is government subsidies for early-stage projects, such as NASA SBIR programme (Lerner 1996). Another possible solution may be financial engineering (e.g., megafunds and securitisation) to finance long-term risky projects (Hull, Lo, and Stein 2019).

6. Discussion and conclusion

In this paper, we aimed to analyse 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.

In the first phase, space developments like Apollo were insulated from the economy. The sector was moulded 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, and R&D, conducted by a

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few large incumbents, mostly addressed specifications of a single customer – the state, via NASA and the DoD. Pronounced centralisation and control left the model highly dependent on government policy. Thereby, such programmes were often subject to slips in schedule and cost (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 artefacts of such programmes' output technological achievements: like Apollo, they involved massive R&D efforts and were executed by a few organisations exempt from economic tests. For the aforementioned reasons, these TAs were not innovations. Nor were they science, because seeking scientific knowledge was not the main objective; science was often sacrificed, as it was in Apollo's case, to 'higher objectives' like national prestige (see our companion paper Chavy-Macdonald, Cornet, and Foray 2023). The concept of TA thus identifies a very particular class of achievements, focused on neither economic nor scientific discovery. However, they can be a great success by the criteria of technological performance and national prestige, as shown by Apollo.

After the TA period, the sector moved to Phase 2, a transition where some economic issues were tackled but the TA logic remained, before entering Phase-3 innovatisation, characterised by increasing decentralisation with government gradually ceding control of space activities to firms (Weinzierl 2018). Importantly, this was accompanied by an emerging entrepreneurial culture. Accordingly, the industry changed radically as young, small, innovative companies focused on cost reductions, new markets and high private returns. Decentralisation meant that NASA, which had at first set its own goals and defined its technology needs, had to rethink its role in the ecosystem, for example by implementing programmes to support innovative firms, or focusing on deep space scientific missions, leaving LEO to private companies (Lambright 2015). Decentralisation also implied a change in the agency's relationships; in particular, it led to innovative PPPs like COTS and CCP. While these programmes still feature a strong role for government, by providing incentives to innovate and commercialise end products they also drive companies to put skin in the game. The government benefits from lower-cost access to services.

Building on Jones (2022), we identified three sets of drivers of these profound transformations: (1) supply drivers are new technological opportunities, decreasing fixed costs of creating new products and services, and decreasing costs of producing distributing and scaling; (2) demand drivers are market size and the emergence of business opportunities, greater willingness to pay, and lower (buyer's) uncertainty; and (3) institutional drivers are the new role of NASA and a market structure featuring more competition. These drivers are further supported by the increase in entrepreneurship and venture capital, leading to two emerging properties of the sector in the form of an increase in R&D expenditures and human capital. This increase in R&D inputs in turn generate an increase in innovation in the sector.

The transition documented here is exceptional, perhaps even unique, in history. Because interest in commercialisation 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 conveying commercialisation. Instead, we think the concept of innovatisation, though new to the innovation economics literature, is better suited to capture the

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logic underlying the changes analysed here. Innovatisation causes great upheavals and simultaneously is a resource multiplier and a generator of new opportunities. All the actors of the prior TA regime – accustomed to certain routines – have come to face new constraints, new challenges, and new 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 provides significant benefits for 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 the nature of space activity: for example, the prospect for welfare gain is rather clear for internet connectivity satellites, while it is 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 apply our framework to studies of the current challenges facing the European space sector and its central actor, ESA. One hypothesis to be 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, but 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

A. Key books and their author

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 organisation of the agency during the Apollo years, in which the author describes NASA's organisational 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 specialised 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.

B. Example component cost reductions

Table B.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 results from better components (de Carvalho et al. 2020), most of which are exogenous improvements due to Moore's Law. Table B.1 shows a 2017 AMD microprocessor, new GPS receiver and gyroscope – yielding ~10× improvements in miniaturisation and performance (not to mention cost) – coming from consumer electronics and now used in small satellites (Weston et al. 2023).

Also from Table B.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 B.1. Satellite component miniaturisation: 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).

C. Sources of satellite costs and dates

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 9, 2023. http://www.fundinguniverse.com/company-histories/orbital-sciences-corporation-history/ Jahn, H, E Lorenz, W Bärwald, and F Lura. 2005. “Affordable Space Missions.” Study Executive Summary Ordered, funded, and promoted by the DLR program board “Technik für Raumfahrtsysteme” (Space Systems Technology) and especially by Mr. L. Fröbel. DLR.
AprizeSat-1	McDowell, Jonathan. 2018. “Jonathan’s Space Home Page.” The History of Spaceflight - Part VIII. July 3, 2018. https://www.planet4589.org/index.html SpaceQuest. n.d. “SPACEQUEST SUCCESS STORIES.” Accessed June 22, 2007. http://www.spacequest.com/success_stories.php
QuakeSat 1, MAST, CSTB-1, AeroCube 2	Krebs 2023

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RapidEye	Sweeting 2018; "Surrey To Supply Bus And More For RapidEye EO Constellation." 2004. Space Daily - Your Portal to Space. June 21, 2004. https://www.spacedaily.com/news/microsat-04i.html
Mayflower-Caerus	Krebs 2023
exactEarth	exactEarth Ltd. June 23rd 2015. "Preliminary Prospectus." Filing to the Canadian Securities Administrators' System for Electronic Document Analysis and Retrieval https://www.sedarplus.ca/csfsprod/data151/filings/02366498/00000001/x%3A%5CSEDAR%5CexactEarth%5CPreliminaryProspectus2015June%5CPreliminaryProspectus.pdf. Wade, Mark. 2019. "AprizeSat." Referenced by Wikipedia: AprizeSat. Encyclopedia Astronautica. 2019. http://www.astronautix.com/a/aprizesat.html.
Weather News Inc.	Keshiba, Yuki. 2017. "First-Ever Private Weather Satellite Has Its Eye on the Arctic." *Nikkei Asia*, August 31, 2017, Online edition, sec. Business. https://asia.nikkei.com/Business/First-ever-private-weather-satellite-has-its-eye-on-the-Arctic. de Carvalho et al. 2020
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
Spire	Cowan, David, Sunil Nagaraj, and Josh Benamram. Memorandum to BVP Group. 2015. "Re: Spire Series B Flash," May 23, 2015. https://www.bvp.com/memos/spire
SpaceX	Barrett, Eamon. 2022. "How Elon Musk's SpaceX Lost 40 Starlink Satellites—Reportedly Worth as Much as $20 Million—All at Once." *Fortune Magazine*, February 10, 2022. https://fortune.com/2022/02/10/spacex-starlink-satellites-solar-storm-lost-elon-musk-internet/ Brodkin, Jon. 2020. "SpaceX Starlink Public Beta Begins: It's $99 a Month plus $500 up Front." *Ars Technica*, October 27, 2020. https://arstechnica.com/information-technology/2020/10/spacex-starlink-public-beta-begins-its-99-a-month-plus-500-up-front/ McDowell, Jonathan. 2022. "Starlink Statistics." Referenced by Wikipedia: List of Starlink and Starshield launches, Feb. 2023. Jonathan's Space Pages. November 2022. https://planet4589.org/space/con/star/stats.html

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D. 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
CCP: Commercial Crew Program
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
HLS: Human Landing 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

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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
USCM: Unmanned Space Vehicle Cost Model
VC: Venture Capital
VHTS: Very High Throughput Satellite

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