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Country-first domestic satellites: A family tree

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ABSTRACT

The history of satellite development is at an inflection point: around half of all countries have made and launched satellites, while another half has not. In this context, the time appears right to take stock of lessons learnt from the development of country-first domestic satellites. These are defined as the first to have been designed, assembled, integrated, and/or tested with significant input from local engineers. This paper reviews, for the first time, the genealogy of the 90 country-first domestic satellites launched into orbit to date. The comprehensive, trans-disciplinary analysis is based on an extensive literature review in multiple languages. Firstly, a family tree of country-first domestic satellites is constructed, mapping out important stakeholders and lineages. Four major generations are identified. Although country-first domestic satellites are often associated with domestic identity, they are without exception the product of international collaboration and technological exchanges. In parallel, a growing global market for satellite development and launch services has played an increasingly important role in their development even in the absence of official country-to-country collaborations. Secondly, the birth traits, life, death, and legacy of such satellites is reviewed in detail. Sustainability of the Earth's orbital environment has typically not been prioritised by mission teams. Most countries having developed a first domestic satellite have also developed a second, but there have been more one-off firsts since the 1990s: microsatellites and CubeSats can be used to test the waters of space engineering without having to make a big commitment. Looking to the future, access to a domestic satellite is becoming easier and easier. The challenge is instead shifting towards ensuring that such an initiative is actually aligned with domestic industry, technologies, and STEM education, as well as sustainability of the Earth's orbital environment. Long-term planning and vision are important in this regard. It is hoped that this review paper will provide a useful reference point for space historians, policymakers, and the pioneers of diverse new satellite missions.

1. Introduction

As of December 2023, 90 countries have developed and put into orbit their own domestic satellites. The satellites and their countries of origin are shown in Figs. 1 and 2. Another 12 countries own non-domestic satellites. A "domestic satellite" in this paper refers to one which has been designed, assembled, integrated, and/or tested with significant input from domestic engineers. For example, a satellite procured from another country and delivered on-orbit in turnkey style is not a domestic satellite. The above numbers show that the world is currently at an inflection point in the history of space development: satellites are definitively shifting from the domain of technologically advanced nations towards being ubiquitous, accessible to all countries willing to develop, launch, and operate one.

Despite this, the fact that around half of all countries have developed domestic satellites means that another half has not. In this context, the time appears right to take stock of the history of country-first domestic satellites. For instance, shedding light on the genealogical ties between them – making a "family tree", in other words – may help generate new perspectives on international collaboration in the space field. A survey of this kind is also expected to provide valuable insights into the challenges, including technical ones, during the "birth", "life", and eventual "death" of a country's first satellite. These may be helpful for other countries willing to develop their own first satellite, or even for space newcomers attempting to develop one in a country that already has domestic satellites. Finally, a comprehensive, trans-disciplinary review of country-first domestic satellites, not limited to their technical specifications but also including the broader context within which they were developed, may help identify patterns for understanding present and future trends in space development: what

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Fig. 1. Images of country-first domestic satellites, arranged chronologically by launch date from top left (Sputnik-1) to bottom right (EIRSAT-1). Images sources are listed in Appendix A.

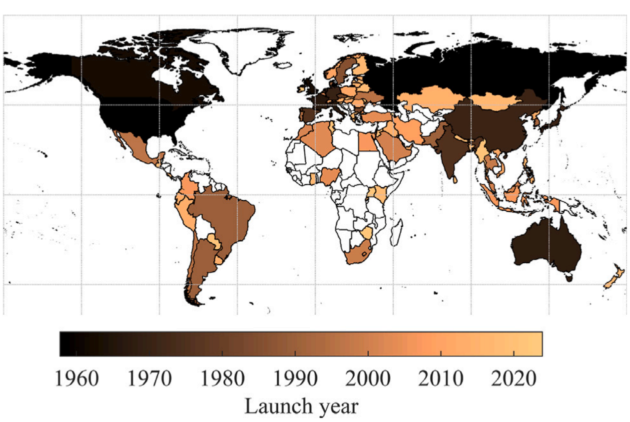

Fig. 2. Country-first domestic satellites by launch year.

will the next generations look like, on the family tree? How will they depend on and feed into wider trends in satellite development?

Information on country-first domestic satellites is surprisingly difficult to find. It is scattered in different databases, each providing part of the picture by catering to a specific community. It is often not available in English. It is usually incomplete, capturing a snapshot of the satellite's development at a given instant in time, or focusing only on the technical at the expense of details on the stakeholders involved, or deliberately omitting unsuccessful mission outcomes. It is sometimes hard to access, provided on websites which have since been archived, or given only in scanned documents. It may even be contradictory, with different authoritative sources listing different facts. In summary, at present there is no comprehensive dataset on country-first domestic satellites. Developing such a dataset is a significant undertaking, and the fruits of such an investigation are expected to be of value in themselves, as a consolidated record of the history of country-first domestic satellites. Is it possible to construct a complete family tree of country-first domestic satellites around the world? Do members of the tree share common characteristics, and can trends be identified in time or in space? Do certain ancestors have more descendants than others? What can be learnt from their birth, life, and eventual death and legacy?

To address these questions, the manuscript is structured as follows. Section 2 presents the methodology. Sources used to obtain data on the 90 country-first domestic satellites are listed, and the challenges and limitations of data collection are discussed. Section 3 constructs a family tree: the main stakeholders involved in funding, building, testing, launching, and operating the satellites are reviewed. The family tree maps out connections between the development histories of the country-first domestic satellites. Section 4 then focuses on the birth traits of each family member on the tree. From a cultural perspective, the satellites' names are expected to provide clues on motivations underlying their development, and patterns in time and space are discussed. From a technical perspective, the design of the satellites' subsystems such as their structure and payloads is expected to yield insights on how their genealogy has been influenced by global technological trends. Finally, Section 5 examines the life and eventual death and legacy of the country-first domestic satellites: their mission objectives and outcomes, and their current status. A discussion is included on the satellites' impact on space development within their respective countries, such as on follow-on domestic satellites. Section 6 summarises important lessons learnt on past generations of country-first domestic satellites, and future perspectives on the next ones.

2. Methodology

Information on country-first domestic satellites is gathered in two steps: (i) for each country, it is checked whether a country-first satellite has been developed; and (ii) if one has, then data is collected on the history of its development and operations. The process is illustrated in Fig. 3 and described in more detail below.

Both steps were applied for all member states of the United Nations as well as the two United Nations General Assembly non-member observer states, i.e., 195 states. Step (i) was conducted via a search on Google, using keywords such as the country's name followed by "first satellite". If no country-first satellite was found, then Step (i) was repeated for the next country. In Step (ii), satellite-specific resources were sought in journals, conference papers, books, news pieces, magazine articles, websites, podcasts, videos, social media, and blogs. A non-exhaustive summary of main references used for each satellite is shown in Table 5 in Appendix B. These provided the satellite's technical specifications, development process, and operations history. The satellite's listed name is the most commonly used one. The information was then cross-checked against the databases listed in Table 1, which are among the most authoritative and complete satellite databases. For reference, countries owning a satellite but not having developed a domestic one are listed in Table 2. The main challenges of the above data gathering method, and approaches used to overcome them, are listed in Table 3.

In some cases, there is room for discussion on which is the true first domestic satellite, particularly when two "firsts" were launched at the same time or when the satellite was developed with limited domestic involvement. In this paper, the following decisions are made. *Saudi Arabia*: SaudiSAT 1A and SaudiSAT 1B were both deployed from the same launch vehicle, within a few seconds of each other [1,2]. According to their international alphanumeric designators (2000-057A and E), SaudiSAT 1A (2000-057A) was released first, and in this paper it is considered as the country first. *Austria*: UniBRITE and TUGSAT-1 were developed under the leadership of two different Austrian universities, and designed and manufactured by the Space Flight Laboratory (SFL) at the University of Toronto Institute of Aerospace Studies (UTIAS). They were launched in the same PSLV rocket in 2013. TUGSAT-1 was deployed around 20s before UniBRITE [3], and is widely considered to be Austria's first domestic satellite. *Lithuania*: Litsat-1 and LithuanicaSAT-1 were released one behind the other from the International Space Station, less than one second apart, with Litsat-1 ahead [4]. Hence for simplicity, Litsat-1 is considered the "first" in this paper, though both are widely recognised as the joint first. *Greece*: LambdaSat, launched in 2014, was built by a team at San Jose State University in the United States comprising Greek nationals [5]. Although one Greek institution, the University of the Aegean, contributed to ground-based operations, the project was initiated and led by the United States team [6]. Hence the later UPSat, launched in 2017, is considered as the country first satellite in this paper. Note that an earlier satellite called HELMARS-SAT is reported to have been developed by the Greek company Thesa in the 1990s, but was never launched due to funding issues despite being flight ready [7]. *Belarus*: An Earth observation satellite called BKA was launched in 2012 for the Belorussian Academy of Sciences, but it was fully developed by the Russian company All-Russian Scientific Research Institute of Electromechanics (VNIIEM) as a near-identical copy of a Russian satellite launched alongside it, with no reported contributions from Belarusian engineers [8]. Hence BSUSat-1, launched in 2018, is considered as the first in this paper. *Slovenia*: TRISAT, a CubeSat, and Nemo HD, a microsatellite, were deployed from the same launch vehicle. They are widely considered to be the joint first satellites of Slovenia [9]. On the one hand, Nemo HD was released into space first, a few minutes before TRISAT [10]. On the other hand, TRISAT was designed, assembled, integrated, and tested in Slovenia, whereas Nemo HD was developed in close collaboration with a Canadian institution. Hence in this paper, TRISAT is considered as the country first. *Kuwait*: The educational 1U CubeSat QMR-KWT was launched in 2021, in a project led by United Arab Emirates based start-up company Orbital Space. One objective was to grow space enthusiasm in Kuwait by inviting students to upload software to the satellite. Design and operations were managed by the UAE, while manufacture, integration, and testing were outsourced to Bulgarian company EnduroSat. No participation by Kuwaiti engineers is reported [11]. KuwaitSat-1, launched in 2023, is more widely recognised as Kuwait's first domestic satellite [12], and it is thus considered as such in this paper. *Armenia*: The 16U Earth observation satellite ARMSAT_1, launched in May 2022, was delivered on orbit by Spanish private company Satlantis to Armenian state-owned company Geocosmos [13]. Based on available information, no Armenian engineers participated in satellite development. Hayasat-1, launched in December 2023, was developed in Armenia by a team of local engineers and scientists [14]. It is thus considered as the first domestic satellite in this paper.

Finally, several satellites have been lost at launch, almost becoming country firsts: the United States' Vanguard TV-3 was launched in December 1957, but its Vanguard rocket failed to achieve orbit [15]; Mexico's UNAMSAT-A was launched around a year before UNAMSAT-B (its flight spare), but was lost when the 4th stage of its launch vehicle exploded [16]; Norway's nCube1 and nCube2 were respectively lost at launch in 2006 and never deployed after launch in 2005 [17,18]; Iraq developed a domestic microsatellite in the late 1980s called Al-Ta'ir, but could not obtain a launch opportunity and never launched it [19].

3. "Family tree": stakeholders and international cooperation

This section presents the "family tree" of country-first domestic satellites. It reviews the timeline of deployments and maps out linkages between important stakeholders. Since the history of country-first satellites is closely linked with the history of space launches, an analysis of the latter is also provided.

3.1. Timeline of deployments and stakeholders

This subsection attempts to trace out a family tree of country-first domestic satellites, by identifying links between them, against the backdrop of broader technological and geopolitical changes. As a starting point, Fig. 4 shows the name and deployment year of each country-first domestic satellite. Since the launch of the first ones in the 1950s – Sputnik-1 by the USSR and Explorer-1 by the US – the number of new deployments has exponentially increased, rising from around 5 or less per decade until the 1980s to over 30 in the 2010s. This trend, caused by various mechanisms including technological and political ones, can be understood with the aid of Figs. 5, 6, 7, and 8.

Fig. 5, organised as a family tree, maps out linkages between country-first domestic satellites over time. It identifies "common ancestors", "lineages", as well as important institutions and other stakeholders such as individuals who shaped their history. Fig. 6 is complementary, and identifies the functions of important stakeholders of each country-first domestic satellite. Similarly, Fig. 7 provides a timeline of main categories of stakeholders acting as prime contractor and as domestic lead for each country-first domestic satellite. Finally, Fig. 8 identifies satellites developed via international collaboration programs yielding more than one country-first domestic satellite.

A complete discussion on the history of each country-first domestic satellite is beyond the scope of a single paper, and instead the following discussion identifies major phases and some of their important characteristics, supported by curated examples. The history of

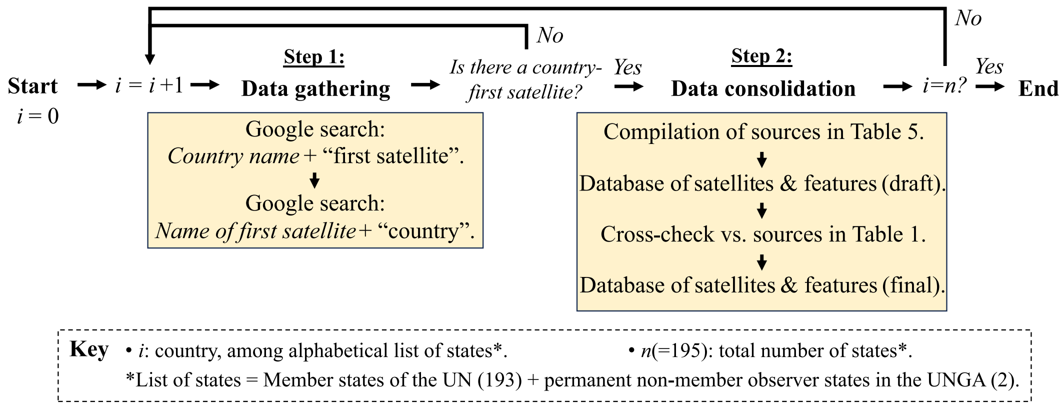

Fig. 3. Process used to identify and gather data on country-first domestic satellites.

Table 1
Major satellite databases, listed alphabetically, with pros & cons of each one.

Database	Pros	Cons
CelesTrak Satellite Catalog (SATCAT) [20]	Lists orbital information of most past and present satellites.	Focus on orbit.
CIA World Fact Book - Space Program Overview [21]	Provides general information on country space programs, e.g., activities and milestones.	Only satellite names and launch dates listed; Incomplete records.
EO Portal Satellite Missions catalogue [22]	Lists spacecraft, launch, mission status, payload data on most Earth observation satellites, with references.	Only Earth observation satellites.
Gunter's Space Page [23]	Lists nation, application, operator, contractors, equipment, configuration, propulsion, power, lifetime, mass, orbit data of most satellites.	Few references; Limited data categories.
Nanosats.eu [24]	Lists almost all launched CubeSats & nanosatellites.	Larger (& smaller) satellites not listed; Missing data for some satellites.
N2YO [25]	Lists orbital information on most past and present satellites.	Focus on orbit.
Satellites.com [26]	Lists name, operator, manufacturer, carrier rocket, launch site of many country-first satellites.	No references; Limited data categories; No updates since 2015.
SatNOGS Database [27]	Lists current status of many satellites, with references, e.g., mission information, status, image, mission timeline, description.	Only basic information provided; Focus on communication.
UCS Satellite Database [28]	Lists up to date information on most in-orbit satellites, with references, e.g., technical details, orbit, purpose, owner, operator, contractor.	Does not list decayed satellites.
UNOOSA Online Index of Objects Launched into Outer Space [29]	Lists basic information on most satellites.	Not all satellites registered; Only basic information provided; Few references.
WEBAU Space Encyclopedia [30]	Lists basic information on most satellites, e.g., manufacturer, platform, operator, mass, shape, equipment, stabilisation, propulsion, design lifetime, description, with references.	Many blank entries; No data after 2020.
Wikipedia List of First Satellites by Country [31]	Lists basic features of satellites first operated by each country, e.g., operator, manufacturer, launch, with references.	No distinction between domestic, non-domestic; Only basic information provided.
Wikipedia Timeline of Artificial Satellites and Space Probes [32]	Lists basic data on selection of spacecraft with focus on established space powers, e.g., launch date, status, description, mass, with references.	Many satellites not listed; Limited oversight & curation; Only basic information provided.
WMO OSCAR [33]	Lists basic information on most satellites for meteorological & Earth observation, e.g., description, mass, power, orbit, space agency, status.	Only basic information provided; Only Earth observation satellites.

country-first domestic satellites can be divided into four overlapping generations, described in more detail below: (1) simple payloads for launch vehicle testing and space science (1950s–70s); (2) government- and national institution-led satellites leveraging know-how and infrastructure from the USSR and US (1960s–80s); (3) academia, amateur, and industry-led capacity building programs based around microsatellites (1980s–2010s); (4) academia, agency, and industry-led capacity building programs based around CubeSats (2000s-present).

Generation 1: Simple payloads for launch vehicle testing and/or space science (1950s–70s). The earliest satellites were closely intertwined with the development of launch vehicles, both literally and figuratively. The groundwork for the first satellites was laid by the V-2 rocket, designed and developed by Wernher von Braun at Peenemünde in Germany [47]. It was used as a foundational element of the USSR and US rocket development programs after the Second World War [48], via Operation Osoaviakhim and Operation Paperclip respectively. In the USSR, the R1 rocket was closely based on the V-2 and in turn led to the R7, a variant of which was used to launch Sputnik-1 in 1957. In the US, the Redstone rocket was closely based on the V-2 and in turn led to the development of Juno-1, which launched the first US satellite, Explorer-1. It was integrated into the rocket's fourth stage. Sputnik-1 was developed by the USSR in the context of the International Geophysical Year 1957-58, and its US counterpart was Vanguard TV-3, lost at launch in December 1957. Explorer-1 was launched two months after the failure of Vanguard, led by the Army Ballistic Missile Agency (ABMA) with the Jet Propulsion Laboratory (JPL) as prime contractor [49,50].

Table 2
Countries with no domestic satellites, but with at least one non-domestic satellite. The first one is listed.

Country	Satellite	Why not a domestic satellite?	Refs.
Afghanistan	Afghansat-1	Leased on orbit by Eutelsat (France)	[34]
Albania	Albania-1	Delivered on-orbit by Satellogic (Argentina)	[35]
Angola	AngoSat-1	Delivered on orbit by RKK Energia (Russia)	[36]
Azerbaijan	Azerspace-1/Africasat-1a	Delivered on orbit by Orbital Sciences Corporation (US)	[37]
Bolivia	Túpac Katari 1	Delivered on orbit by China Great Wall Industry Corp. (part of China Aerospace Science and Technology Corp.) (China)	[38]
Ethiopia	ETRSS-1	Delivered on orbit by China Academy of Space Technology (part of China Aerospace Science and Technology Corp.), with some training of 21 Ethiopian technicians focusing on operations (China)	[39,40]
Laos	LaoSat-1	Delivered on orbit by China Great Wall Industry Corp. (part of China Aerospace Science and Technology Corp.) (China)	[41]
Qatar	Es'Hail-1	Sold on orbit by Eutelsat (France)	[42]
Sudan	SRSS-1	Delivered on orbit by Shenzhen Aerospace Dongfanghong HIT Satellite Ltd. (part of China Aerospace Science and Technology Corp.) (China)	
Tonga	Esiafi-1	Sold on orbit by Seattle Scientific Corporation Parallax (US)	[43]
Turkmenistan	TürkmenÄlem 52E/MonacoSat	Delivered on orbit by Thales Alenia Space (France)	[44]
Venezuela	VeneSat-1	Delivered on orbit by China Great Wall Industry Corp. (part of China Aerospace Science and Technology Corp.) (China)	[45]

Table 3
Challenges for identifying and gathering data on country-first domestic satellites.

Challenge	Description	Mitigation approach
Data availability: archival status	Some websites have been archived.	Use Wayback Machine [46].
Data availability: language	Some resources not available in English.	Authors proficient in French, Spanish, and Japanese. Use Google Translate and/or DeepL for others.
Data inconsistencies	Different sources present conflicting facts.	Use most authoritative sources and/or use data appearing most frequently across all sources.
National recognition	Competition and discussion over "first", e.g., between private, government-backed initiatives.	"First" is based only on chronology.
Political changes	Countries have merged or split.	"Country-first domestic satellite" defined as the first one gaining national recognition within that country, though it may have been developed/launched before the country took its current form.
Simultaneous "firsts"	Multiple "first" satellites from same country deployed in quick succession.	The one deployed earliest is the "first".

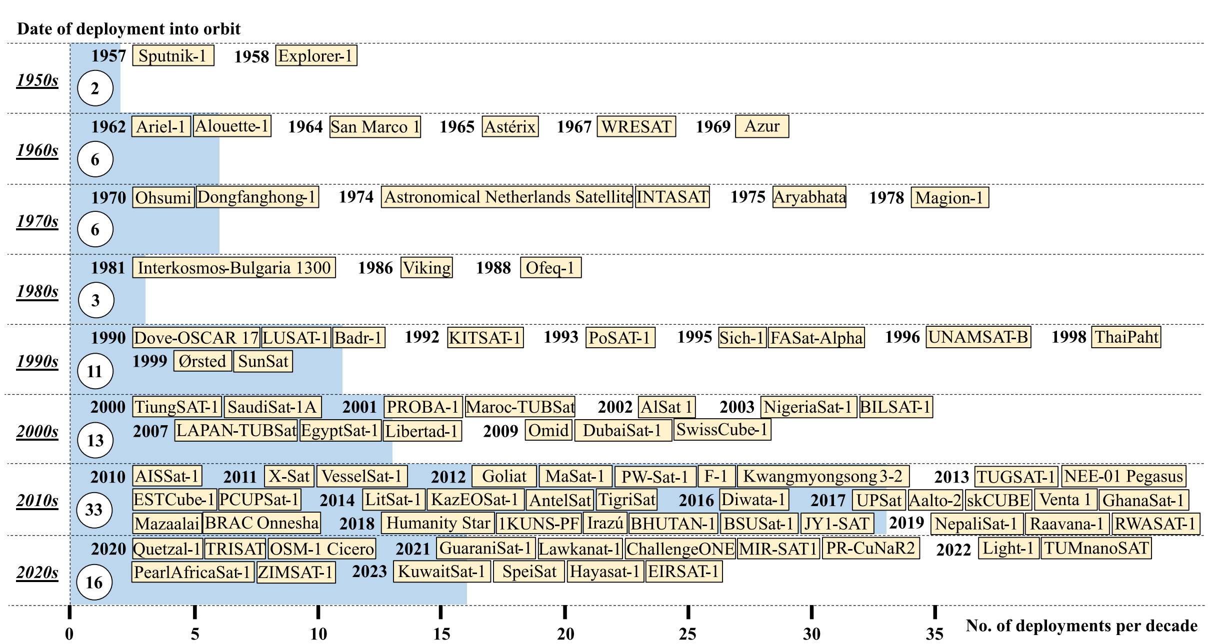

Fig. 4. Timeline of country-first domestic satellites, with name and year of deployment, and number of deployments per decade.

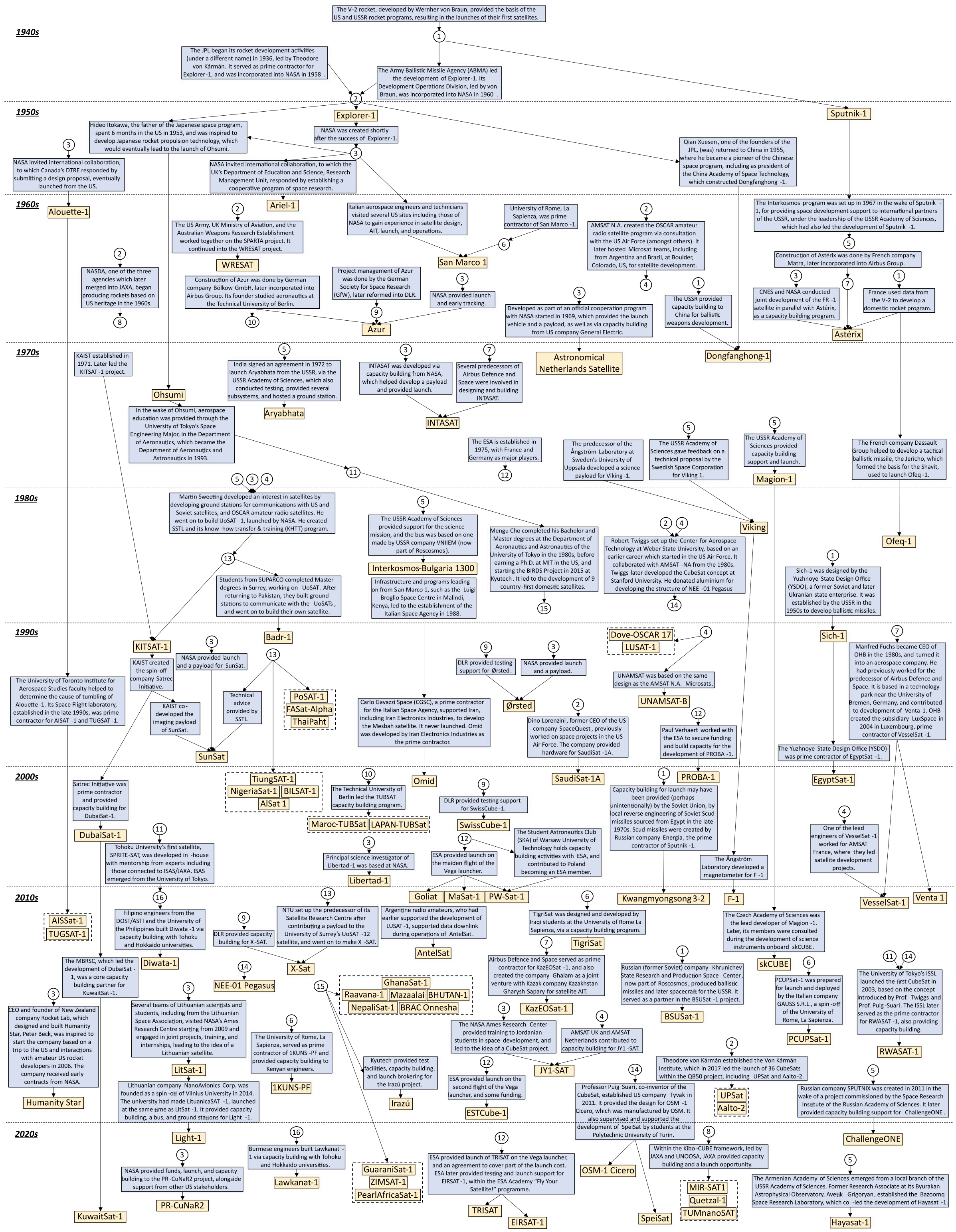

Fig. 5. Timeline of selected major links between country-first domestic satellites. For ease of readability, numbers are used as nodes between items hard to connect via lines.

Similarly, in the 1960s–70s France's Astérix satellite mainly served to test the performance of the Diamant-A launch vehicle [51], while Australia's WRESAT was integrated into the third stage of the Sparta rocket [52], and Japan's Ohsumi into the fourth stage of the Lambda 4S launcher [53]. China's Dongfanghong-1 tested a novel Doppler ranging system for post-launch tracking [54]. In addition to providing information on launch vehicle performance, the earliest country-first domestic satellites also conducted simple space science experiments, as discussed in more detail in Section 4.

Generation 2: Government- and national institution-led satellites leveraging know-how and infrastructure from the USSR and US (1960s–80s). In the wake of the success of Sputnik-1 and Explorer-1, the USSR and the US established institutions, infrastructure, and international partnerships which propelled forwards a second generation of country-first domestic satellites, under the leadership of governments and

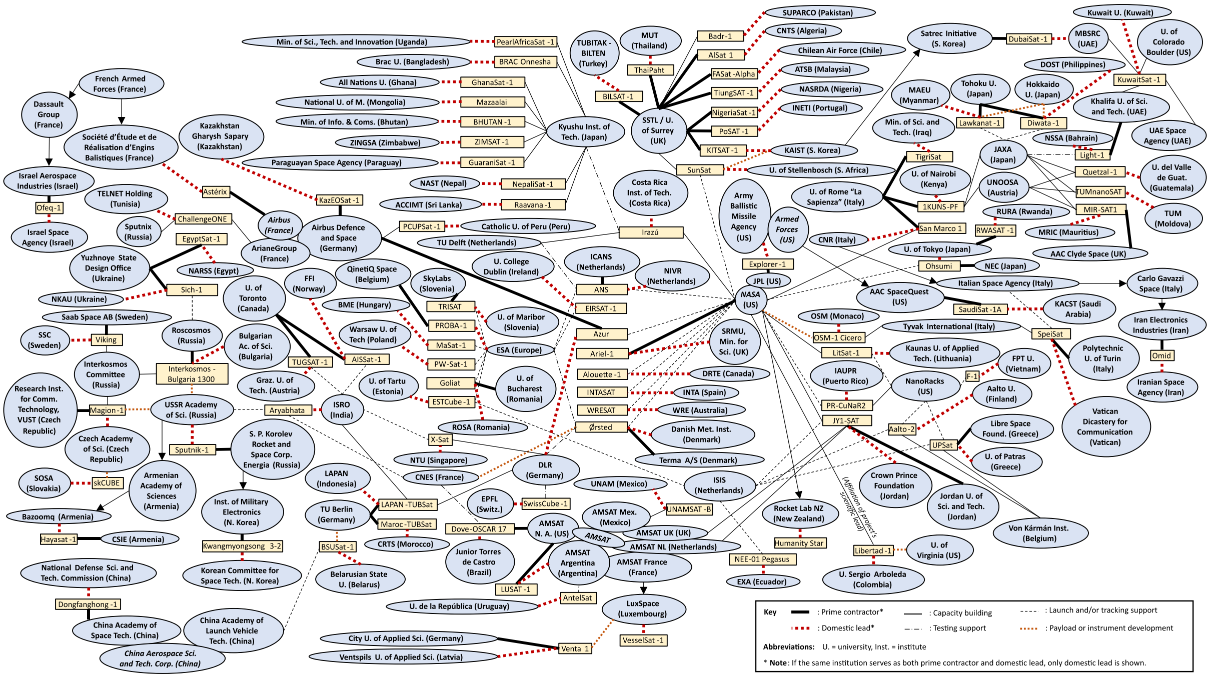

Fig. 6. Links between selected major stakeholders of country-first domestic satellites, showing their functions.

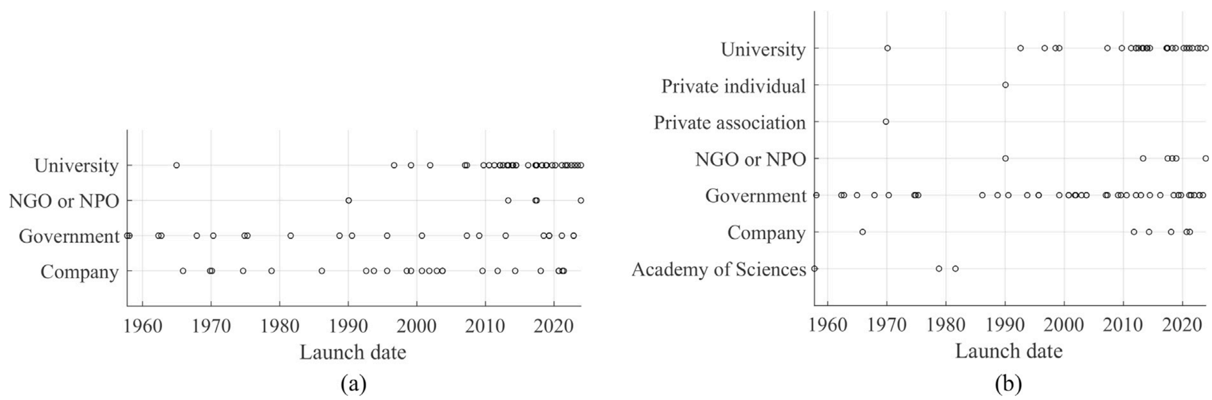

Fig. 7. Timeline of stakeholders playing the role of (a) prime contractor and (b) domestic lead for country-first domestic satellites.

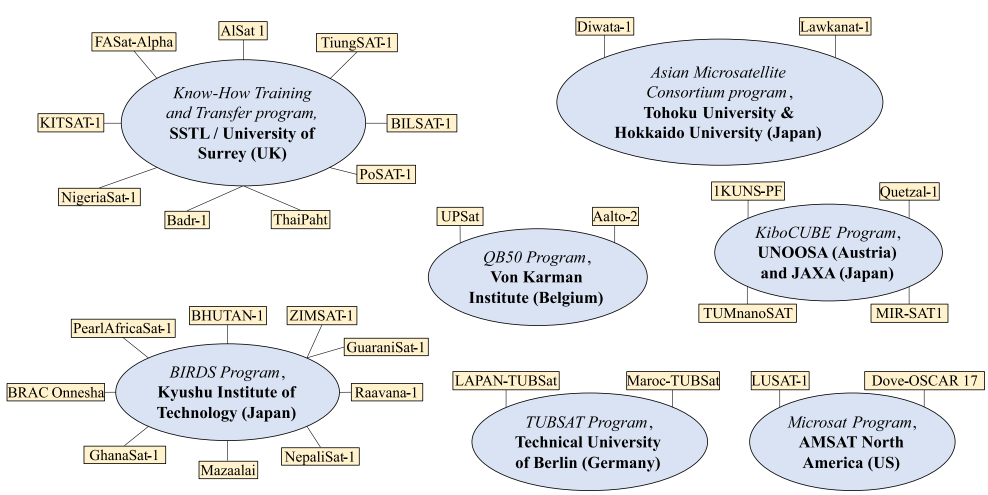

Fig. 8. International collaboration programs yielding several country-first domestic satellites.

national-level institutions. On the USSR side, the Interkosmos program was established in 1967 [55], led by the USSR Academy of Sciences. It supported the development of country-first domestic satellites within the USSR's political sphere of influence. These included: Bulgaria's Interkosmos-Bulgaria 1300 satellite, Czechoslovakia's Magion-1, and Sweden's Viking-1. It also provided partial development, testing, launch, and tracking of India's Aryabhata satellite. In parallel, the USSR's ballistic missile program informed the development of those of China [56], Ukraine [57], and North Korea [58], and thereby those of their country-first domestic satellites Dongfanghong-1, Sich-1, and Kwangmyongsong 3-2.

On the US side, offers of assistance to the international community were provided for developing and launching satellites. These were availed of by the UK, whose satellite Ariel-1 was produced at the NASA Goddard Space Flight Center [59]; by Italy, whose engineers received training in the US by NASA and others before developing San Marco 1 [60]; by Germany, Canada, the Netherlands, Spain, Australia, and Denmark, who received support for launching Azur, Alouette-1, ANS, INTASAT, WRESAT, and Ørsted respectively (in exchange for hosting a US payload in some cases, e.g., onboard ANS, INTASAT, and Ørsted); and by Japan, which received support for telemetry reception via NASA ground stations for its Ohsumi satellite [53].

Moreover, it was in the US that two individuals who would go on to play leading roles in the Chinese and Japanese space programs had formative experiences. Qian Xuesen, co-founder of the JPL – incorporated into NASA in 1958 [49] – forcibly returned to China in 1955 due to political reasons and led the development of its domestic space program [61]. Hideo Itokawa, Professor at the University of Tokyo, spent 6 months in the US in 1953 and was inspired to develop rocket propulsion technology upon his return to Japan, eventually leading to the launch of Ohsumi [62]. Moreover, NASDA, one of the three agencies which later merged to form the current Japan Aerospace Exploration Agency (JAXA), began producing rockets in the 1960s based on US heritage.

Generation 3: Academia, amateur, and industry-led capacity building programs based around microsatellites (1980s–2010s). Building on the legacy of the 1950s–70s, a third generation of country-first domestic satellites emerged via the establishment of communities of space amateurs, university space capacity building programs, and commercial space players. This period was marked by the growing adoption of small satellites, and especially microsatellites, discussed in more detail in Section 4. As explained by Martin Sweeting, this resulted from "the advent and widespread availability of microelectronics that enabled physically smaller satellites to be built by smaller teams with modest facilities", in combination with "a different management approach", noting that "small satellites are a state of mind rather than defined simply by physical parameters" [63].

Regarding space amateurs, in the 1960s the Radio Amateur Satellite Corporation (AMSAT) was established in the US, with affiliated groups in other countries, to manage and provide capacity building for the development of the OSCAR series of amateur satellites [64]. The first satellites of Brazil and Argentina, Dove-OSCAR 17 and LUSAT-1, were developed via capacity building received from AMSAT North America in Boulder, Colorado, US [65], and the first satellite of Mexico, UNAMSAT-B, was later based on the same design but made in Mexico [16].

The OSCAR satellites also inspired Martin Sweeting, then a young researcher at the University of Surrey, UK, to develop ground stations for communicating with USSR and US satellites in the 1970s, leading to the development of his own OSCAR satellite. This experience in turn provided the foundations for the creation of the spin-off company SSTL and its know-how training and transfer (KHTT) program [66], which led to the development of 9 country-first domestic satellites (see Fig. 8) for Pakistan (Badr-1), South Korea (KITSAT-1), Portugal (PoSAT-1), Chile (FASat-Alpha), Thailand (Thai-Paht), Malaysia (TiungSAT-1), Algeria (AlSat-1), Turkey (BILSAT-1), and Nigeria (NigeriaSat-1), over the twenty years from 1984 to 2003 [67]. South Africa's country-first domestic satellite, SunSat, was also developed via informal technical advice from SSTL. According to Martin Sweeting, "The programs carried out in conjunction with the University of Surrey have assisted in the formation of five new national space agencies and six spin-out companies" [63].

Shortly afterwards, in Germany, the Technical University of Berlin (TU Berlin) developed the TUBSAT capacity building program which launched the country-first domestic satellites of Morocco and Indonesia, Maroc-TUBSat and LAPAN-TUBSat, in the 2000s [68]. TU Berlin has a connection with the first German satellite, Azur, since the founder of German company Bölkow GmbH – later incorporated into Airbus – which served as its prime contractor, had studied aeronautics there in the 1930s [69]. Later still, in the 2010s, Tohoku University and Hokkaido University, working as prime contractors for the bus and onboard instruments respectively, provided capacity building to engineers from the Philippines and Myanmar, leading to the launch of their country-first domestic satellites Diwata-1 and Lawkanat-1. Tohoku University had earlier acquired satellite development expertise via capacity building from other Japanese stakeholders [70], which can be viewed as descendants of activities resulting from Japan's first satellite Ohsumi.

Regarding contributions from industry, Airbus, actively involved in satellite development projects of the 1960s onwards (e.g., as prime contractor of France's Astérix, in the guise of former company Matra), provided a fertile environment for next-generation satellite development projects. For instance, Manfred Fuchs, who had previously worked for a predecessor of Airbus Defence and Space (Entwicklungsring Nord, or ERNO), became CEO of the Bremen-headquartered German company OHB in the 1980s and turned it into an aerospace company. OHB later contributed to the development of Latvia and Luxembourg's country-first domestic satellites, Venta-1 and VesselSat-1.

Generation 4: Academia, agency, and industry-led capacity building programs based around CubeSats (2000s-present). As will be discussed in more detail in Section 4, the invention of the CubeSat standard in the early 2000s provided a step change in the history of country-first domestic satellites, opening up the doors to participation by a wider diversity of actors, often via capacity building programs established based on prior satellite development initiatives. The CubeSat was invented by Robert Twiggs of Stanford University and Jordi Puig Suari of Calpoly, both in the US. Professor Twiggs began his career in the US Air Force, before establishing the Center for Aerospace Technology at Weber State University, which closely collaborated with AMSAT North America in its early satellite development projects [71]. During the construction of Ecuador's country-first domestic satellite, NEE 01-Pegasus, launched in 2013, Professor Twiggs personally donated aluminium material used in its 1U structure [72]. Professor Puig Suari established the US company Tyvak in 2011, which provided the design for OSM-1, Monaco's first domestic satellite, and also offered support and supervision for the development of SpeiSat, the Vatican's first domestic satellite.

The first adopter of the CubeSat concept, with the launch of XI-V (not a country-first domestic satellite) in 2003 [73], was Shinichi Nakasuka of the University of Tokyo, the institution that led the development of Japan's first satellite Ohsumi in the 1960s–70s. Professor Nakasuka later conducted a capacity building project with Rwandan engineers, resulting in the development of Rwanda's first domestic satellite, the CubeSat RWASAT-1, launched in 2019 [74]. However, the most notable example of country-first domestic satellite development via university-led capacity building is the BIRDS Program [75]. Its principal investigator, Mengu Cho, in fact obtained his undergraduate and Master degrees in aerospace engineering at the University of Tokyo in the 1980s. The BIRDS Program has launched 9 country-first domestic satellites, all 1U CubeSats, between 2017 and 2023. Note that this is the same number as SSTL/the University of Surrey (see "Generation 3"), but launched within a period of only 6 years as opposed to 20. These are: GhanaSat-1, Mazaalai, BRAC Onnesha, BHUTAN-1, NepaliSat-1, Raavana-1, GuaraniSat-1, PearlAfricaSat-1, and ZIMSAT-1, for Ghana, Mongolia, Bangladesh, Bhutan, Nepal, Sri Lanka, Paraguay, Uganda, and Zimbabwe respectively.

Another important academia-led CubeSat development program, conducted by the von Kármán Institute in Belgium, is QB50 [76]. The institute was established by von Kármán in the 1950s; he had earlier been a founder of the JPL, which served as prime contractor of the first US satellite (see "Generation 1"). 36 satellites were put into orbit as part of QB50, including the country-first domestic satellites of Greece and Finland, UPSat and Aalto-2. In parallel, another early academic pioneer of space activities, the University of Rome La Sapienza, which had served as prime contractor of Italy's first satellite San Marco 1 in the 1970s, contributed to three country-first domestic satellites, for Kenya, Iraq, and Peru: 1KUNS-PF, TigriSat, and PCUPSat-1. In a historical "full circle", La Sapienza offered capacity building to Kenyan engineers, who five decades earlier had helped to kick-start the Italian space program by providing a near-equatorial launch site and space centre in Malindi, Kenya [60]. TigriSat was designed and developed by Iraqi students in Italy, while PCUPSat-1 was developed by the Catholic University of Peru domestically but launch and deployment were provided by Italian company GAUSS S.R.L., a spin-off of the University of Rome La Sapienza.

The fourth generation of country-first domestic satellites has also been the generation of space agency-led projects. For instance, JAXA and UNOOSA, via the KiboCUBE program [77], have facilitated the launch of satellites for Mauritius, Guatemala, and Moldova: MIR-SAT1, Quetzal-1, and TUMnanoSAT. ESA has also offered launch support programs, via its Vega launcher [78], for the first domestic satellites of Hungary, Poland, Romania, Estonia, and Slovenia: MaSat-1, PW-Sat-1, Goliat, ESTCube-1, and TRISAT. Moreover, ESA provided funding for the development of PROBA-1, Belgium's first domestic satellite, a microsatellite, after negotations by Paul Verhaert [79,80]. The ESA Education Office also offered capacity building and a launch opportunity for EIRSAT-1, the first domestic satellite of Ireland, in the "Fly your Satellite!" Programme [81].

In summary, four generations of country-first domestic satellites have emerged since the 1950s. Important trends regarding their genealogy are as follows:

(a) *International cooperation is always present.* Although many countries portray their country-first domestic satellites as a symbol of national technological prowess [82], as will be seen in Section 4, they in fact, without exception, all share a common genealogy. For instance, at first glance Israel's Ofeq-1 satellite may appear to have been developed fully within the country. Indeed the prime contractor of both the satellite and its Shavit launch vehicle was Israel Aerospace Industries, and the project lead was the Israel Space Agency [83]. However, in the 1960s the French company Dassault had led a collaborative ballistic missile development project with Israel, leading to its Jericho missile [84], and eventually to the Shavit rocket and to the launch of Ofeq-1. At the same time, a growing global market for satellite development and launch services is playing a bigger role in country-first satellite development even in the absence of official country-to-country collaborations, especially since the advent of the CubeSat, as will be discussed in more detail in Sections 4 and 5.

(b) *Successive cycles of capacity building.* International capacity building initiatives have been at the foundation of country-first domestic satellites from the outset. In particular, there are several notable examples of multi-cycle capacity building, where the initial recipients of capacity building have become the providers for a next generation of satellite projects. For example, in the 1970s Martin Sweeting at the University of Surrey developed an interest in satellites via interaction with the amateur radio community, among other factors. He set up the university's microsatellite program in the early 1980s, which in the early 1990s then helped develop South Korea's country-first domestic satellite, KITSAT-1. Korea-based KAIST was the project leader. KAIST later created the spin-off company Satrec Initiative, which provided capacity building for the United Arab Emirates' (UAE) first satellite, DubaiSat-1, in the 2000s. The UAE's Mohammad Bin Rashid Space Centre (MBSRC) was project leader. In the 2020s, the MBSRC in turn provided capacity building for the development of Kuwait's country-first domestic satellite, KuwaitSat-1. This is one of several examples of "lineages" of country-first domestic satellites.

(c) *Importance of key individuals.* Many country-first domestic satellite development programs have been the fruit of significant efforts by single individuals. Examples include Qian Xuesen in China [61], Hideo Itokawa in Japan [62], Junior Torres De Castro in Brazil [85], and Paul Verhaert in Belgium [80]. Individuals have also been pivotal in setting up multi-satellite capacity building programs: notable examples are Martin Sweeting for SSTL's KHTT program [66] and Mengu Cho for Kyutech's BIRDS program [75].

(d) *Multi-satellite programs.* As shown in Fig. 8, one third of all country-first domestic satellites have been developed via international collaboration programs yielding more than one country-first domestic satellite. The SSTL/University of Surrey's KHTT program and the BIRDS program alone have supported the development of 18 such satellites, providing hands-on training in the UK and Japan respectively to dozens of engineers, some of whom returned to their home countries to establish follow-on space technology programs (see, e.g., the previously mentioned case of South Korea).

In summary, the histories of the 90 country-first domestic satellites form an interconnected web. Their genealogy comprises key common ancestors, notably Sputnik-1, Explorer-1, and the surrounding space development efforts in the USSR and US in the 1950s and 1960s. These gave rise to an exponentially increasing number of descendants, owing to easier access to space technologies via the popularisation of microsatellites and CubeSats, but also to the efforts of key individuals especially via multi-satellite capacity building programs. As was briefly discussed, the history of country-first domestic satellites is linked to that of launch vehicles. In particular, since the number of countries with launch capability is significantly less than the number of countries having launched country-first domestic satellites, international collaboration has been essential for placing these satellites into orbit. Trends in launch vehicle development and utilisation are therefore important to understand the history of country-first domestic satellites.

3.2. Launch vehicles of country-first domestic satellites

Launch is an important hurdle in the development of a country-first domestic satellite, owing to two main factors: availability, constrained by the limited number of countries with orbital launch capability; and cost, which has drastically dropped over time but still accounts for a major fraction of that of an overall satellite development project.

Regarding the first factor, availability, only 13 countries have or have had the capability to perform orbital launches using their own launch vehicles: Russia (formerly the USSR), the US, France, Japan, China, the UK, India, Israel, Ukraine, Iran, North Korea, New Zealand, and South Korea. In addition, Algeria, Australia, Kazakhstan, Kenya, and Spain have provided launch bases for successful orbital launches, and the European Union collectively has orbital launch capability via the Guiana Space Centre in French Guiana. Regarding the second factor, cost, a monopoly on launch vehicle development was long held by governments and national agencies, until the comparatively recent establishment and success of private companies such as SpaceX in the US, Rocket Lab in New Zealand, and i-Space in China, though with significant government backing in the form of funding, contracts, and infrastructure. In other words, orbital launch capability remains a scarce and valuable resource, which has correspondingly shaped the history of country-first domestic satellites as shown in Figs. 9 and 10. Three major trends are summarised below.

(a) *Bespoke launches for large satellites leveraging US infrastructure (1950s–80s).* Nine of the 10 earliest country-first domestic satellites were put into orbit by different launch vehicle families: Sputnik-1 by Sputnik, Explorer-1 by Juno, Ariel-1 by Delta, Alouette-1 by Thor-Agena, San Marco 1 by Scout, Astérix by Diamant, WRESAT by Sparta, Ohsumi by Lambda, and Dongfanghong-1 by Long March. The majority of these launches were made from the US (Cape Canaveral, Vandenburg Air Base, and Wallops Flight Facility) or using US rocket technology, and NASA offered its ground station infrastructure such as the STADAN stations (see Section 4) to perform satellite tracking and communication. This early head start by the US, buttressed by its aforementioned international cooperation programs for satellite development and launch, explains why the US has, still today, by far launched more country-first domestic satellites than any other nation, as can be seen in Fig. 9(a). This has not been without benefits for the US space community: for example, NASA hosted payloads onboard the first domestic satellites of Spain, Denmark, and South Africa (INTASAT, Ørsted, and SunSat) in exchange for providing launch.
The former USSR played a similar role as the US, but on a smaller scale, in the context of the Interkosmos program as mentioned previously. The earliest satellites were often the primary and only payload onboard their launch vehicle, partly owing to their relatively large mass (in the order of 100 kg, see Fig. 10), to the launch vehicles' limited payload mass capability, and to the purpose of some satellite missions being to test the performance of the launch vehicle itself, as discussed in more detail in Section 5.

(b) *Piggybacking of smaller satellites via diversification of international launch partnerships (1970s–2000s).* The earliest country-first domestic satellite launched via piggyback, i.e., as a secondary passenger alongside larger primary cargo, was Spain's INTASAT in 1974, onboard a US Delta 2310 rocket. The trend of piggyback launches then continued via the USSR's Cosmos launch vehicle family (mainly launched from Plesetsk, Russia) and France's Ariane (from French Guiana, France), in the 1970s–2000s and 1980s–1990s respectively. Many of the launched satellites weighed in the order of tens of kilograms. Several country-first domestic satellites were launched together: for instance, Argentina's LUSAT and Brazil's Dove-OSCAR 17 in 1990, both as secondary payloads; Denmark's Ørsted and South Africa's SunSat in 1999; and Malaysia's TiungSAT-1 and Saudi Arabia's SaudiSat-1A in 2000. This period marked a diversification in launch sites of country-first domestic satellites away from the US, towards Russia and French Guiana, and later Kazakhstan (at the Russia-operated Baikonur launch base) and India (at the Satish Dhawan Space Centre), each of which has launched around 10 such satellites, as shown in Fig. 9(a).

(c) *Consolidation of piggyback launches via a few launch vehicle families, including private ones (2000s-present).* Most recently, since the 2000s, piggyback launches have firmly established themselves as the primary launch mode for country-first domestic satellites, notably because many have been CubeSats with a mass in the order of 1 kg, as shown in Fig. 10. A few launch vehicle families have emerged as the go-to option for launching such satellites, as shown in Fig. 9: the Russian Dnepr, the Indian PSLV, the European Vega, the US Antares, and the US Falcon. This reduced variety of launch vehicles is the result of three main factors.
The first is the establishment of dedicated piggyback launch programs, like the one offered by the Education Office of the European Space Agency onboard the Vega launcher [78]. The second is the increase in popularity of deployment from the ISS, especially for CubeSats, as discussed in more detail in Section 4.2.1. The ISS release option has made a significant impact on the launch method. Indeed, since the early 2010s, NASA's Commercial Resupply Services (CRS) program has awarded contracts to SpaceX and Northrop Grumman Space Systems (formerly Orbital Sciences Corporation) to perform several tens of resupply missions to the ISS, using the Falcon 9 and Antares launch vehicles respectively. Japan's H-2B has also performed several ISS resupply missions, with a more modest cadence. The Falcon 9, Antares, and H-2B were in fact all developed specifically to resupply the ISS. The third factor is challenges facing the development of next-generation launchers, including technical ones – e.g., for Japan's H-3 [86] and ESA's Ariane 6 [87] – and geopolitical ones – e.g., embargoes on Russia-made launcher technology. Indeed, the Antares 200 series, used since 2016, is currently being discontinued in favour of the fully US-made 300 series since its first stage is produced in Ukraine and Russia [88]. The H-3 is planned as the successor of the H-2B.
The above three factors have consolidated SpaceX's supremacy in the global launch market. Since and including the earliest launch of a country-first domestic satellite onboard the Falcon 9 in 2017 (Bangladesh's BRAC Onnesha), 16 of the next 30 country-first domestic satellites have also been launched on a Falcon 9.

In summary, the history of country-first domestic satellites is closely linked to that of launch vehicles. These place constraints on available launch locations and hence require international partnerships to achieve orbit. Initially heavily reliant on the US, such partnerships have become increasingly diversified. However, the US has recently regained dominance due to the global geopolitical situation, to technical setbacks amongst other major launching nations, and to the emergence of SpaceX as a highly competitive private launcher. These partnerships have led to technical exchanges between small satellite development teams launching country-first domestic satellites in the same launch manifest, and satellite design changes to accommodate the demands of the launching nation. Therefore, launch has clearly shaped the history of country-first domestic satellites.

This section constructed and analysed the family tree of country-first domestic satellites. Attention was drawn to important linkages between significant stakeholders, involved not only in the development but also the launch and operations of these satellites. The most important point is that all country-first domestic satellites either share a common lineage or ancestor, and that their history can be described in terms of a sequence of generations. These generations have been shaped by successive cycles of capacity building, often led by individual pioneers. In addition, since the late 1980s, multi-satellite programs have become a major vector for country-first domestic satellites. Most recently, the growing global market for satellite development and launch services is playing an increasingly significant role in the development of country-first domestic satellites, even in the absence of official country-to-country collaborations, one cause being the invention of the CubeSat standard. Overall, the above analysis reveals that such satellites are always the fruit of international collaboration, even though they are usually held up as a high watermark of national technological prowess, as discussed in the next section.

4. "Birth": cultural and technical features

The family tree in Section 3 is a useful entry point into the genealogy of country-first domestic satellites. However, as discussed, the development of these satellites was not only shaped by cross-pollination between them, but also by broader global technological trends. The technical features of the satellites, similar to "birth traits", provide

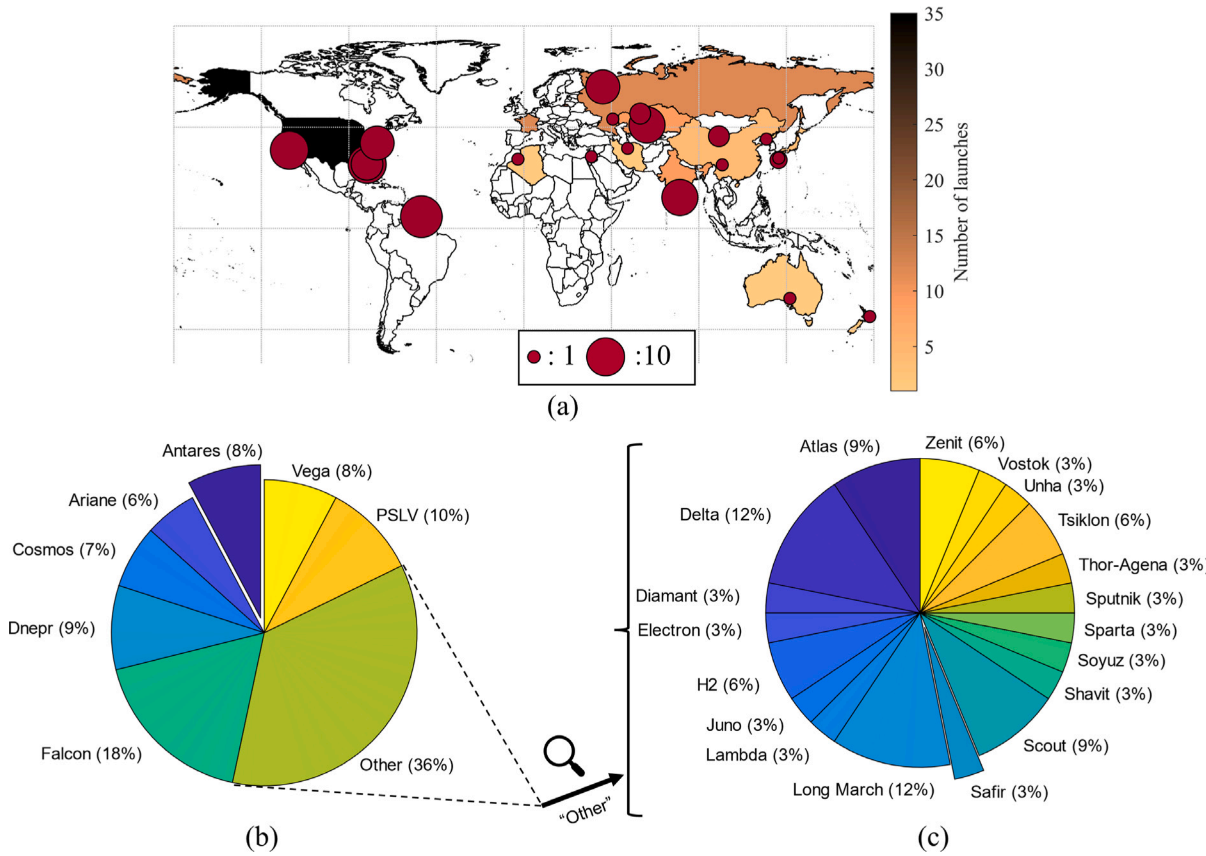

Fig. 9. Launches of country-first domestic satellites. (a) Launch location. Countries are coloured by the number of satellites launched from their territory. Launch sites are shown by circles with diameter proportional to number of provided launches. (b) Most frequently used launch vehicle families. (c) Least frequently used launch vehicle families, as a fraction of the "Other" category in (b). Values in (b) and (c) are rounded to the nearest percent.

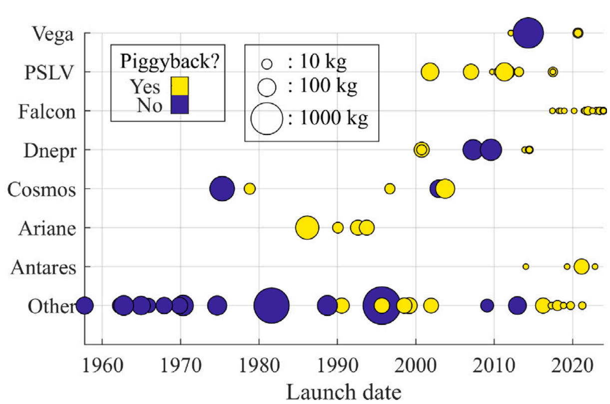

Fig. 10. Timeline of launches onboard vehicles in Fig. 9(b). The satellite's launch mass is shown by a circle with diameter proportional to its mass. The piggyback status is shown by the circle's colour.

further clues on how their development has been shaped by such trends. Another revealing birth trait is the satellite's name, which hints at the motivations underlying its development. The purpose of this section is to provide a detailed review of these birth traits, as a further means of understanding the satellites' genealogy.

4.1. Cultural features: Name

Firstly, the names of the country-first domestic satellites are reviewed. They are divided into three categories, according to whether the satellite was named after: its country, its domestic culture, or a stakeholder institution. An additional "Other" category is included. A detailed review of the etymology of each satellite's name is beyond the scope of this paper: only major trends and noteworthy examples are highlighted. As shown in Fig. 11, almost all of the satellites fall into one of the three categories, with around one third in each.[1] Eight satellites do not fit into any of the three categories, and are listed as "Other".[2] In brief, the most important lessons learnt from the names of country-first domestic satellites about their genealogy are as follows.

(a) *A symbol of national and cultural identity:* Most of the satellites are named either after their country or with reference to domestic culture. This trend is consistent over time and space. It suggests that country-first domestic satellites tend to be associated with national and local cultural identity. For instance: the UK's Ariel-1 "was named in February 1962 for the spirit of the air who was released by Prospero in Shakespeare's play The Tempest" [91];

[1] Some of the satellites are in several categories at once: Interkosmos-Bulgaria 1300 is named after Bulgaria and the 1300th anniversary of the Bulgarian state (celebrated in 1981); Maroc-TUBSat after Morocco and the Technical University of Berlin; PearlAfricaSat-1 based on Uganda being known as the "Pearl of Africa"; and BRAC Onnesha after BRAC University and a name with positive connotations in Hindi and Bengali. For simplicity, the former three are placed in the "named after country" category, and the latter in "named after domestic culture".

[2] The origin of ChallengeONE's name is uncertain, Azur is named after the blue colour of its solar panels [89], and six satellites are named after their respective mission objectives: Magion-1 (Magnetosphere Ionosphere 1), PROBA-1 (PRoject for OnBoard Autonomy 1), AISSat-1 (Automatic Identification System Satellite 1), X-SAT (eXperimental SATellite), VesselSat-1, and Humanity Star ("A Star for Humanity" [90]).

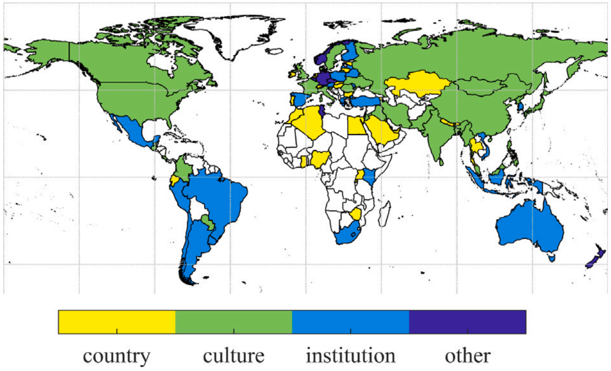

Fig. 11. Map showing names of country-first domestic satellites, divided into four categories, those having been named: after the name of their country, with reference to domestic culture, after the name of an institution, and in other ways.

Iraq's TigriSat refers to the Tigris, one of Mesopotamia's largest rivers that flows through the capital Baghdad; Mongolia's Mazaalai "is a rare bear that inhabits the Gobi Desert of Mongolia – this animal cannot be found anywhere else" [92]; and Sri Lanka's Raavana-1 is named after King Raavana, who "lived nearly 7000 years ago in Sri Lanka (...) since he is the first King to use a aircraft" [93].

In the BIRDS program (see Section 3), participating students and stakeholders decided the satellite's name freely. Guatemala's Quetzal-1 refers to a local bird species, and was named by secondary school student José Miguel Ortega Yung via a public outreach campaign conducted by Guatemalan newspaper Prensa Libre [94]. In summary, national identity has been incorporated into the names of country-first satellites in various ways and by different means. The above examples suggest that national pride has been an enduring motivation for their development, regardless of time and location. However, some variation can nevertheless be observed, coinciding with the four generations of country-first domestic satellites identified in Section 3, as discussed below.

(b) *Time variation:* Most of the satellites in Generations 1 and 2 (see Section 3) were named after domestic culture, rather than the name of a country or project stakeholder. By contrast, satellites named after a project stakeholder became more common in Generations 3 and 4. One likely cause is a growing shift of satellite development leadership away from national agencies and institutions towards a broader mix of private, academic, and other players. For instance, Argentina's LUSAT-1 was named after the Argentine amateur radio community, while Mexico's UNAMSAT-B, launched in 1996 was the earliest country-first domestic satellite to be named after a university, the National Autonomous University of Mexico (UNAM). Moreover, satellites named after their country of development have also become more common in Generations 3 and 4. Indeed, although the start of the space age is usually thought of as a race for national prestige in space, of the 10 earliest country-first domestic satellites, paradoxically none bear the name of their country of origin (see Fig. 4). By contrast, of the 10 most recently launched country-first domestic satellites, seven bear the name of their country of origin.

One interpretation is that when only a handful of countries had launched domestic satellites, their efforts stood out and were perceived as drawing wide recognition of the country's achievements regardless of whether its name featured in the satellite's name or not. Conversely, with 90 countries having joined the list at present, naming a country-first satellite based on the country's name may have become a tool to ensure its lead nation stands out. In summary, time trends in the names of country-first domestic satellites reflect their genealogy: a few early ancestors have given rise to a broadening variety of descendants, and in this context, names have been adopted as a tool to boost recognition of the satellites' lead countries and institutions.

(c) *Geographical variation:* As can be seen in Fig. 11, naming patterns seem to follow geographical trends. However, these are mainly a coincidental by-product of the above-mentioned time trends. Indeed, many of the earliest country-first domestic satellites (see Fig. 2) were named after local culture, and it so happens that they were developed in Russia, the United States, Western Europe, and East Asia, all located in the northern hemisphere. Nevertheless, it is interesting to note that in Latin America, country-first domestic satellites tend to be named more frequently after a stakeholder institution, and in Africa and the Middle East after their lead country.

In summary, the names of country-first domestic satellites provide insights on their genealogy, complementing the family tree developed in Section 3. In particular, national pride appears as an important motivating factor for the development of such satellites: the majority bear a name reflective of domestic culture or are actually named after the country itself. In addition, naming trends have changed over time. More satellites are now named after academic and private institutions, reflecting the diversification of stakeholders within their family trees away from national and government institutions. Satellites also increasingly bear the name of their lead country, reflecting a more and more populated family tree in which it has become more challenging to stand out and draw attention to the country's space efforts on the global stage.

4.2. *Technical features: structure and subsystems*

In addition to cultural features, technical features of country-first domestic satellites are another important source of information on their genealogy. A survey of such features may help to understand how their development has been shaped by broader technological trends, and may uncover additional connections between them. The analysis is conducted by major subsystem: structure and mass; communications; imaging payload; attitude control; and orbit and propulsion.

4.2.1. *Structure and mass*

The most basic feature of a satellite is its size and mass. Fig. 12 shows the launch mass and launch date of country-first domestic satellites. Shading indicates whether the satellite was launched via piggyback. Major mass categories are shown: microsatellite (mass <100 kg), nanosatellite (<10 kg), and picosatellite (<1 kg). The two main points are as follows.

(a) The four generations of satellites defined in Section 3 can be identified in Fig. 12: the earliest country-first domestic satellites were microsatellites or larger, launched via dedicated rockets (1950s–70s); launch options were diversified by international collaboration programs, leading to the first piggyback launches (1960s–80s); the advent of microsatellites and multi-satellite capacity building programs led to piggyback launches becoming the go-to option for launch (1980s–2010s); and most recently nanosatellites have become the overwhelming form factor of choice for country-first domestic satellites (2000s-present).

(b) Arguably the single most influential event in the history of country-first domestic satellites has been the invention of the CubeSat. The earliest country-first domestic satellite to be a CubeSat was Colombia's Libertad-1, launched in April 2007 as shown in Fig. 12(a). Since then, most country-first domestic satellites have adopted the CubeSat form factor, and many have been 1U-sized (i.e., 10 by 10 by 10 centimetres) as shown in Fig. 12(b). The key contribution of the CubeSat concept is not miniaturisation, but standardisation. Indeed, despite significant

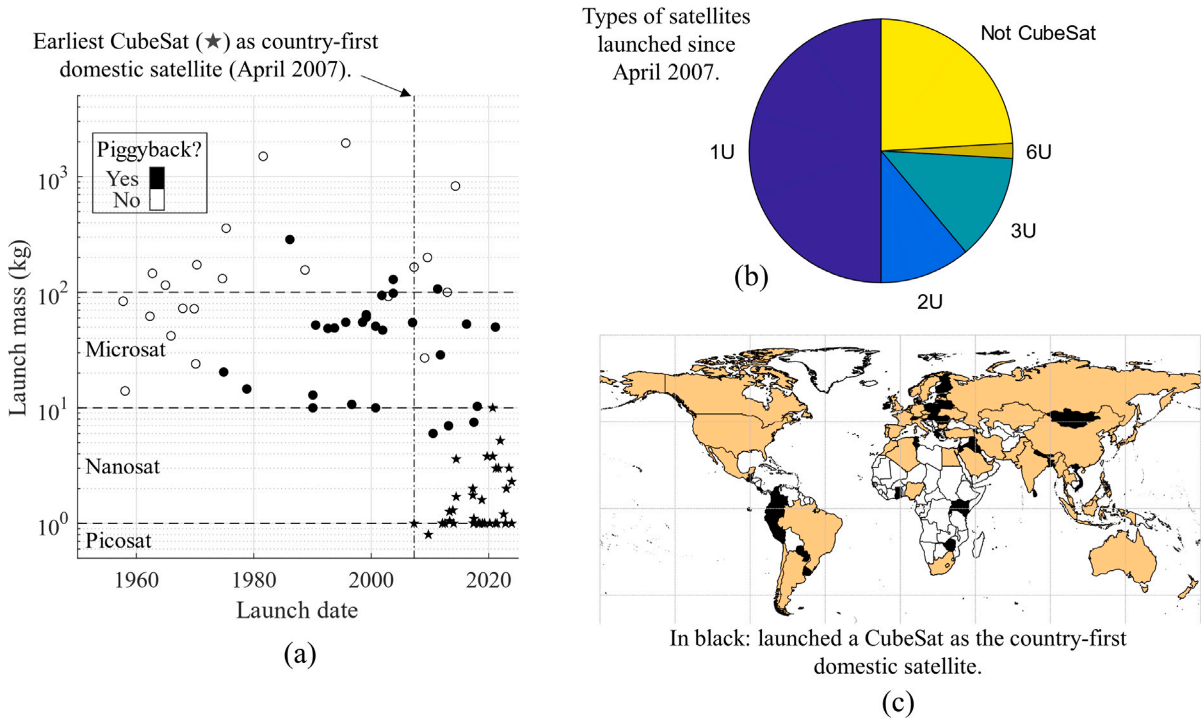

Fig. 12. Country-first domestic satellite mass and size. (a) Launch mass and date. Data points are coloured according to piggyback status. Star symbols are used for CubeSats, and circles otherwise. (b) Types of satellites launched since April 2007, the launch date of the earliest CubeSat as a country-first domestic satellite. (c) Countries (in black) having launched a CubeSat as their country-first domestic satellite.

advances in computing and electronics, the average mass of country-first domestic satellites launched prior to 2000 was relatively constant and in the large microsatellite range. This suggests that, at the time, raising performance within a fixed mass budget was viewed as more important than miniaturisation of the entire satellite, even though piggyback launch options were available. Indeed, although the earliest nanosatellite to become a country-first domestic satellite, LUSAT-1, was launched in 1990, the second, SaudiSat-1A, was only launched a full 10 years later in 2000.[3]

By contrast, this paradigm drastically shifted with the advent of CubeSats. They caused a sudden step change towards miniaturisation. This miniaturisation has not proceeded further, for example to picosatellites or PocketQubes (one eighth the volume of a 1U CubeSat, i.e., 5 by 5 by 5 centimetres): a monopoly has been established by the CubeSat. Indeed, this is due to the emergence of a strong, integrated, and dedicated supply chain for CubeSat development (e.g., see the KiboCUBE program referred to in Section 3,) construction (e.g., see [95]), and deployment. For the latter, two notable examples are Japan's Small Satellite Orbital Deployer (J-SSOD) [96] and the US private NanoRacks CubeSat Deployer [97], both installed on the International Space Station (ISS) and operational since 2012 and 2014 respectively, sharing the Kibo Japanese Experiment Module (JEM). The advent of the CubeSat has opened satellite development to a wider diversity and larger number of countries than before, as shown in Fig. 12: more than half of all country-first domestic satellites (54 out of 90) have been launched since and including Libertad-1 in 2007, of which 41 (i.e., 76%) CubeSats.

In summary, changes in the size and mass of country-first domestic satellites reflect the different generations identified in Section 3. In particular, the invention of the CubeSat has profoundly shaped their history since the 2000s. The adoption of this standard by the majority of new country-first domestic satellites around the world reveals that their family tree has become increasingly supported by a global space market. Its offerings include infrastructures for purchasing commercial off-the-shelf (COTS) components, and for launch opportunity services. In other words, even if there is no country-to-country exchange or other official collaborations, these infrastructure trends have had large impacts on satellite developers' activities. Size and mass have also impacted other technical features of country-first domestic satellites, and in turn these provide more clues about their genealogy.

4.2.2. Communications

Communication is needed to exchange data with the satellite in orbit. This requires suitable infrastructure onboard the satellite and on the ground, as well as an appropriate carrier frequency for the communication signal. Patterns in how these constraints have been dealt with by successive country-first domestic satellites provide further hints on their genealogy, in line with the four generations of satellites identified in Section 3, as described below. The discussion focuses specifically on communication for uplink of commands and downlink of telemetry. The timeline of main communication bands used for these purposes is shown in Fig. 13.

(a) *Generations 1 and 2: VHF communications leveraging US-based infrastructure, with a focus on downlink (1950s–80s).* Many of the earliest satellites provided only downlink, with no capability to receive commands. Examples are Sputnik-1, Explorer-1, Astérix, and WRESAT. Sputnik-1 transmitted a simple two-tone pulse (at 20 and 40 MHz, straddling the limit between the HF and VHF bands) with information on spacecraft interaction with the orbital environment (internal temperature and pressure) [98]. The purpose of these satellites was to provide basic house-keeping information and conduct simple geophysics experiments, for which no commands were needed. The VHF band was used due to its compatibility with relatively small onboard electronic

[3] Both satellites weighed 10 kg, at the limit between nanosatellites and microsatellites.

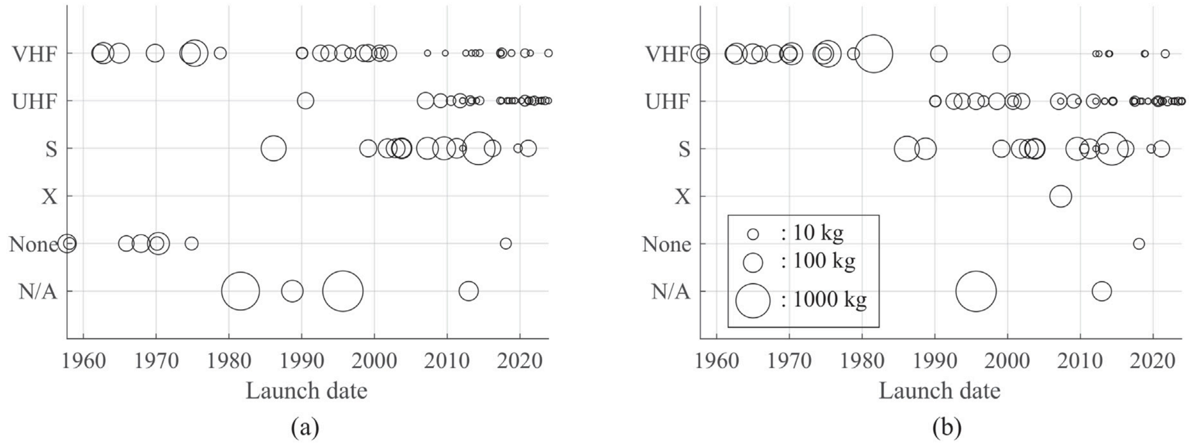

Fig. 13. Time history of main frequency bands used by country-first domestic satellites for (a) command uplink and (b) telemetry downlink. Data points are sized by satellite launch mass.

transmitter components and low power requirements. The Minitrack system, and later STADAN and STDN systems of ground stations, developed and managed by NASA, were used to support communications with many of these early satellites, initially operating at 108 MHz and later shifted to 136–137 MHz in line with ITU requirements [99]. In this sense, the US played an important role in the genealogy of communication systems onboard the earliest country-first domestic satellites, by driving their design features and requirements.

(b) *Generation 3: UHF downlink alongside VHF uplink, driven by the amateur radio community (1980s–2000s).* Command uplink became a mainstay of country-first domestic satellite communication systems with the advent of combined VHF uplink and UHF downlink, initiated by the LUSAT-1 and Dove-OSCAR 17 satellites launched in 1990. This marked the start of a long and ongoing contribution of the amateur radio community to country-first domestic satellites, as discussed in Section 3. To this day, frequencies in the range of 140–150 MHz (part of the VHF band) for uplink and 430–440 MHz (part of UHF) for downlink remain highly popular among country-first domestic satellites, since they are within amateur frequency bands and are thus easier to access both for satellite development teams and other end users. In this way, the amateur radio community played a significant role in lowering barriers for country-first domestic satellite development and in expanding their reach.

(c) *Generation 4: Diversified communication options, trending towards higher data rates (2000s-present).* In recent years, there has been a shift towards higher frequency bands for both uplink and downlink, to increase the amount of data that can be exchanged with the satellite. As will be seen in the next subsection, many recent country-first domestic satellites perform Earth imaging, requiring higher data rates for downlink. This has led to growing usage of the S-band, not only for imagery acquisition but also for telemetry downlink and command uplink. In fact, the earliest country-first domestic satellite to use the S-band (for both uplink and downlink) was Sweden's Viking, launched in 1987 to perform high-frequency (every few tens of seconds) UV auroral imaging, but S-band usage among such satellites did not become common until the 2000s. However, as shown in Fig. 13, its use remains limited to larger satellites, due to comparatively high power and mass requirements. Indeed, the UHF band is still the most popular choice for smaller satellites like CubeSats. In addition, based on available data, Egypt's EgyptSat-1 is the only country-first domestic satellite to use the even higher frequency X-band as the primary medium for telemetry downlink.

In summary, trends in communication subsystem design onboard country-first domestic satellites are aligned with the findings of Section 3: the US played a major role in shaping the history of those in Generations 1 and 2, via collaborative use of its extensive ground station network; and the amateur radio community helped to open up subsequent generations to a wider pool of developers and end users, via amateur frequency bands. Most recently, a shift has occurred towards higher-frequency communication, in the S-band, driven by congestion of lower frequency amateur bands and the use of data-intensive imaging payloads.

4.2.3. Imaging payload

Four distinct periods can be identified with regards to the use of imaging payloads onboard country-first domestic satellites, aligned with the four generations discussed in Section 3.

(a) *Generation 1: Absence of imaging payloads (1950s–70s).* Most of the earliest satellites did not use imaging payloads. As explained in Section 3, the main reason is that they aimed at testing launch vehicle performance and conducting simple science experiments in orbit. Imaging technology was also too power-intensive, data-intensive, and complex to be compatible with available energy, mass, and communication budgets.

(b) *Generation 2: Simple analogue imaging payloads for basic science experiments (1970s–80s).* The earliest imaging experiments were conducted with bulky photodetectors, focusing on UV observations. Australia's WRESAT was the earliest country-first domestic satellite to carry a telescope, for measuring the Earth's ultraviolet halo [100]. The Netherlands' ANS was equipped with a Cassegrain telescope and photomultiplier tubes for ultraviolet astronomy [101], and Bulgaria's Interkosmos-Bulgaria 1300 had a similar instrument for Earth ultraviolet airglow imaging [102]. Sweden's Viking marked the transition to the third period, with the first use of a CCD photodetector onboard a country-first satellite, in 1986, again for Earth airglow UV imaging [103].

(c) *Generation 3: Imaging payloads become a mainstay and gain performance, via digital CCD sensors and digital satellite communication (1990s–2000s).* Imaging payloads became a mainstay onboard country-first domestic satellites owing to two factors. The first is the mass production and miniaturisation of digital imaging sensors, specifically CCDs [104]. Based on available information, the earliest country-first domestic satellite to carry a CCD sensor for imaging in the visible region was South Korea's KITSAT-1, launched in 1992. The second factor is the transition from analogue to digital satellite communications. Analogue communications were widely used until the 1980s, primarily employing

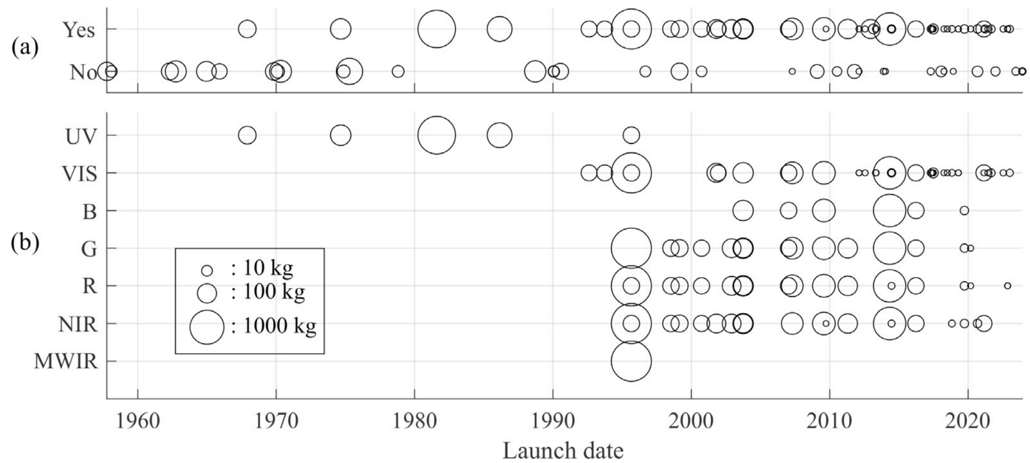

Fig. 14. Time history of imaging payloads equipped onboard country-first domestic satellites. (a) Is the satellite equipped with an imaging payload? (b) Frequency range to which the payload is sensitive. Multiple points are shown per satellite if several imaging sensors are present. The launch date and mass are shown. Acronyms are as follows: UV = ultraviolet, VIS = visible range, B = blue, G = green, R = red, NIR = near infrared, MWIR = mid-wavelength infrared.

frequency modulation to achieve moderate carrier to noise ratios yet high signal to noise ratios [105]. Starting from the 1980s, there was a shift towards digital communications, opening up higher data rates. The combined advent of digital camera sensors and digital satellite communication made downlinking images significantly easier and more accessible to newcomers.

(d) *Generation 4: Miniaturised imaging via the CMOS sensor (2010s-present).* In the last twenty years, CMOS sensors have edged ahead of CCD ones for applications requiring low-power, compactness, and medium image quality. Based on available information, Egypt's EgyptSat-1 was among the earliest country-first domestic satellites to use a CMOS sensor, for infrared imaging [106]. Switzerland's 1U SwissCube, the earliest country-first domestic satellite CubeSat to be equipped with a camera, used a CMOS sensor for near-infrared imaging of the Earth's airglow [107]. CMOS sensors have been used on many subsequent country-first domestic satellites, opening up remote sensing to size and power-constrained CubeSats, as shown in Fig. 14.

In summary, imaging payloads onboard country-first domestic satellites have been shaped by global technological trends: a change in mission objectives, and miniaturisation of imaging sensors. In turn, a growing focus on Earth observation and remote sensing has created new demands for better attitude control.

4.2.4. Attitude control

The history of attitude control of country-first domestic satellites follows similar trends to those of imaging payloads, and is briefly discussed. A timeline is shown in Fig. 15. Again, parallels with the four generations defined in Section 3 are observed.

(a) *Generation 1: Simple passive control, or no control (1950s–70s).* The earliest satellites were either not equipped with any attitude control system, or with a simple passive system, i.e., not requiring any electrical input power. Spin stabilisation was the most common passive attitude control method. Simple damping devices were used onboard the UK's Ariel-1 (inertia booms and a yo-yo mass) [108] and Australia's WRESAT (a viscous fluid loop) [100].

(b) *Generation 2: The start of active control (1970s–80s).* Active attitude control started to be used in line with more ambitious mission objectives with stricter pointing requirements. The Netherlands' ANS, launched in 1974, is the earliest country-first domestic satellite to use active attitude control: three magnetic torquers and three reaction wheels, for astronomical observation (see previous subsection) [101].

(c) *Generation 3: Widespread use of active control, based around different schools of thought (1990s–2000s).* Active control became more widespread in the 1990s, led by two main approaches: the combination of the magnetic torquer and gravity gradient boom, and that of the magnetic torquer and reaction wheel, as can be seen in Fig. 15. The former approach was used by most of the satellites developed in the University of Surrey/SSTL's KHTT program (see Fig. 8), but also by unrelated contemporary satellites such as Denmark's Ørsted. Based on available information, there was no formal cooperation between the project teams of these two initiatives, suggesting that this common feature is the fruit of broader global trends in satellite design at that time. The latter approach, requiring more power and more sophisticated control algorithms, became widespread only later, from the 2000s onwards.

(d) *Generation 4: Miniaturisation of active control and incorporation into CubeSats (2010s-present).* In the past 15 years, for the first time active attitude control has been used by nanosatellites and CubeSats, owing to miniaturisation and improvements in power generation and storage. Magnetic torquer-only, and magnetic torquer plus reaction wheel, are the two most popular choices for active control. The earliest uses onboard a country-first domestic satellite CubeSat were respectively by Switzerland's SwissCube in 2009 [107], and Greece's UPSat in 2017 [109]. Passive control still remains popular, especially for 1U CubeSats, and the most common method is via permanent magnets combined with hysteresis dampers. This approach has been used by six of the nine country-first domestic satellites developed in the BIRDS program (see Fig. 8).

The history of attitude control systems in country-first domestic satellites was shaped by broader trends in miniaturisation of enabling technologies such as electrical power systems. Similar attitude control approaches were used at the same time by different satellite development teams without official cooperation between them. Hence, the genealogy of country-first domestic satellites should not only be construed as a web of direct, explicit connections as described in Section 3, but as based on a less visible yet broader supporting network of enabling technologies. Their advancement has increased access to more ambitious missions (as discussed in Section 5), by a wider variety of nations, in lower cost satellite form factors like CubeSats. The final subsystem discussed in this section is orbit and propulsion.

4.2.5. Orbit and propulsion

A satellite's orbit is among the main drivers of its design requirements. Conversely, based on the orbit, information can be deduced on

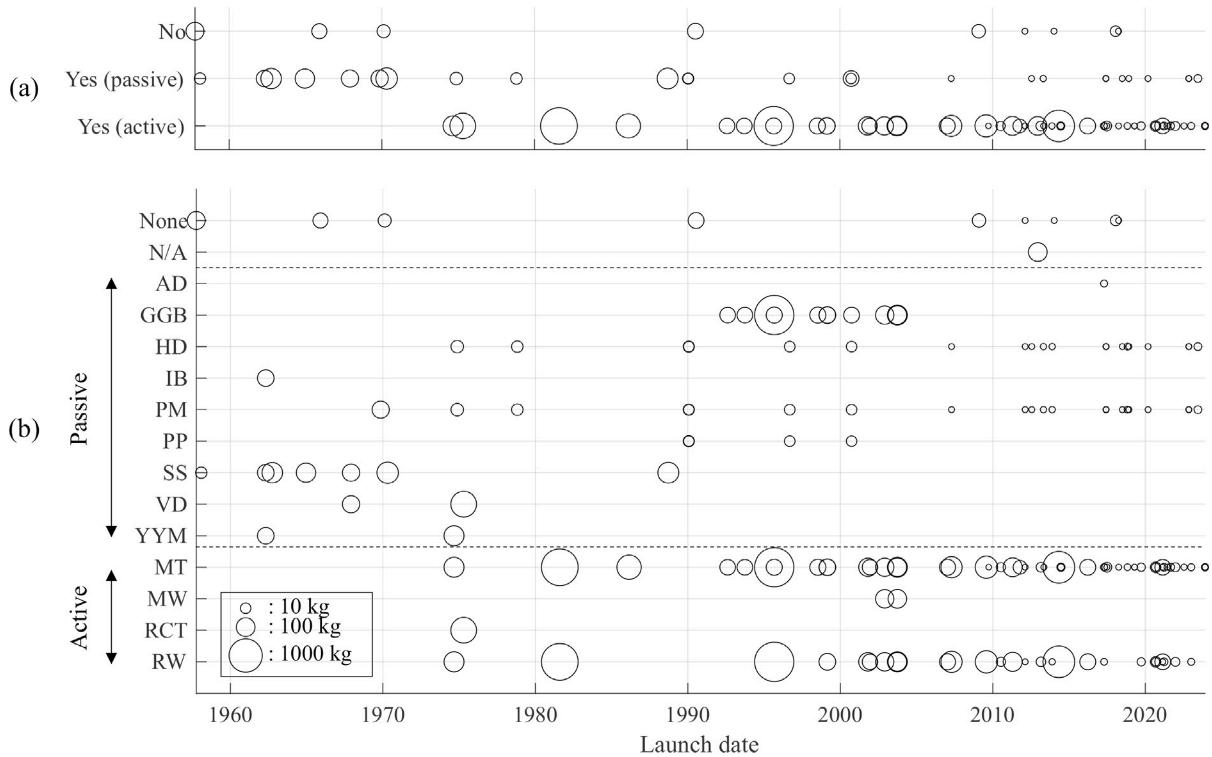

Fig. 15. Attitude control payloads onboard country-first domestic satellites. (a) Is the satellite equipped with a payload for active and/or passive attitude control? (b) Type of such payload(s). Data points show the satellite's launch date and mass. In (b), if several systems are used onboard a given satellite, then multiple data points are shown. "N/A" indicates that information was not found, and "None" that the satellite is not equipped with any attitude control devices. Acronyms are as follows. Passive devices: AD = air drag (used intentionally as part of the mission design); GGB = gravity gradient boom; HD = hysteresis damper; IB = inertia boom (designed to change inertia so that longitudinal spacecraft axis remains the spin axis); PM = permanent magnet; PP = photon pressure; SS = spin stabilisation; VD = viscous damper; YYM = yo-yo mass (jettisoned, to despin satellite). Active devices: MT = magnetic torquer; MW = momentum wheel; RCT = reaction control thruster; RW = reaction wheel.

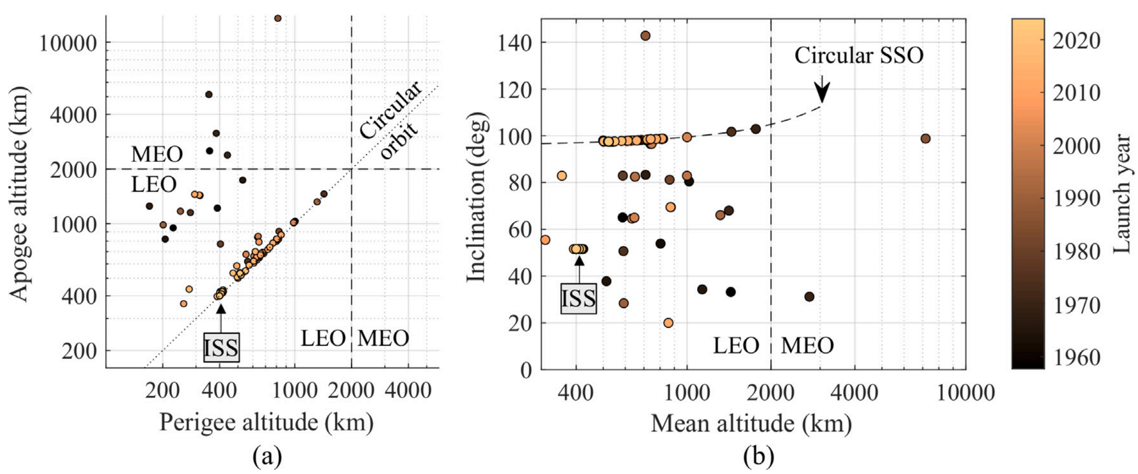

Fig. 16. Orbit of country-first domestic satellites at deployment. (a) Perigee and apogee altitude. (b) Inclination vs. mean altitude, i.e., average of the perigee and apogee altitudes. The circular orbit condition is shown in (a), and circular Sun-synchronous orbit (SSO) condition in (b). Data points are coloured by launch year. Log–log axes are used in (a), and semi-log axes in (b). The orbit of the International Space Station (ISS) is shown.

mission objectives and launch conditions. Hence, orbital information is expected to provide useful insights on the genealogy of country-first domestic satellites, as explained below. In fact, many observations are in line with the four generations of satellites described in Section 3. Fig. 16 shows a time history of the size and inclination of the orbits of country-first domestic satellites.

(a) *Generations 1 and 2: Launch vehicle testing and geophysics missions (1950s–80s)*. Many of the earliest country-first domestic satellites were sent into low-inclination, high-altitude, eccentric orbits. This shows a focus on launch vehicle testing, for two reasons. Firstly, the low inclination, which in many cases is near the minimum value (specified by the launch site's latitude), highlights an attempt to maximise the available launch energy. For instance, Japan's Ohsumi was launched into a 31.2° orbit, matching the latitude of the launch site at Uchinoura, in Southern Japan. Secondly, the average orbital altitude is high, with several satellites entering medium Earth orbit (MEO) as shown in Fig. 16(a). This suggests an intent to demonstrate launch vehicle performance, rather than to achieve high-value mission orbits. For instance, China's Dongfanghong-1 was inserted into a 440-by-2384 km altitude orbit, even though its objective of broadcasting a well-known national song to ground receiving stations in China may have been more easily achieved from a lower altitude, circular orbit. In addition, the orbital eccentricity, indicated by a departure from the dashed "circular orbit" line in Fig. 16(a), is high in many of the earlier missions. One reason is for the satellite to traverse various altitude regions in the course of each orbit. This is desirable to study a wide range of geophysical environments, which was the objective of many early missions, as discussed in Section 3.

(b) *Generation 3: A shift towards circular orbits, with a focus on Sun-synchronous ones (1980s–2010s).* Since the 1980s, the majority of country-first domestic satellites have been inserted into circular orbits. Specifically, near-circular Sun-synchronous orbits (SSOs) have emerged as a popular choice, used by 40 of the 90 country-first domestic satellites. This condition is shown by the curved dashed line [110] in Fig. 16(b). Spain's INTASAT was the earliest country-first domestic satellite to be inserted into such an orbit, in 1974. Advantages include periodic lighting conditions, desirable in Earth observation and other scientific missions. The popularisation of SSOs was caused by easier access to imaging payloads, high data-rate communication systems, and compact attitude control systems, as mentioned previously. Another factor was more launch opportunities specifically targetting SSOs.

(c) *Generation 4: A prevalence of deployments from the ISS (2010s-present).* As discussed at the start of Section 4, the CubeSat has caused a step change in the development of country-first domestic satellites, due to the standardisation of their size, and hence development and deployment. Regarding the latter, the ISS has emerged as one of the dominant platforms for releasing CubeSats into orbit: 23 country-first domestic satellites, of which 21 CubeSats, have been deployed in this way, all since 2012. These appear as a tightly-packed cluster of points in Fig. 16(a) and (b), located close to 400 km altitude at an inclination of 51.6°, matching the orbit of the ISS. In other words, the availability of launch opportunity services has increased access to country-first domestic satellites, even without direct country-to-country exchanges or collaborations.

Not mentioned above is orbit control via propulsion. In fact, only four country-first domestic satellites have used propulsion systems: Algeria's AlSat-1, Turkey's BILSAT-1, Nigeria's NigeriaSat-1, and Kazakhstan's KazEOSat-1. The former three were developed in the UK under SSTL's lead, and the latter in France under Airbus Defence and Space's lead. All were launched after 2000, use a monopropellant thruster (butane for the former three, hydrazine for the latter), and are large satellites weighing around 100 kg or more. This shows that propulsion remains challenging onboard country-first domestic satellites, especially smaller ones.

In summary, Section 4 provided an in-depth review of the "birth traits" of country-first domestic satellites. Two types of features were identified: cultural ones, in the form of the satellite's name; and technical ones, in the form of specifications of the satellite's subsystems. On the cultural side, most country-first domestic satellites are named either after their country or with reference to domestic culture. They are consistently associated with national identity: domestic pride appears to be a motivating factor for their development. There has been a shift in naming patterns since the 1990s: more satellites incorporate the name of their country or that of a stakeholder institution into their own. This reflects the diversification of stakeholders and nations engaged in satellite development. It has become more challenging to draw international attention to the country or institution's space achievements.

On the technical side, time changes in subsystem design onboard country-first domestic satellites echo the four generations of satellites identified in Section 3. Simple downlink-only low-frequency (VHF) communications, the absence of imaging payloads and of active attitude control, and high-altitude low-inclination orbits are all consistent with early satellites focusing on launch vehicle testing and performing simple geophysics experiments (Generations 1 and 2 in Section 3). The growing involvement of the amateur radio community in country-first domestic satellite development and operations is reflected by increased usage of the UHF/VHF amateur radio bands for downlink and uplink, which raised access to support for developing such satellites (Generation 3 in Section 3). During this time, the technological maturation and miniaturisation of CCD and later CMOS imaging sensors provided one impetus for more Earth observation missions, supported by a shift from passive to active attitude control, higher-frequency communication especially for downlink, and the use of circular orbits including Sun-synchronous ones. Most recently (Generation 4 in Section 3), the invention of the CubeSat has caused a step change in the development of country-first domestic satellites. With standardisation have come dedicated supply chains and deployment methods, allowing for easier access to satellites by more nations and stakeholders. This trend has both been promoted and capitalised upon by collaborative international CubeSat development programs, like the BIRDS program and the KiboCUBE opportunity (see Section 3 and Fig. 8).

The above-mentioned technological developments have been fostered via official partnerships between satellite project teams and domestic and international stakeholders, but also by broader global technological movements. Specifically, the miniaturisation, maturation, cost reduction, and standardisation of enabling technologies has led to the emergence of more accessible supply chains for satellite development and deployment. In this sense, the genealogy of country-first domestic satellites depicted in the family tree in Section 3 is not self-contained, and has grown against a backdrop, or "root system", of diffuse, global, easier access to satellite development and launch. In other words, even if there is no country-to-country exchange or other official collaborations, these infrastructure trends have had large impacts on satellite developers' activities.

5. "Life", "Death", and legacy: operations and outcomes

The purpose of Section 4 was to review the "birth traits" of country-first domestic satellites, to gain insights into their genealogy. This complementary section examines their operations or "life", end of mission or "death", and their ensuing legacy on domestic and global satellite development.

5.1. Mission objectives

The mission objectives of country-first domestic satellites are the main determinant of their "life". As mentioned in Sections 3 and 4, such objectives have become increasingly sophisticated. Their evolution provides insights on the genealogy of country-first domestic satellites, as discussed below.

Fig. 17 shows the main mission objective of each satellite, separated into six categories. In reality, a given satellite usually has multiple objectives. For example, science objectives are sometimes realised via Earth observation; communications and technology demonstration can be conducted in parallel; capacity building is done alongside science, etc. Fig. 17 shows only the highest-level objective. The listed objectives are defined as follows: communication = data transmission and/or reception by the satellite; Earth observation = taking pictures of the Earth; education = training members of the satellite development team and/or a wider community in space systems design, testing, and operations; science = obtention of scientific data; and technology demonstration = evaluating the on-orbit performance of a previously untested component or system. One mission is listed as "Other": New Zealand's Humanity Star, which served as space art [90]. Mission objectives have changed in alignment with the four generations of satellites identified in Section 3: from launch vehicle testing, to geophysics and science, to education and capacity building, to commercial applications.

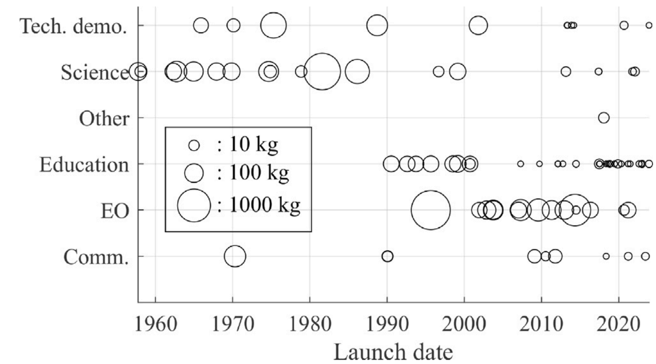

Fig. 17. Main mission objective of country-first domestic satellites. The launch date and mass are shown. Abbreviations are as follows: Tech. demo. = technology demonstration; EO = Earth observation; Comm. = communications.

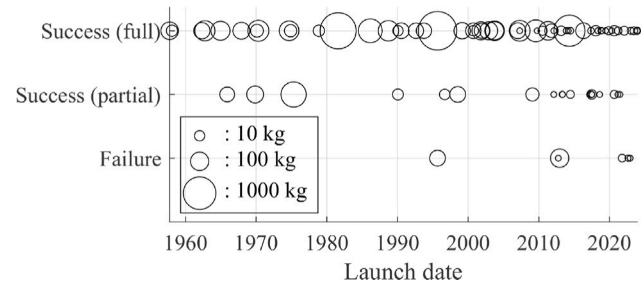

Fig. 18. Mission outcome of country-first domestic satellites, by launch date and mass.

(a) *Generations 1 and 2: Science, and technology demonstration missions (1950s–80s).* As mentioned in Section 3, satellite development began in the context of the International Geophysical Year 1957–58. The USSR's Sputnik-1 and the US' Explorer-1 were both developed against a backdrop of science as a core driving force behind space exploration. (Note that the US intended to launch Vanguard TV-3 as part of its participation in the International Geophysical Year. Explorer-1 was launched after the failure of Vanguard.) This starting point set the tone for mission objectives until the end of the 1980s, with investigations performed on cosmic rays (Explorer-1, Azur), the Earth's atmosphere (Sputnik-1, WRESAT), ionosphere and its effect on radio-wave propagation (Alouette-1, San Marco 1, INTASAT), and magnetic field (Magion-1, Interkosmos-Bulgaria 1300). In parallel, some satellites placed a greater focus on demonstrating the feasibility of space exploration from an engineering perspective, by confirming the space-worthiness of the launch system (Astérix) or satellite (Ohsumi, Aryabhata). This strong alignment between objectives of successive country-first domestic satellites, even those with no official collaboration between their development teams, is further evidence of the significant and lasting influence of the USSR and US on the first generations of satellite developers.

(b) *Generation 3: A diversification of mission objectives, via leadership from universities, amateurs, and industry (1990s–2010s).* Prior to the 1990s, the lead organisations of country-first domestic satellites were predominantly located within national governments and institutions, as discussed in Section 3. However, from the 1990s onwards a more diverse mix emerged, comprising universities, companies, and amateurs. Notably, the University of Surrey/SSTL's KHTT program provided capacity building to teams from nine different countries (see Fig. 8), with education as the satellite's primary mission objective for the earlier ones, shifting towards Earth observation as program managers and international partners gained experience. For instance, Algeria's AlSat 1, Nigeria's NigeriaSat-1, and Turkey's BILSAT-1 were all incorporated into SSTL's 1st generation Disaster Monitoring Constellation (DMC) as fully-fledged Earth imaging platforms alongside one operated by the British National Space Centre (predecessor of the UK Space Agency).
Low-resolution Earth imaging had in fact been performed by country-first domestic satellites since the 1960s (see Section 4), but only as a means of gathering scientific data, rather than for obtaining high-quality Earth images in themselves. In parallel, communication emerged as another main mission objective, at first as a means of simple broadcasting and store-and-forward operations for the amateur radio community (Argentina's LUSAT-1, Mexico's Dove-OSCAR 17), and later for fully-fledged commercial and governmental applications like AIS maritime tracking (Norway's AISSat-1, Luxembourg's VesselSat-1).

(c) *Generation 4: CubeSats as a flexible platform with various capabilities, convenient for capacity building (2010s-present).* Since the 2010s, CubeSats have significantly widened access to and become the dominant vector for country-first domestic satellites, as discussed in Section 4. Owing to their short development time and operations cycle, and low cost, CubeSats are still primarily used as tools for space engineering education as shown in Fig. 17, with only basic engineering or scientific functions. Examples include the nine country-first domestic satellites developed in the BIRDS program (see Fig. 8).
However, in the last five years, more ambitious objectives have been aspired to. For instance, Monaco's OSM-1 Cicero is a 6U CubeSat that performs commercial sales of high-quality Earth imaging data to the National Oceanic and Atmospheric Administration (NOAA) for weather forecasting [111]. Tunisia's ChallengeONE is a 3U CubeSat providing LoRa communication links to Internet of Things ground terminals [112]. Puerto Rico's PR-CuNaR2 is a 3U CubeSat to study low-energy collision between particles in microgravity, for investigating planetary formation [113]. Nevertheless, for now the smallest, 1U CubeSats remain constrained mostly to educational missions, owing to the severe power, mass, and volume budgets.

The timeline of mission objectives of country-first domestic satellites underscores the existence of four successive generations of such satellites, as discussed in Sections 3 and 4. They result from the combined influence of intergovernmental and later broader international collaborations (generations 1 and 2), initiatives by a growing variety of stakeholders including academia and industry (generation 3), and technological developments such as the maturation of imaging, attitude control, and communications payloads as well as the invention of the CubeSat standard (generations 3 and 4). Nevertheless, mission objectives are only aspirational. The actual mission outcomes, discussed in the next subsection, provide further insights on the "life", and also "death", of country-first domestic satellites.

5.2. Mission outcomes

The mission outcomes of the 90 country-first domestic satellites are reviewed, along with known causes of mission end. Based on an extensive search, the cause of failure in around one third of missions is not publicly reported, and is listed accordingly. One challenge in assessing performance is that in several instances, success criteria of country-first domestic satellites have been modified after launch or mid-way during development, to reflect changing expectations and capabilities. In this paper, when available, the criteria used are those stated as close as possible to, yet before, launch.

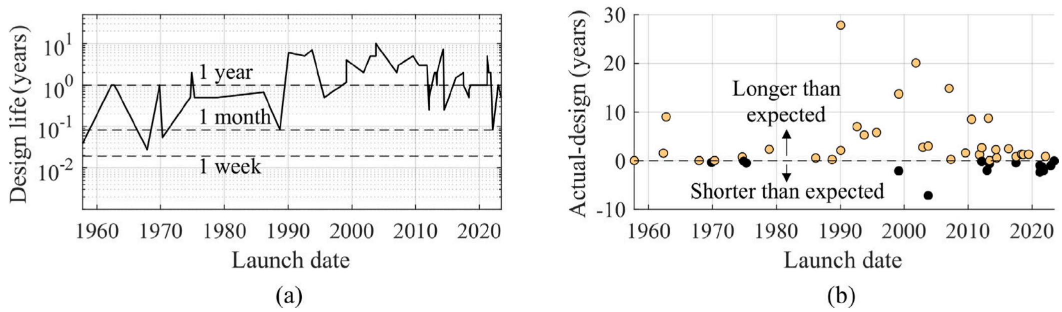

Fig. 19. Lifetime of country-first domestic satellites. (a) Design life. (b) Actual life minus design life: positive values indicate a longer lifetime than expected. Data shown is for those 53 satellites where publicly reported values are available, includes ongoing missions, and is current as of December 2023.

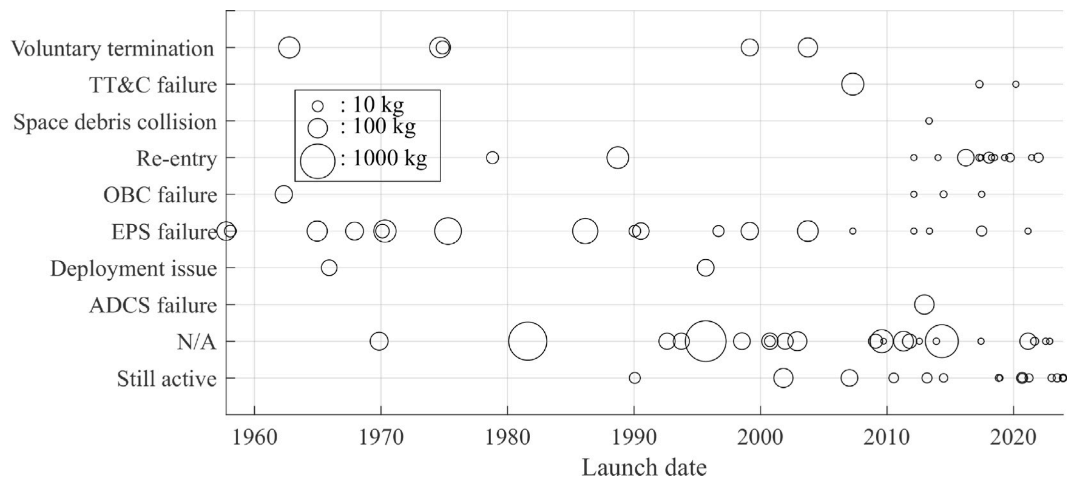

Fig. 20. Main cause of mission end, by launch date and satellite mass. "N/A" denotes cases where the cause is unknown, and "Still active" denotes cases where the mission is still ongoing. Data points are sized according to the satellite's launch mass.

Fig. 18 shows the mission outcome.[4] Full success means that all of the nominal mission objectives were successfully accomplished. Partial success means that only part of the nominal mission objectives were successfully accomplished, or that the mission was shorter than the nominal mission lifetime. Failure means that none or almost none of the nominal mission objectives were accomplished, or that the mission was significantly shorter than the nominal mission lifetime. Fig. 19 shows the satellite's design and actual lifetimes, including only those satellites for which both types of data are available. Fig. 20 shows the main cause of mission end. Important observations are as follows.

(a) The large majority – 82 out of 90, or 91% – of the missions achieved partial or full success, as shown in Fig. 18. This success rate is high, especially considering that almost half are CubeSats, which – not limited to country-first domestic satellites – have had a mean failure rate in the range of 20%–30% over the past decade [114]. Indeed, of the 41 country-first domestic satellites which have been CubeSats (see Section 4), only 5 or 12% have ended in failure, with 14 partial successes and 22 full successes. The high success rate of country-first domestic satellite missions suggests that special attention and efforts have been invested into their development, going beyond the norm for a usual satellite project. This is supported by the results in Fig. 19: most satellites for which data is available have exceeded their design life, in some cases by a significant margin. For example, according to the latest reports, Argentina's LUSAT-1, launched in 1990, is still emitting a pulse at 437.125 KHz (in the medium frequency, or MF, band) 33 years later [115]. Another likely contributor to the relatively high success rate is the use of modest, realistic mission objectives by most country-first domestic satellites, especially for CubeSats, as discussed in Section 5.1.

(b) Those failures that did occur happened from the 1990s onwards: Chile's FASat-Alpha was launched as a secondary payload onboard Ukraine's Sich-1, and failed to deploy from it [116]; communications were never established with Vietnam's F-1 [117]; North Korea's Kwangmyongsong 3-2 is reported to have tumbled uncontrollably after deployment without successful communications [118]; no public information was found on the mission outcomes of Puerto Rico's PR-CuNaR2, suggesting failure; based on available information, contact with Moldova's TUMnanoSAT was never achieved; and no signal was received from Uganda's PearlAfricaSat-1 nor Zimbabwe's ZIMSAT-1 after their deployment [119].
The higher – though still low, as mentioned above – failure rates in the 1990s onwards compared to in earlier decades can be understood based on the four generations of country-first domestic satellites described in Section 3. More projects started to be led by universities and industry, with fewer resources than national governments. This caused a higher rate of failures and partial successes. For example, Brazil's Dove-OSCAR 17, a microsatellite developed by Junior Torres de Castro as a private individual with support from the Brazilian amateur

[4] The outcome of Myanmar's Lawkanat mission is not publicly available, and is hence not shown nor considered later in this section. EIRSAT-1 and Hayasat-1, launched on 1 December 2023, are assumed on a preliminary basis to have achieved full success. For EIRSAT-1, data from one payload has successfully been received. For Hayasat-1, communications have successfully been established with the satellite.

radio community, never achieved its primary mission objective of broadcasting messages of peace over radio amateur frequencies [120]. However, telemetry was successfully received and it exceeded its planned operating life of six years [85], hence it can be classified as a partial success. The most commonly reported failure modes during this period, shown in Fig. 20, have been electrical power system (EPS) failure, on board computer (OBC) failure, and telemetry tracking and command (TT&C) system failure. CubeSats also contributed to this trend, as discussed above.

(c) By contrast, until the 1980s most satellites had been developed under government leadership with the aid of large, advanced industrial contractors and significant resources, as discussed in Section 3. These big investments and cutting-edge design, manufacture, and testing capabilities resulted in mostly full and occasionally partial success among all of the earliest country-first domestic satellites. Indeed, as shown in Fig. 20, the dominant cause of mission end during this period was EPS failure. Many of the earliest satellites (Sputnik-1, Explorer-1, San Marco 1, WRESAT, Dongfanghong-1) were equipped with non-rechargeable batteries which depleted after a relatively short design life of a few days or weeks, while some (Ariel 1, Ohsumi, Aryabhata, Viking) experienced degradation of their solar cells and other EPS components causing eventual depletion of equipped rechargeable batteries. Some missions were actually voluntarily terminated. Alouette-1 was switched off after 10 years of data collection [121], ANS after 15 months "To the great dismay of many scientists" [122], and INTASAT after two years by planned activation of a kill switch [123].

In summary, on average, country-first domestic satellites have had a low mission failure rate, suggesting that they receive more attention and care from their developers than is the norm for a typical satellite project. In addition, mission outcomes follow trends consistent with the four generations of satellites identified in Section 3. The earliest country-first domestic satellites tend to have lower failure rates than more recent ones, owing to more significant resources being available to their developers, and to the recent advent of lower-cost and higher-risk platforms like CubeSats. Electrical power system failure has consistently been among the leading causes of mission end, included by design in the earliest missions and occurring accidentally in more recent ones. Though most of the country-first domestic satellites have already completed their missions or become inactive, many remain in orbit. This is only one part of their legacy, discussed in the next subsection.

5.3. Legacy

The legacy of country-first domestic satellites is briefly considered. Firstly, their impact on subsequent space development activities within their respective countries is analysed. Secondly their global impact, on the Earth orbital environment, is assessed.

5.3.1. Country-second domestic satellites

The legacy of country-first domestic satellites within their country is considered. Did they have a lasting impact on the development of local space technology, STEM education, and space enthusiasm? To begin to answer this question, Fig. 21 shows the time delay until the country launched a second domestic satellite. If the country launched two domestic satellites at the same time, the time delay shown is that to the third domestic satellite.[5] Cases where no further satellites were launched are also identified. The findings are in alignment with the four generations of satellites defined in Section 3. The main points are as follows.

(a) *Most countries have launched a second domestic satellite.* 61 of the 90 countries (or around two thirds, 68%) have launched a second domestic satellite. The average time period between launch of the first and second is around five and a half years, and the median is three and a half years. Hence, most country-first domestic satellites have led to the development of a second. However, this trend shows significant time variation, as explained below. There is a clear distinction between generations 1 and 2 (1980s and before), and generations 3 and 4 (1990s and after) (see definitions in Section 3). In the former case, all countries have launched a second domestic satellite. In the latter, only around half have launched a second one.

(b) *Many second domestic satellites prior to 1990s, with large government-led projects and strong multi-stakeholder partnerships.* The main reasons for this trend are as follows. In generations 1 and 2, domestic satellite development was conducted within one or several of the following contexts: (i) launch vehicle development (e.g., USSR, US, France, Japan, China, India, Israel), (ii) international collaboration involving a multi-satellite deal (e.g., Ariel program with NASA in UK, Alouette-ISIS program with NASA in Canada, San Marco program with NASA in Italy, Interkosmos/Magion program with USSR in Czech Republic), and (iii) one-off satellite development with strong multi-stakeholder partnerships and/or large initial outlay (e.g., Germany's Azur by a consortium of domestic companies in Bremen, the Netherlands' ANS by a consortium of domestic companies, Sweden's Viking by multiple domestic companies and universities). In all three cases, strong initial momentum was built up, which significantly reduced the barrier for developing a second domestic satellite. This also explains the short time period between first and second domestic satellites in most instances prior to the 1990s, as seen in Fig. 21. In addition, the large initial financial, diplomatic, and/or technological commitment typically led to the development of stable roots for the growth of a domestic space industry.

(c) *Fewer second domestic satellites after the 1980s, with university-led capacity building programs and advent of CubeSat.* By contrast, in generations 3 and 4, the context of domestic satellite development shifted towards the following: (i) non-committal experimentation in university-led capacity building programs (e.g., SSTL/University of Surrey's KHTT program, Kyutech's BIRDS program), (ii) stand-alone programs led by individuals, universities, or other institutions via limited interaction with other domestic stakeholders (e.g., Brazil and Argentina's amateur radio satellites Dove-OSCAR 17 and LUSAT-1; Vietnam's F-1), and (iii) CubeSat projects (see Section 4). As a result, it has become easier for countries to test the waters of satellite development without needing to commit significant resources to it. A first domestic satellite can now be built and operated with only a small amount of indigenous infrastructure.
For example, 25 of the 30 country-first domestic satellites developed via the international collaboration programs shown in Fig. 8 were built overseas in facilities provided by the program lead (11 in Japan, 9 in the UK, 2 in Germany, 2 in the US, 1 in Italy), and not domestically. As a result, domestic

[5] The following choices are made. *Chile*: strictly speaking, the country did launch a second domestic satellite, FASat-Bravo in 1998, but it was simply an identical replacement for FASat-Alpha built in the UK and is not counted. *Saudi Arabia*: SaudiSat-1B was deployed at the same time as SaudiSat-1A, and here the next domestic satellite, SaudiSat-1C, is assumed. *Austria*: UniBRITE-1, led by the University of Vienna, was deployed at the same time as TUGSAT-1, and here the next domestic satellite, PEGASUS, is assumed. *Lithuania*: LituanicaSAT-1, led by Vilnius University, was deployed at the same time as LitSat-1, and here the next domestic satellite, LituanicaSAT-2, is assumed. *Slovenia*: Nemo HD, led by Space SI, was deployed at the same time as TRISAT, and here the next domestic satellite, TRISAT-R, is assumed.

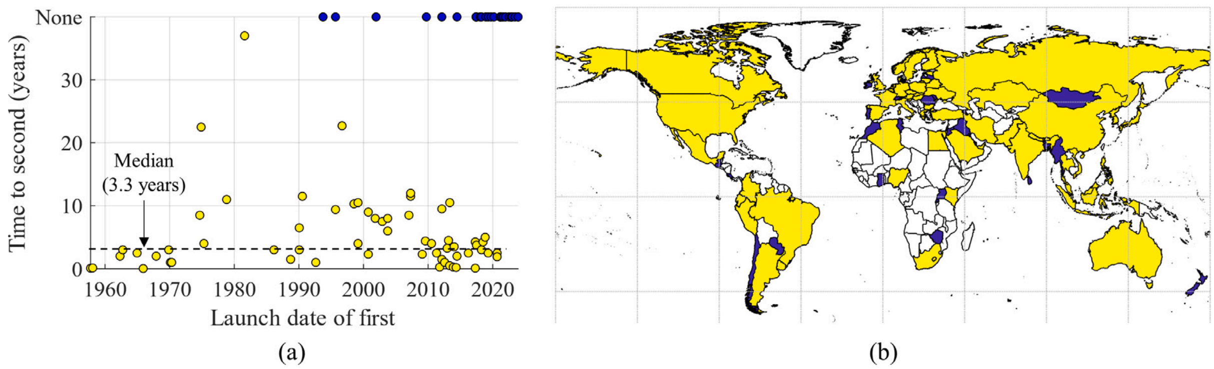

Fig. 21. Was a second domestic satellite launched after the first? (a) Time delay between launch of first and second domestic satellites. The launch date is that of the former. (b) Map of countries with status of second domestic satellite. In both (a) and (b), yellow indicates that a second domestic satellite was launched, and blue not. Data is current as of December 2023.

facilities for satellite assembly, integration, and testing were usually not needed as part of the project and therefore not built, though many participating countries did develop domestic ground infrastructure to communicate with their satellite. However, building a domestic satellite in-country, as was often aspired to after the development of the country's first, requires significantly more resources and a longer-term commitment. Such an investment may not receive priority, especially if the mission outcome of the first domestic satellite did not meet expectations, as discussed later. Indeed, 14 of the 30 countries represented in Fig. 8 did not launch a second domestic satellite. In summary, since the entry barrier for developing a country-first domestic satellite has significantly reduced in recent decades, ironically the launch of such a satellite typically has had less impact on the country's overall space capability development than in the past. In other words, the launch of a domestic satellite is less indicative of a country's space technology capability than it used to be.

(d) *The country-first domestic satellite's mission outcome influences the chance of follow-on missions.* In Section 5.2, mission outcomes of country-first domestic satellites were categorised into full success, partial success, and failure. Interestingly, this outcome is strongly correlated with whether or not subsequent domestic satellites are developed. Among countries with full success, partial success, and failure of their first domestic satellite mission, 75%, 64%, and 29% respectively went on to develop at least one more domestic satellite. On the one hand, these values are biased by the trends discussed in Section 5.2: full success was most common in generations 1 and 2 due to larger resources typically being devoted to satellite development, and these resources also increase the likelihood of follow-on projects; whereas higher-risk and lower-cost satellites in generations 3 and 4 make it easier to develop a single satellite without needing to commit to subsequent ones, and also raise the likelihood of mission failure. On the other hand, undesirable mission outcomes visibly dampened domestic satellite development efforts in some cases. For instance, Mexico's first domestic satellite, UNAMSAT-B, launched in 1996, provided telemetry for only a few weeks in orbit due to unexpectedly low onboard temperatures. It was unable to complete its primary mission of studying micrometeoroids in Earth orbit [16]. In addition, an earlier version of the satellite, UNAMSAT-A, was lost at launch vehicle failure. The next domestic satellite after UNAMSAT-B was not launched until 22 years later [124]. Similarly, Latvia's country-first domestic satellite, Venta-1, launched in 2017, was unable to fulfil its primary mission objective of AIS signal relay due to rotation issues [125]. Moreover, its development was significantly delayed by budget issues and disagreements between stakeholders [125]. As a result, no further domestic satellites have been developed nor are publicly planned. Despite this, a second domestic satellite is not always proof of domestic space capability development, as explained below.

(e) *The number of domestic satellites is not always indicative of space capability development.* Some countries have launched multiple domestic satellites, but these have had a limited impact on growing the country's overall space capabilities. A notable example is Australia. It was among the earliest to launch a domestic satellite – WRESAT, in 1967, led by the government – and shortly thereafter launched its second – Australis-OSCAR 5, in 1970, led by radio amateurs. However, changing priorities among international partners and the Australian government led to a long lull in domestic space activities [100]: for example, the third domestic satellite – FedSat – was launched only 32 years later, in 2002 [126]. Another interesting example is Peru. Based on available information, it has launched four satellites (PUCPSat-1, POCKET-PUCP, UAPSAT-1, and Chasqui) but only in 2013–2014, with a reportedly limited impact on the local space industry. One potential cause is that, since they were developed in three separate projects with limited interaction between their respective stakeholders, they did not consolidate into broader domestic space development.

(f) *Lack of long-term planning or vision by stakeholders.* One reason for not having a second satellite easily or soon is a lack of long-term planning by project stakeholders. Uruguay offers an interesting case study. Researchers in the Faculty of Social Sciences of the Universidad de la República, which led the development of the first domestic satellite AntelSat, conducted a retrospective study of its impact on capacity building among involved stakeholders and on nation-wide innovation capability in Uruguay, e.g., via interviews of key project members [127]. The authors write that "despite some encouraging and positive signs, several aspects raise doubts about the possibility to systematically replicate experiences like this one" (translated and adapted from Spanish). Two such aspects are highlighted: the absence of formal, institutionalised partnerships between university and industry stakeholders, and of the will to establish such links; and the absence of government interest and involvement. The study concludes that, to amplify the impact of a project like AntelSat, there is a need to "act in a decisive and structured manner within the framework of a solid scientific-technological policy that articulates and interlinks the variety of actors with all their potential in a complex system of dense and dynamic interrelationships supported by a broad social consensus" (translated and adapted from Spanish) [127]. This case study shows that, regardless of the mission outcome (i.e., AntelSat achieved full success by capturing and downlinking Earth images), it is harder to secure

funding and support for the second satellite when the main stakeholder is a university. Note that Uruguay is a unique case because it has gone on to produce dozens more satellites, under Argentinian leadership, with no apparent direct connection to AntelSat. Private company Satellogic, founded in Argentina in 2010, is launching a constellation of microsatellites designed in Argentina, and manufactured, assembled, integrated, and tested in a free trade zone in Uruguay including by local engineers, with the first operational one launched in May 2016 [128].
Australia is another noteworthy case study. Development of its first domestic satellite, WRESAT, launched from Woomera, was led by the Weapons Research Establishment. This was a government organisation later renamed as the Defence Science and Technology Group, positioned under the Australian Department of Defence. A detailed history of the Australian space program at Woomera was commissioned by the Department of Defence, drawing upon extensive archive materials. The 500-page study, first published in 1989, notes that "in the 1960s, Woomera played host to many bold space enterprises: the international consortium ELDO and its large three-stage satellite launcher rocket, EUROPA 1; the British Black Arrow and Australia's first and only home-built satellite, WRESAT. For a few years Australia had the opportunity and the resources to become an international space power but, for several reasons which are documented here, the chance was lost and the launcher facilities at Woomera were demolished" [100]. Contributing factors included a lack of long-term planning within the Weapons Research Establishment. It relied heavily on UK funding to run Woomera facilities until the end of the 1960s, and did not plan for subsequent operations until near the end of the 1962–1968 Australian-UK Thorneycroft Agreement. This example shows that when the main stakeholder of a country-first domestic satellite is a government agency, long-term planning at the agency level is extremely important, especially by the highest ranking person who is not a political appointee, as discussed below. How visionary that person is determines the fate of the second satellite and the direction of broader domestic space development.

(g) *Disruptions due to policy change.* Disruptions on a policy level have impacted the genealogy of first domestic satellites in their respective countries. Such disruptions range from simple government change due to democratic elections, to political and economic turmoil. One good example of the former case is Malaysia. Prime Minister Mahathir Mohamad was an early proponent of Malaysian space activities, within the broader context of his vision for "a scientifically advanced and progressive society that could contribute to scientific and technological civilisation" [129]. His first premiership from 1981 to 2003 witnessed the inauguration of the National Planetarium, the Space Science Study Division (BAKSA), and the National Space Agency (AAN), the latter two of which later merged into ANGKASA, since 2019 reformed into the Malaysian Space Agency (MYSA). It also saw the launch of country-first domestic satellite TiungSAT-1 in 2000. By contrast, under the premiership of Najib Razak in 2009 to 2018, there was a long lull in domestic space activities, partly caused by the premature failure of RazakSAT in 2010: "space activities in Malaysia, specifically in the upstream segment, entered a quiet phase. Despite an approved budget by the government of RM200 million for the RazakSAT-2 program, it did not continue as per the initial plan (...) the next generation of satellite programs (...) were no longer a priority for the government" [129].
Three good examples of the latter case, with stronger political and economic turmoil, are as follows. Spain's INTASAT was developed under government leadership shortly before the death of Prime Minister Franco and the transition to democracy. Only around 20 years later was a follow-on project considered and started [130]. Bulgaria's Interkosmos-Bulgaria 1300 was developed with strong support from the Soviet space program in the 1980s, which was significantly restructured in the transition to post-Soviet Russia in the 1990s. Bulgaria launched its second domestic satellite, EnduroSat One, only 37 years later in 2018 [131]. Myanmar's Lawkanat-1 was requisitioned by international partners in Japan following the 2021 military coup. Plans for a second domestic satellite have ostensibly been put on hold [132].

In summary, most country-first domestic satellites have led to a second one being developed. One-off firsts, with a limited impact on national space development, have become more frequent in the last few decades with the advent of low-cost satellite projects such as those involving CubeSats. These can be used to test the waters of space engineering without having to make a big commitment. In this sense, domestic satellites have become less representative of national space technology capability. One factor for whether there will be a second domestic satellite is the mission outcome of the first: full success typically raises the likelihood, compared to failure. Even so, lack of long-term planning or vision by stakeholders can negatively seal the fate of the second satellite regardless of the mission outcome. When the main domestic stakeholder is a university, strategic planning is important to secure good funding for the second satellite. When it is a government agency, the highest ranking person who is not a political appointee plays an important role: how visionary that person is may determine the second satellite's fate. Indeed, simple policy changes, even in the absence of political or economic turmoil, can create strong discontinuities after the first domestic satellite. Finally, the existence of a first, second, or even more domestic satellites is not always indicative of the country's space technology ability: some have launched several satellites without leading to the establishment of a mature domestic space industry and ecosystem.

A detailed discussion on the national legacy of each country-first domestic satellite – for example, on the nation's space industry, STEM education, and space enthusiasm – is beyond the scope of a single paper, but would be an interesting topic for future work. For instance, the development of Explorer-1 in the US was accompanied by a significant revamping of the STEM education system across the United States [133], in the wake of Sputnik-1's success.

5.3.2. Earth orbital environment

The above discussion focused on the legacy of country-first satellites within their lead nation. This subsection discusses their legacy on a global level, with a focus on the Earth orbital environment. Fig. 22 shows the orbital lifetime of country-first domestic satellites, and Fig. 23 their registration status in the United Nations Register of Objects Launched into Outer Space. The former indicates their impact on the population of man-made objects in Earth orbit including space debris, and the latter on harmonisation of access to satellite launch and mission data. Both have become increasingly important in recent years, with the fast growing number of satellites in orbit. The main points can be summarised as follows.

(a) The majority of the satellites, 50 out of 90, or 56%, are still in orbit. This value comprises three main contributions, approximately in line with the four generations identified in Section 3. The earliest category is satellites launched in the 1950s–70s (generation 1). Most of these satellites (64%) have already de-orbited, owing to their eccentric orbits with a low perigee and high air drag, as discussed in Section 4. The most recent category is satellites launched in the 2010s onwards (generation 4): the majority have been deployed from the ISS into high-drag near-circular orbits (see Section 4), and hence most (57%) have also already de-orbited. However, the middle category, consisting

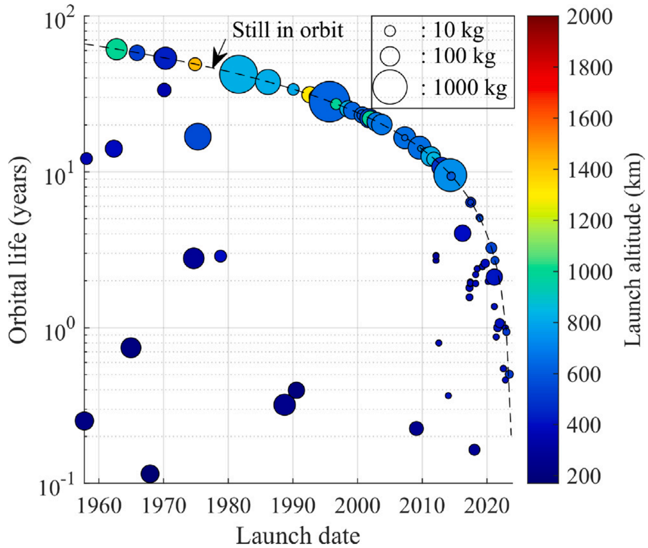

Fig. 22. Orbital lifetime of country-first domestic satellites. Those still in orbit are located on the dashed black line, which forms a curve in the semi-log plot. Those below the line have already re-entered the Earth's atmosphere. Points are coloured by launch perigee altitude and sized by mass. Data is current as of 13 December 2023.

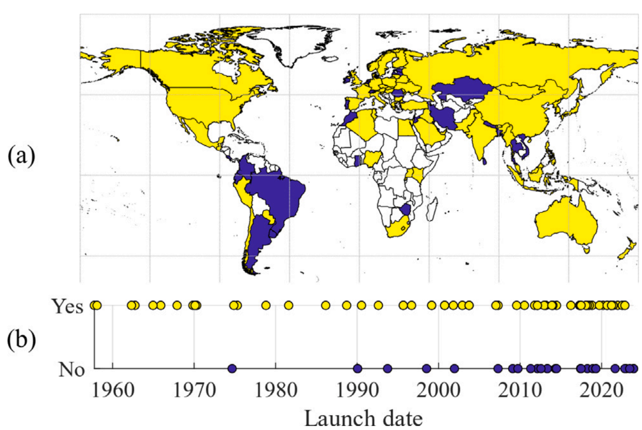

Fig. 23. Status of registry of country-first domestic satellites in the United Nations Register of Objects Launched into Outer Space: (a) map and (b) timeline showing status of registration. Yellow indicates it is registered, and blue that it is not.

of 27 satellites launched between 1980 and 2010 (generations 2 and 3), has a de-orbit rate of only 11%: the large majority remain in orbit. This trend reflects a growing awareness and promotion of space sustainability and space debris mitigation among the international community: satellite deployment opportunities from the ISS have been provided partly in this context. Indeed, a significant change which took place in 2002 is the introduction of the Inter-Agency Space Debris Coordination Committee's (IADC) Space Debris Mitigation Guidelines [134]. These recommend de-orbit of satellites passing through LEO – the case for all country-first domestic satellites launched to date – within 25 years from mission end, with 90% probability. Many country-first domestic satellite developers have followed the recommendation since its introduction in 2002, as evidenced by the growing proportion of satellites launched into lower altitude – and hence shorter-lived – orbits, as in Fig. 22.

Nevertheless, the large number of country-first domestic satellites still in orbit reflects an overall legacy of low concern for the Earth's orbital environment: its stewardship has only recently been inculcated into such satellite development programs. In fact, it is worth noting that ironically, collision with space debris has actually caused the premature end of a country-first domestic satellite mission, as shown in Fig. 20. Ecuador's NEE-01 Pegasus is suspected to have been hit by a spent rocket body in May 2013, causing loss of communication with the ground station [72]. Global emphasis on space sustainability has become even more pronounced with the introduction in September 2022 of the FCC's 5-year rule for post-mission de-orbit in LEO [135]: the next generations of country-first domestic satellites may be shaped even more strongly by space sustainability considerations.

(b) The majority (68%) of country-first domestic satellites have been registered in the United Nations Register of Objects Launched into Outer Space.[6] This register was opened and has been maintained since 1962. The earliest satellites (e.g., Sputnik-1, Explorer-1) were added retrospectively. It serves as a resource to establish international liability and responsibility for space objects, and is overseen by the United Nations Office for Outer Space Affairs (UNOOSA). In parallel, each country which has ratified the 1976 Registration Convention (one of the five major international space treaties) is committed to establishing a national registry of space objects. However, not all countries having launched a country-first domestic satellite have ratified the 1976 Registration Convention: as of 1 January 2023, only 57 of the 90 such countries (63%) have done so [137]. This is one reason for the declining frequency of registrations since the 1990s, observed in Fig. 23: satellite projects are increasingly led by countries not having ratified the 1976 Registration Convention, and/or with no domestic registration mechanisms. Another reason is the involvement of a wider variety of stakeholders in the development of country-first domestic satellites than simply government institutions. Universities, amateurs, and companies may not be as familiar with procedures for satellite registration, even if their country has domestic registration mechanisms. Hence, developers of country-first domestic satellites still have some way to go towards making information on their launch and operations as accessible as possible.

However, the situation is expected to improve [138], one reason being that space newcomers have to rely on launch services by established space powers, as explained in Section 3. These countries have adopted domestic space laws and best practises promoting responsible space activities. Consequently, many will not launch a satellite unless it is registered to the UN, at the risk of being liable to damage caused by the satellite in their capacity as the launch state. For example, in the case of satellites launched by the Kyushu Institute of Technology on behalf of BIRDS program partner countries, JAXA only signs the launch contract after confirming that the international partners have agreed on registering to the UN after deployment.

In summary, until recently, country-first domestic satellites have not emphasised sustainability of the Earth orbital environment. As a result, they have left a legacy of numerous defunct objects in orbit, as well as only a moderate number of registrations in the United Nations Register of Objects Launched into Outer Space. Satellite deployment from the ISS has started to change this trend since the early 2010s, leading to shorter de-orbit times. It is likely that next generations of country-first domestic satellites will increasingly be shaped by space sustainability constraints, in a growingly congested Earth orbital environment.

[6] The average rate of registration, not limited to country-first domestic satellites, is 87% for all "satellites, probes, landers, crewed spacecraft and space station flight elements" launched to date. This number is biased towards major space powers with extensive launch and registration experience [136].

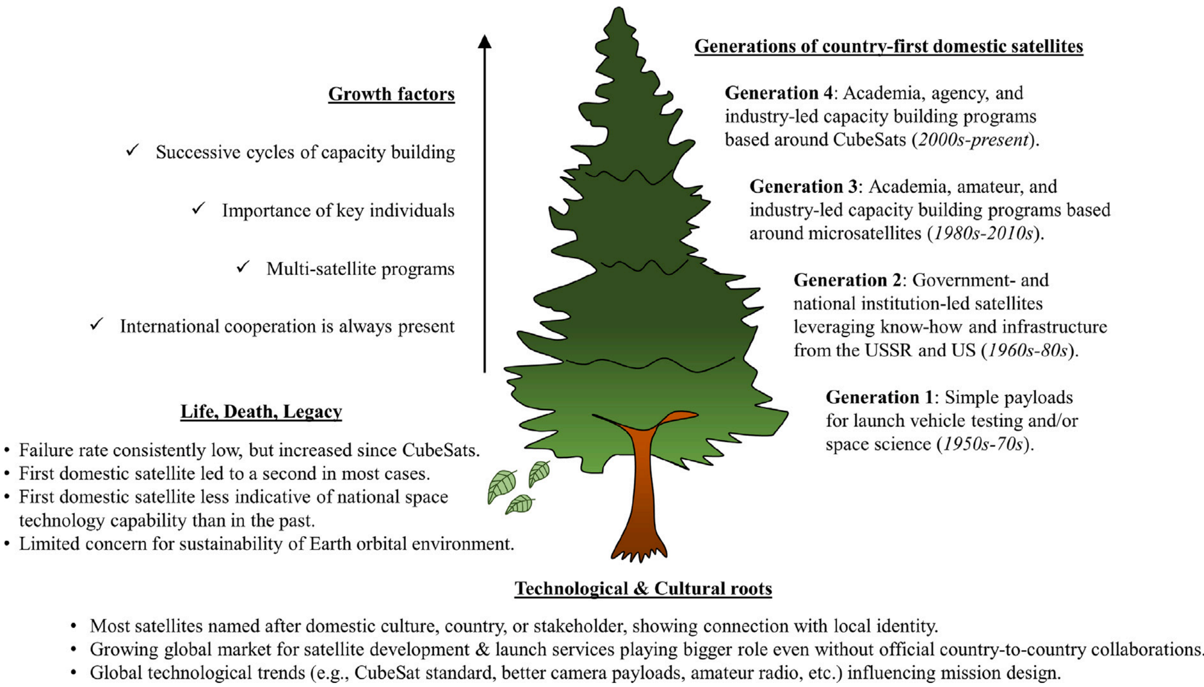

Fig. 24. Lessons learnt on the genealogy of country-first domestic satellites.

6. Lessons learnt and future perspectives

Lessons learnt and future perspectives on country-first domestic satellites are briefly summarised. Fig. 24 provides a visual overview.

6.1. Lessons learnt

1. *Family tree.* Country-first domestic satellites share a common genealogy. It is defined by consistent international collaboration and varied forms of technological cross-pollination. Four overlapping generations can be identified. In the 1950s–70s, the earliest country-first domestic satellites were used as simple payloads for launch vehicle testing and space science (generation 1). In the 1960s–80s, more sophisticated missions were developed, still with a focus on space science, led by governments and national institutions, leveraging know-how and infrastructure from the USSR and US (generation 2). The 1980s–2010s saw a significant expansion in the number and variety of country-first domestic satellites, spurred by academia, amateur, and industry-led capacity building programs based around microsatellites (generation 3). Most recently, since the 2000s, CubeSats have caused a step change in the history of country-first domestic satellites, dramatically widening access to their development, launch, and deployment (generation 4).
In the past two decades, easy-to-access supply chains and launch opportunities have enabled development of more domestic satellites, even in the absence of official country-to-country collaborations: the global space market and new infrastructure trends have been leveraged. The history of launch vehicles has also influenced that of country-first domestic satellites, by directing patterns of international collaboration and influencing mission objectives. Important recurring themes underlying the genealogy of country-first domestic satellites (discussed in Section 3) include: several successive cycles of capacity building, the role of key individuals, and multi-satellite programs. The main point is that all country-first domestic satellites share a common lineage: while often portrayed as the technological prowess of a nation, they are in fact without exception the fruit of technological exchanges and inspirations across borders, though less and less reliant on official country-to-country collaborations.
2. *Birth.* From a cultural viewpoint, the names of country-first domestic satellites reflect their genealogy. Over time, there has been a shift from naming such satellites based on domestic culture, towards naming them after their lead country or a stakeholder institution. This reflects a more and more populated family tree: it has become challenging for one country or institution to stand out and draw attention to its satellite development achievements. Most country-first domestic satellites continue to be named either with reference to local culture or actually based on the country's name itself: national pride and identity seem to be important motivating factors for their development.
From a technological viewpoint, time trends in subsystem design onboard country-first domestic satellites show that they have not only been shaped by official partnerships between stakeholders, as suggested in Section 3, but also by broader systematic technological currents. In terms of size and structure, the invention of the CubeSat standard has dramatically widened access to satellite development by fostering dedicated supply chains and deployment opportunities. In terms of communications, amateur radio frequency bands and communities have enabled easier development of telemetry, tracking, and command subsystems. Demand for higher frequency communications has grown with the maturation of imaging payloads and especially those based on digital CCD and CMOS sensors. This demand has been met by a shift from analogue to digital satellite communications, as part of the evolution of mission objectives from simple science experiments towards Earth observation, prompting more use of active attitude control.
Interestingly, the incorporation of new technologies into country-first domestic satellites has often occurred at the same time in different countries even without official collaborations. This shows that the family tree discussed in Section 3 is supported and complemented by a broad network of roots. The growing global market for space technologies like satellite components, and services such as launch opportunities, provides

scaffolding for domestic satellite development even in the absence of official country-to-country partnerships.

3. *Life, death, and legacy.* On average, country-first domestic satellites have a low mission failure rate. This suggests they receive more attention and care than is the norm for a typical satellite project, and reflects relatively modest and realistic mission objectives in most cases. Based on available information, the dominant cause of mission end has consistently been electrical power system failure. Moreover, many have exceeded their design life, in some cases by over a decade. The earliest country-first domestic satellites tend to have lower failure rates than more recent ones. The main reason is the use of lower-cost and higher-risk CubeSats since the 2010s.
In terms of their legacy, most country-first domestic satellites have led to the development of a second one. Cases of one-off firsts with limited impact on domestic space development have become more common in the last few decades. This is due to the advent of lower-cost projects, which can be used to test the waters of space engineering without needing a significant commitment. Developing a country-first domestic satellite is therefore easier than ever before, but is consequently less indicative of the country's overall space technology capability. It also has less impact in growing follow-on programs and a domestic space ecosystem. In addition, failure during the first mission can reduce enthusiasm for a second one. Regardless of the mission outcome, a lack of long-term planning and vision by project stakeholders can negatively seal the fate of subsequent domestic space activities and funding.
Regarding the legacy of country-first domestic satellites on the Earth orbital environment, their developers have only recently begun to strongly incorporate space sustainability into mission design. Over half of such satellites are still in orbit, many inactive. A non-negligible fraction have not been registered in the United Nations Register of Objects Launched into Outer Space, though the situation is expected to improve.

6.2. Future perspectives

Looking towards the future, a few predictions can be made on directions and objectives likely to be taken up by the next generations of country-first domestic satellites.[7]

1. *Sustainability: A growing focus on the space environment.* Sustainability of the Earth orbital environment has not been a major focus of country-first domestic satellites to date. However, the next ones will be shaped by stricter guidelines and regulations for satellite launch and deployment. More missions specifically designed to promote best practises in space debris mitigation are expected. In particular, the recommendation to de-orbit space objects within 5 years after mission end will lead many satellites to be launched into lower altitude LEO, below 500 km. Since the ISS provides deployment below 450 km altitude, it is likely to continue to be used by country-first domestic satellites.
2. *Size: Further miniaturisation, e.g., PocketQubes.* The CubeSat standard caused a step-change in country-first domestic satellite development. However, until now, no such satellites have been smaller than 1U. In future, smaller form factors like PocketQubes could be used to further drive down costs, but technical, legal, regulatory, and financial constraints exist and should be addressed. One notable discussion point is space debris. For instance, due to their small size, PocketQubes are more difficult to track than CubeSats and it is harder to predict orbital collision risks. This important problem has yet to be fully investigated and addressed [140].
3. *Impact: Conversion of country-first into country-second satellites, a local space industry, STEM education, and space enthusiasm.* Around half of the countries having not developed nor launched a domestic satellite are in the United Nations' list of Least Developed Countries (LDC). Based on the experiences of LDCs – and developing countries more broadly – which have already launched a domestic satellite, it is challenging to convert such an effort into meaningful economic and social impact within the country. As discussed previously, one reason is that developing a satellite has become easier than ever, especially for CubeSats. In other words, developing the first satellite is quite easy, but the process may not lay firm foundations for developing a second one, or for growing a local space industry, or promoting domestic STEM education on a large scale, or raising space enthusiasm, as it tended to in the early days of space development. In this regard, long-term strategic planning and vision are needed. More studies are required to address these challenges, if developing countries wish to establish sustainable domestic space industry and education ecosystems.
4. *Propulsion: More frequent use of thrust.* Only four country-first domestic satellites have used propulsion systems. They all weighed in the order of hundreds of kilograms. In recent years, propulsion for small satellites has gained maturity and reduced in cost. It is likely that next-generation country-first domestic satellites will incorporate propulsion systems to realise novel mission objectives in Earth orbit and beyond.
5. *Stakeholders: Diversification towards highschools, private individuals, etc.* More and more diverse stakeholders are developing country-first domestic satellites. This trend is likely to continue. In future, projects led by highschools and independent individuals are expected.

7. Conclusion

The genealogy of all the 90 country-first domestic satellites was reviewed in detail for the first time, via a comprehensive, trans-disciplinary analysis. A family tree of such satellites was produced, mapping out their cultural and technical birth traits, and studying their life, death, and legacy. Four distinct and overlapping generations of country-first domestic satellites were identified. The most important point is that they all share common lineages. Although often portrayed as a symbol of national identity and technological prowess – as reflected by their names – they are in fact without exception the fruit of international cooperation and collaboration. The development of country-first domestic satellites has historically been supported by official bilateral and multilateral partnerships. However, in the last two decades, the global market for satellite technologies and launch services has played an increasingly important role even without official country-to-country collaborations.

Looking to the future, more than half of all countries have not yet launched a domestic satellite. Among these, a large proportion are defined by the UN as Least Developed Countries. Access to a domestic satellite is becoming easier. However, since less initial investment is required, such satellites are becoming less indicative of a country's overall space technology capability. Instead, the challenge is now to ensure that domestic satellites are actually anchored in and aligned with the development of local industry, technologies, and STEM education. One important requirement is long-term planning and vision. Frameworks for addressing such challenges are needed: they are a priority for future work. Moving forward, it is hoped that this review paper will provide a useful reference point for space historians, policymakers, and the pioneers of diverse new satellite missions.

[7] Among the next planned ones, Honduras' Morazán MRZ-SAT is slated for launch in 2024 [139].

Table 4
Sources of images used in Fig. 1.

Satellite	Image source
Sputnik-1	https://en.wikipedia.org/wiki/Sputnik_1
Explorer-1	https://www.theengineer.co.uk/content/archive/january-1958-explorer-1-america-s-first-satellite
Ariel-1	https://en.wikipedia.org/wiki/Ariel_1#/media/File:Ariel_1_satellite,_London_Science_Museum.JPG
Alouette-1	https://en.wikipedia.org/wiki/Alouette_1#/media/File:Alouette_1.jpg
San Marco 1	https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1964-084A
Astérix	https://img.generation-nt.com/asterix-1_01DB016501630615.jpg
WRESAT	https://www.honeysucklecreek.net/supply/WRESAT/WRESAT_Images/pc_wresat_orr_uzzell_med.jpg
Azur	https://heise.cloudimg.io/width/1392/q30.png-lossy-30.webp-lossy-30.foil1/_www-heise-de_/imgs/18/2/7/8/5/2/6/2/AZUR_Satellit-8e59b8440eddf4d4.jpeg
Ohsumi	https://www.u-tokyo.ac.jp/en/whyutokyo/hongo_hi_009.html
Dongfanghong-1	http://www.xinhuanet.com/politics/2020-04/24/c_1125902168.htm
ANS	https://en.wikipedia.org/wiki/Astronomical_Netherlands_Satellite#/media/File:ANS_backup_flightarticle.jpg
INTASAT	https://d7lju56vlbdri.cloudfront.net/var/ezwebin_site/storage/images/_aliases/img_1col/reportajes/intasat-historia-del-primer-satelite-espanol-puesto-en-orbita/223689-6-esl-MX/INTASAT-Historia-del-primer-satelite-espanol-puesto-en-orbita.jpg
Aryabhata	https://en.wikipedia.org/wiki/Aryabhata_(satellite)#/media/File:Aryabhata_Satellite.jpg
Magion-1	https://www.ufa.cas.cz/en/institute-structure/department-of-ionosphere-and-aeronomy/magion-history/magion-1-3/
Interkosmos-Bulgaria 1300	https://www.bta.bg/en/news/culture/482197-life-size-model-of-bulgaria-s-first-artificial-satellite-to-be-shown-in-sofia-fo
Viking	https://www2.irf.se/program/stp/?dbfile=Viking&dbsec=P3
Ofeq-1	https://space.skyrocket.de/doc_sdat/ofeq-1.htm
LUSAT-1	http://www.lusat.org.ar/
Dove-OSCAR 17	https://space.skyrocket.de/doc_sdat/dove.htm
Badr-1	https://en.wikipedia.org/wiki/Badr-1#/media/File:Badr-1_satellite.jpg
KITSAT-1	https://space.skyrocket.de/doc_sdat/kitsat-1.htm
PoSAT-1	https://space.skyrocket.de/doc_sdat/posat-1.htm
FASat-Alpha	https://www.sstl.co.uk/getmedia/9ac3a23a-a084-40db-8e3d-3cb9c6fab4bd/FASAT-A.jpg?width=750
Sich-1	https://web.archive.org/web/20141228070739/http://www.yuzhnoye.com/en/company/history/earth-resources-satellites.html
UNAMSAT-B	https://space.skyrocket.de/doc_sdat/unamsat-a.htm
ThaiPaht	https://www.sstl.co.uk/space-portfolio/launched-missions/1990--1999/thai-paht-(tmsat)-launched-1998
Ørsted	https://en.wikipedia.org/wiki/%C3%98rsted_(satellite)#/media/File:Oersted_satellite_model.jpg
SunSat	https://www.eoportal.org/satellite-missions/sunsat
TiungSAT-1	https://space.skyrocket.de/doc_sdat/tiungsat-1.htm
SaudiSat-1A	https://space.skyrocket.de/doc_sdat/saudisat-1.htm
PROBA-1	https://eoportal.org/ftp/satellite-missions/p/PROBA1_221021/PROBA_Auto23.jpeg
Maroc-TUBSat	https://www.eoportal.org/api/cms/documents/163813/212664/TUBSAT_AutoF
AlSat 1	https://africanews.space/algeria-celebrates-the-20th-anniversary-of-the-alsat-1/
NigeriaSat-1	https://www.sstl.co.uk/space-portfolio/launched-missions/2000--2009/nigeriasat-1-launched-2003
BILSAT-1	https://www.sstl.co.uk/getmedia/1e8b0679-12eb-4c6c-996a-d18398126515/BILSAT-1-flight-ready.jpg?width=1000
LAPAN-TUBSat	https://www.eoportal.org/api/cms/documents/163813/212664/TUBSAT_AutoB
Libertad-1	https://www.usergioarboleda.edu.co/satelite-libertad-1/
EgyptSat-1	https://upload.wikimedia.org/wikipedia/commons/thumb/6/64/EgyptSat-1_SaudiSat-3_satellite_cluster.jpg/390px-EgyptSat-1_SaudiSat-3_satellite_cluster.jpg
Omid	https://www.b14643.de/Spacerockets_1/Rest_World/Safir-1B-IRILV/Satellites/Satellites.htm
DubaiSat-1	https://www.eoportal.org/api/cms/documents/163813/2571677/DubaiSat1_AutoF.jpeg
SwissCube-1	https://space.skyrocket.de/img_sat/swisscube__2.jpg
AISSat-1	https://www.eoportal.org/api/cms/documents/163813/5706502/AISSAT12_Auto18.jpeg
X-Sat	https://www.eoportal.org/api/cms/documents/163813/2105422/XSat_AutoC.jpeg
VesselSat-1	https://www.eoportal.org/api/cms/documents/163813/2001425/VesselSat_Auto8.jpeg
MaSat-1	https://www.eoportal.org/api/cms/documents/163813/1719915/MaSat1_Auto4.jpeg
PW-Sat-1	https://external-content.duckduckgo.com/iu/?u=https%3A%2F%2Fpw-sat.pl%2Fwp-content%2Fuploads%2F2013%2F02%2Fs2.png&f=1&nofb=1&ipt=f3149d70c1bf077a1295834b5026d2b8d1ed5fcf8a5ec52d875433531677a5f6&ipo=images
Goliat	https://www.eoportal.org/api/cms/documents/163813/174920/Goliat_Auto6.jpg/a46d9c76-65aa-4dbd-b9de-7c05c0ec5387?t=1338293739000
F-1	https://en.wikipedia.org/wiki/F-1_(satellite)#/media/File:F-1_CubeSat_Flight_Model.jpg
Kwangmyŏngsŏng 3–2	https://space.skyrocket.de/img_sat/kwangmyongsong-3__2.jpg
TUGSAT-1	https://external-content.duckduckgo.com/iu/?u=https%3A%2F%2Fimages.derstandard.at%2Fimg%2F2017%2F02%2F22%2FTUGSAT-1.jpg%3Fw%3D1600%26s%3D72676965&f=1&nofb=1&ipt=d57226de005b731ecd9cd46e0810f323f89e902091e9721dd545db81fa4661ed&ipo=images
NEE-01 Pegasus	https://www.eoportal.org/api/cms/documents/163813/486129/NEE_Pegasus_Auto1
ESTCube-1	https://ukamsat.files.wordpress.com/2013/05/estcube-1-at-press-conference-in-tallinn-before-shipping-january-21-2013.jpg?w=598
PCUPSat-1	https://www.nanosats.eu/img/sat/thumb4/thumbnail_PUCP-SAT-1_1.jpg
LitSat-1	https://space.skyrocket.de/img_sat/litsat-1__1.jpg
KazEOSat-1	https://www.eoportal.org/api/cms/documents/163813/3286940/KazEOSat1_AutoB.jpeg
TigriSat	https://space.skyrocket.de/img_sat/tigrisat__1.jpg
AntelSat	http://www.amsat.org/wordpress/wp-content/uploads/2014/10/antelsat__1-300x183.jpg
Diwata-1	https://upload.wikimedia.org/wikipedia/commons/1/1f/Diwata-1.jpg
Aalto-2	https://www.aalto.fi/sites/g/files/flghsv161/files/styles/2_3_1380w_600h_n/public/2019-02/16f1c3f0-8191-428b-9d42-13750f8696e8.jpg?h=5f1b5b34&itok=PTBl_P2Q
UPSat	https://upload.wikimedia.org/wikipedia/commons/7/73/Upsatinspace.jpg
GhanaSat-1, Mazaalai, and BRAC Onnesha	https://i.ytimg.com/vi/be3hjrh-AY8/maxresdefault.jpg
Venta-1	https://www.eoportal.org/api/cms/documents/163813/2832640/Venta1_Auto2.jpeg
skCUBE	https://www.eoportal.org/api/cms/documents/163813/3341416/skCUBE_AutoC.jpeg
Humanity Star	https://space.skyrocket.de/img_sat/humanity-star__1.jpg
Irazú	https://db-satnogs.freetls.fastly.net/media/satellites/satelite-irazu-tec.png

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Table 4 (*continued*).

1KUNS-PF	https://space.skyrocket.de/img_sat/1kuns-pf_2.jpg
BHUTAN-1	https://upload.wikimedia.org/wikipedia/commons/c/cf/BHUTAN-1_over_Earth_%28Iss056e130515%29_%28cropped%29.jpg
BSUSat-1	https://db-satnogs.freetls.fastly.net/media/satellites/BSUSat_1.jpg
JY1-SAT	https://ukamsat.files.wordpress.com/2018/11/jy1sat-cubesat.jpg?w=600
NepaliSat-1, and Raavana-1	https://twitter.com/NanoSpacecrafts/status/1118552646640705541/photo/1
RWASAT-1	https://africanews.space/wp-content/uploads/2019/05/D6tSxgGWwAUbI9J.jpg
Quetzal-1	https://www.satellitetoday.com/wp-content/uploads/2020/04/Screen-Shot-2020-04-28-at-3.11.13-PM.png
OSM-1 Cicero	https://static.wixstatic.com/media/d5ce97_c65d3e6752ff4f2c96c2c81b6e6c6f8e~mv2.jpg/v1/fill/w_864,h_576,al_c,q_85,usm_0.66_1.00_0.01,enc_auto/d5ce97_c65d3e6752ff4f2c96c2c81b6e6c6f8e~mv2.jpg
TRISAT	https://www.um.si/wp-content/uploads/2021/12/IMG_9176-2.jpg
Lawkanat-1	https://space.skyrocket.de/img_sat/lawkanat-1__1.jpg
GuaraniSat-1	https://cdn.mos.cms.futurecdn.net/AkViviAzkLptsFDBGsTYsm-970-80.png.webp
ChallengeONE	https://carthagemagazine.com/wp-content/uploads/2021/02/Challenge-One-Tunisian-Satellite-2-1024x768.jpg
MIR-SAT1	https://spacemauritius.com/wp-content/uploads/2021/09/20200629_101950..jpg
PR-CuNaR2	https://space.skyrocket.de/img_sat/pr-cunar-2__2.jpg
Light-1	https://admin.eoportal.org/documents/163813/6772615/image3.jpg/bcec9eb5-1568-41d8-b803-e198eecc7bdb?t=1670371747425
TUMnanoSAT	https://nanosat.utm.md/wp-content/uploads/2022/06/Deschidere-antene-scaled.jpg
PearlAfricaSat-1, and ZIMSAT-1	https://www.nanosats.eu/img/sat/PearlAfricaSat_TAKA_ZimSat.jpg
KuwaitSat-1	https://space.skyrocket.de/img_sat/kuwaitsat-1__1.jpg
SpeiSat	https://twitter.com/Nicolag1998/status/1667996837108744194/photo/2
Hayasat-1	https://armenpress.am/rus/news/1122193/
EIRSAT-1	https://www.esa.int/Education/CubeSats_-_Fly_Your_Satellite/Meet_the_team_EIRSAT-1

Table 5
Main sources of data on country-first domestic satellites used in this paper.

Country	Satellite name	Main references
Algeria	AlSat 1	[141–143]
Argentina	LUSAT-1	[115,144–146]
Armenia	Hayasat-1	[14,147,148]
Australia	WRESAT	[52,100,126,149]
Austria	TUGSAT-1	[150,151]
Bahrain	Light-1	[152–154]
Bangladesh	BRAC Onnesha	[155,156]
Belarus	BSUSat-1	[157–160]
Belgium	PROBA-1	[79,161]
Bhutan	BHUTAN-1	[162–164]
Brazil	Dove-OSCAR 17	[85,144,165]
Bulgaria	Interkosmos-Bulgaria 1300	[102,166–168]
Canada	Alouette-1	[121,169,170]
Chile	FASat-Alpha	[116,171]
China	Dongfanghong-1	[54,172]
Colombia	Libertad-1	[173–176]
Costa Rica	Irazú	[177,178]
Czech Republic	Magion-1	[179,180]
Denmark	Ørsted	[181–184]
Ecuador	NEE-01 Pegasus	[72,185]
Egypt	EgyptSat-1	[106,186,187]
Estonia	ESTCube-1	[188–190]
Finland	Aalto-2	[191,192]
France	Astérix	[51,193–195]
Germany	Azur	[196–199]
Ghana	GhanaSat-1	[155,200–202]
Greece	UPSat	[109,203,204]
Guatemala	Quetzal-1	[205–207]
Hungary	MaSat-1	[208–211]
India	Aryabhata	[212,213]
Indonesia	LAPAN-TUBSat	[214–216]
Iran	Omid	[217,218]
Iraq	TigriSat	[219,220]
Ireland	EIRSAT-1	[81,221–223]
Israel	Ofeq-1	[83,224,225]
Italy	San Marco 1	[60,226,227]
Japan	Ohsumi	[53,228,229]
Jordan	JY1-SAT	[230,231]
Kazakhstan	KazEOSat-1	[232,233]
Kenya	1KUNS-PF	[234–236]
Kuwait	KuwaitSat-1	[237,238]
Latvia	Venta 1	[125,239]
Lithuania	LitSat-1	[240,241]
Luxembourg	VesselSat-1	[242,243]
Malaysia	TiungSAT-1	[129,244,245]

(*continued on next page*)

Table 5 (*continued*).

Country	Satellite name	Main references
Mauritius	MIR-SAT1	[246–249]
Mexico	UNAMSAT-B	[16,124,144,250]
Moldova	TUMnanoSAT	[251–253]
Monaco	OSM-1 Cicero	[111,254–256]
Mongolia	Mazaalai	[92,155,156,257]
Morocco	Maroc-TUBSat	[258,259]
Myanmar	Lawkanat-1	[260–262]
Nepal	NepaliSat-1	[263–265]
Netherlands	Astronomical Netherlands Satellite	[101,122,266,267]
New Zealand	Humanity Star	[90,268]
Nigeria	NigeriaSat-1	[269–273]
North Korea	Kwangmyŏngsŏng 3–2	[274–277]
Norway	AISSat-1	[278–282]
Pakistan	Badr-1	[283–286]
Paraguay	GuaraniSat-1	[287–289]
Peru	PCUPSat-1	[290,291]
Philippines	Diwata-1	[292,293]
Poland	PW-Sat-1	[78,294–296]
Portugal	PoSAT-1	[297–300]
Puerto Rico	PR-CuNaR2	[113,301,302]
Romania	Goliat	[303–305]
Russia	Sputnik-1	[98,306–308]
Rwanda	RWASAT-1	[74,309,310]
Saudi Arabia	SaudiSat-1A	[311–315]
Singapore	X-Sat	[316–318]
Slovakia	skCUBE	[319–323]
Slovenia	TRISAT	[324,325]
South Africa	SunSat	[326–329]
South Korea	KITSAT-1	[330–332]
Spain	INTASAT	[123,333,334]
Sri Lanka	Raavana-1	[263–265,335]
Sweden	Viking	[336–338]
Switzerland	SwissCube	[107,339]
Thailand	ThaiPaht	[340,341]
Tunisia	ChallengeONE	[112]
Turkey	BILSAT-1	[342,343]
Uganda	PearlAfricaSat-1	[75,265,344]
Ukraine	Sich-1	[57,345–347]
United Arab Emirates	DubaiSat-1	[348–351]
United Kingdom	Ariel-1	[59,108,352,353]
United States	Explorer-1	[49,50,354–356]
Uruguay	AntelSat	[357–359]
Vatican	SpeiSat	[360–362]
Vietnam	F-1	[363,364]
Zimbabwe	ZIMSAT-1	[75,265,344]

CRediT authorship contribution statement

Maximilien Berthet: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Shinichi Nakasuka:** Writing – review & editing, Conceptualization. **Mengu Cho:** Writing – review & editing, Conceptualization. **Kojiro Suzuki:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Sources of images used in Fig. 1

Sources of images used in Fig. 1 are listed in Table 4. All can freely be accessed online. Some images have been cropped.

Appendix B. Main sources of data on country-first domestic satellites

Table 5 shows the main references used in this paper to obtain data on country-first domestic satellites.

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