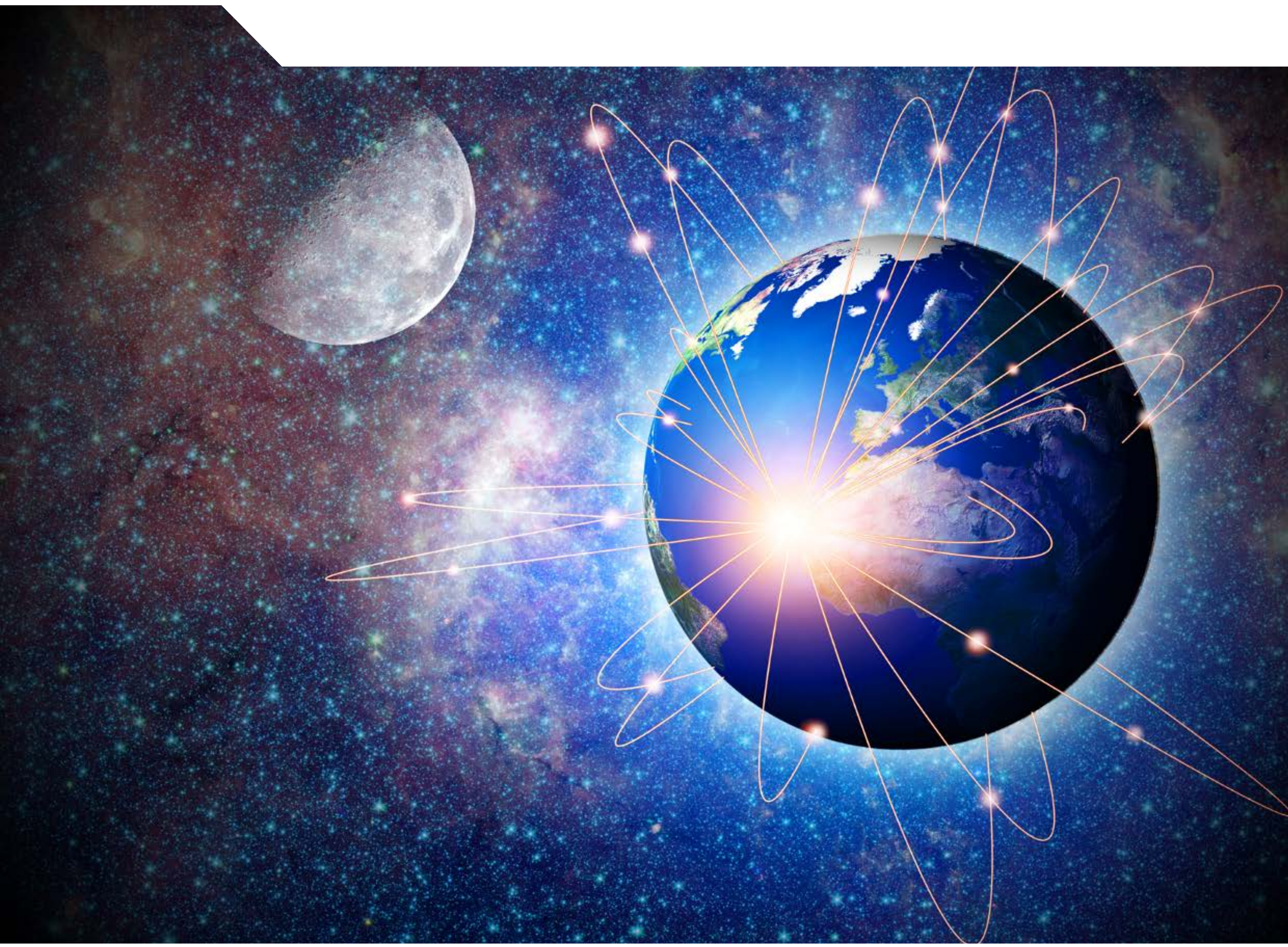
The Space Economy in Figures

HOW SPACE CONTRIBUTES TO THE GLOBAL ECONOMY



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BETTER POLICIES FOR BETTER LIVES

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Foreword

The OECD publication *The Space Economy in Figures: How Space Contributes to the Global Economy* provides an original overview of the global space sector.

This report is the fourth in a series of OECD publications dedicated to the space economy (previous reports were published in 2007, 2011 and 2014). In a little more than a decade, the space sector has experienced considerable development throughout the world, with greater impacts on the larger economy boosted by both globalisation and digitalisation. It is also on the verge of significant changes, with new commercial space systems – from satellite broadband constellations to spaceflight – becoming operational.

This latest publication documents these trends using original indicators from public and private data sources, highlighting the growing importance of space activities for the economy, social wellbeing and science. Furthermore, it provides lessons-learned for policymakers in how space technologies can be linked to socio-economic impacts. As well as updating existing OECD indicators, this new edition showcases newly-established OECD indicators, leveraging close co-operation across relevant policy areas in the OECD and with the ever-growing space community. These indicators include measures of space projects and official development assistance, bibliometric data used as proxies for innovation, new broadband indicators, and new datasets that contribute to extended country profiles.

The report includes seven chapters covering major trends in the space sector plus country-specific profiles of recent developments. The chapters are:

- ***The ongoing transformation of the global space sector*** (Chapter 1). This chapter provides an introduction to the transformation of the global space sector from three different angles: reviewing institutional and private investment trends, examining evolutions of the space economy, confronting current hype and market realities, and finally focusing on global space innovation activities (using proxies such as bibliometrics and patents).
- ***The returns from space investments*** (Chapter 2) examines three different approaches to how space investments can be linked to socio-economic impacts. An assessment of the types of benefits derived from space programmes are first provided, based on an international literature review. In addition, new OECD indicators on the growing role of space applications in official development assistance projects (ODA) are presented for the first time. Finally, the growing relevance of technology transfers and commercialisation from the space sector to the wider economy is highlighted.
- ***Remedying the gender gap in a dynamic space sector*** (Chapter 3) provides a brief overview of employment in the space sector. It also presents one of the first exercises at the international level to present indicators to evaluate the space sector from a gender perspective. It provides exploratory indicators on government space agencies, higher education institutions and the private sector as well as female tertiary education enrolment and graduation statistics in space-related fields.
- ***Digital (r)evolution in manufacturing and in the production of space systems*** (Chapter 4) examines how digitalisation is affecting the space sector, with a focus on key developments in satellites and space launchers. It also identifies possible emerging space activities (space tourism, in-orbit servicing, space mining and resources extraction).
- ***Space exploration and the pursuit of scientific knowledge (Chapter 5)*** reviews recent developments in space exploration and space sciences, the progress made in human spaceflight missions, as well as the growing challenges posed by space debris. It presents some key missions planned for the next decade and highlights specific trends, such as the rise of citizen science and crowdsourcing.

- ***A new satellite communications environment*** (Chapter 6) briefly reviews the state of play in satellite communications. For decades, satellite communications have been the fastest growing commercial space market, driving innovation and growth along the space sector's value chains. New technologies, business models and consumer behaviours are disrupting markets (e.g. television, backhaul, broadband and internet of things), with impacts throughout existing value chains. In addition, specific policy issues, particularly related to spectrum allocations, may bring further uncertainties.
- ***Bringing space down to earth*** (Chapter 7). The last chapter focuses on the growing volume and variety of satellite data and signals, and how they affect downstream applications such as weather and climate monitoring, earth observation and satellite positioning, navigation and timing. Building on advances in analytics and machine learning, ecosystems of innovative start-ups are using satellite data and signals in original ways and developing brand new products and services.
- Finally ***extended country profiles*** are provided with new indicators, featuring members of the OECD Space Forum, as well as selected invited economies.

This publication is based on research and analytical work conducted by the OECD Space Forum Secretariat in the Science and Technology Policy Division, within the Directorate for Science, Technology and Innovation (STI). These activities fit into the broader programme of work of the OECD Committee for Scientific and Technological Policy (CSTP), under the direction of Dominique Guellec. The publication was prepared under the guidance of Claire Jolly, Head of Unit, with support in conducting research and analysis from Marit Undseth, Policy Analyst, Mattia Olivari, Economist, and events' organisation and editing from Chrystyna Harpluk, Project Coordinator. Editorial assistance was provided by Angela Gosmann, STI Publications, and Jennifer Allain, Editor. Sylvain Fraccola, also from STI, provided support with country profile graphics.

The indicators in this report build on data regularly provided by member countries' authorities and on data available from other OECD and international sources. The data primarily come from official sources (such as OECD databases, statistical offices, national space agencies). In some cases data are sourced directly from industry. The published indicators have been chosen based on the reliability and timeliness of the required data.

The team particularly thanks the institutions that are members of the OECD Space Forum for providing information, data and comments instrumental to the preparation of this report. We also thank the representatives of industry, small businesses, academia, ministries, and national delegates from the OECD Committee for Scientific and Technological Policy, who contributed substance during interviews and many OECD Space Forum workshops (see acknowledgements section).

Acknowledgements

The OECD Space Forum Secretariat in the OECD Directorate for Science, Technology and Innovation (STI) wishes to acknowledge with sincere thanks the support provided by the organisations forming the Steering Group of the OECD Space Forum: The Canadian Space Agency (CSA), Canada; Centre National d'Etudes Spatiales (CNES), France; Deutsches Zentrum für Luft- und Raumfahrt (DLR), Germany; Agenzia Spaziale Italiana; (ASI), Italy; the Korea Aerospace Research Institute (KARI), Korea; the Mexican Space Agency, Mexico; the Netherlands Space Office, the Netherlands; the Norwegian Space Agency and the Ministry of Trade, Industry and Fisheries, Norway; the Swiss Space Office, Switzerland; the UK Space Agency, United Kingdom; National Aeronautics and Space Administration (NASA), United States; and the European Space Agency (ESA). We appreciate the efforts of the individual members of the Steering Group and their colleagues, who have provided valuable guidance and kind support, including through the co-organisation and participation in OECD workshops, provision of original material, and detailed reviews of background papers that were used for this publication.

The Space Forum Steering Group Members include: David Haight, Chief Economist (Canadian Space Agency, Canada); Murielle Lafaye, Space foresight and socio-economic impacts (Centre national d'Etudes Spatiales, France); Hendrik Fischer, Deputy Head, Department Strategy and Communication in the DLR Space Administration (Deutsches Zentrum für Luft- und Raumfahrt, Germany); Simona di Ciaccio, Presidency's Technical Cabinet, and Danilo Rubini, Head of Technology Office (Agenzia Spaziale Italiana, Italy); Jung Ho Park, Senior Researcher (Korea Aerospace Research Institute, Korea); Rosa Ma. Ramírez de Arellano y Haro, General Director of International Affairs and Space Security (Agencia Espacial Mexicana, Mexico); Thomas Bleeker, Senior Adviser (Netherlands Space Office, the Netherlands); Magnus Bjerke, Senior Advisor (the Royal Ministry of Trade, Industry and Fisheries, Norway) and Geir Hovmork, Deputy Director General (Norwegian Space Agency); Barbara Richardson, Strategy Manager, and Nick Cox, Head of Technology Strategy (UK Space Agency, United Kingdom); Patrick Besha, Senior Policy Advisor (National Aeronautics and Space Administration, United States); Luca del Monte, Head of Industrial Policy and SME Division and Charlotte Mathieu, Head of the Industrial Policy and Economic Analysis Section (European Space Agency).

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Many experts kindly contributed to this publication with comments and substance, and we wish to acknowledge several OECD colleagues for their contributions to this report, notably Hélène Dernis on patents from the Economic Analysis and Statistics (EAS) Division in STI and Aimée Nichols on official development assistance from the Financing for Sustainable Development (FSD) Division in the Development Co-operation Directorate. Chapter 6 benefitted from comments from Verena Weber, Acting Head of the Communication Infrastructures and Services Policy Unit, Digital Economy Policy Division in STI.

In addition to the efforts of the organisations and individuals noted above, the drafting of this publication benefitted from six OECD workshops and symposia held in the 2016-18 time period, which gathered in total more than 250 experts from ministries, space agencies and other administrations, international organisations, industry, consulting firms and academia. We warmly thank the participants and acknowledge their contributions in references throughout this report. Selected workshops include:

- “Economic Models for the Low-Earth Orbit and beyond”, OECD Space Forum workshop, 25 October 2018, OECD Headquarters, Paris
- “The Transformation of the Space Industry: Linking Innovation and Procurement”, OECD Space Forum workshop, 27 April 2018, OECD Headquarters, Paris.
- “Close-up on AI in Space Applications”, dedicated session at the OECD Symposium *AI: Intelligent Machines: Smart Policies*, 26 October 2017, OECD Headquarters, Paris.
- “Economic and Innovation indicators for the Space Sector”, OECD Space Forum workshop, 22-23 June 2017, OECD Headquarters, Paris.
- “Technology Transfer and Commercialisation From Space Programmes: Enabling Conditions, Processes and Economic Impacts”, workshop co-organised by the Space Agency Technological Transfer Officers (SATTO) Group and the OECD Space Forum, 21 June 2017, CNES, Paris.
- “Innovation and the Space Sector”, OECD Space Forum symposium, 27 October 2016, OECD Headquarters, Paris.

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Abbreviations and acronyms

ADB	Asian Development Bank
AI	Artificial intelligence
AIA	Aerospace Industries Association
AIS	Automatic identification system
ASI	Agenzia Spaziale Italiana
AWS	Amazon Web Services
BGAN	Broadband global area network
BRIC	Brazil, Russian Federation, India and China
BRIIC	Brazil, Russian Federation, India, Indonesia and China
BRIICS	Brazil, Russian Federation, India, Indonesia, China and South Africa
C3S	Copernicus Climate Change Service
CAST	China Aerospace Science and Technology Group
CEOS	Committee on Earth Observation Satellites
CGMS	Coordination Group for Meteorological Satellites
CM-SAF	Satellite Application Facility on Climate Monitoring
CNES	Centre national d'études spatiales
CNRS	Centre national de la recherche scientifique
CPOM	Centre for Polar Observation and Modelling
CSA	Canadian Space Agency
DBS	Direct broadcasting satellite
DLR	Deutsches Zentrum für Luft-und Raumfahrt
DTH	Direct-to-home satellite
DWD	Deutcher Wetterdienst
EARSC	European Association of Remote Sensing Companies
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
EGNOS	European Geostationary Navigation Overlay Service
EO	Earth observation
EPO	European Patent Office
ESA	European Space Agency
ESOC	European Space Operations Centre
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAA	Federal Aviation Administration
FTE	Full-time equivalent
GAGAN	GPS-aided GEO augmented navigation
GBAORD	Government budget appropriations or outlays for research and development
GCOS	Global Climate Observing System
GEO	geosynchronous orbit
GIFAS	Groupement des Industries Françaises Aéronautiques et Spatiales
GLONASS	Global Navigation Satellite System
GPS	Global Positioning System
GSA	European GNSS Agency
GSO	Geo-synchronous orbit
IADC	Inter-Agency Space Debris Coordination Committee
IDA	International Development Association

IDB	International Development Bank
INSEE	Institut National de la Statistique et des Études Économiques
ISRO	Indian Space Research Organisation
ISS	International Space Station
ITU	International Telecommunications Union
JMA	Japan Meteorological Agency
JAXA	Japan Aerospace Exploration Agency
JPO	Japan Patent Office
KARI	Korea Aerospace Research Institute
KASS	Korea Augmentation Satellite System
KIPO	Korean Intellectual Property Office
KMA	Korea Meteorological Administration
KNMI	Koninklijk Nederlands Meteorologisch Instituut
LEO	Low-Earth orbit
LINZ	Land Information New Zealand
MSAS	MTSAT Satellite Augmentation System
NASA	National Aeronautics and Space Administration
NASRDA	National Space Research and Development Agency (Nigeria)
NCEI	National Centers for Environmental Information
NESDIS	National Environmental Satellite, Data, and Information Service
NOAA	National Oceanic and Atmospheric Administration
NSC	Norwegian Space Centre
NSO	Netherlands Space Office
OECD	Organisation for Economic Co-operation and Development
ONERA	Centre français de recherche aérospatiale
OSI-SAF	Satellite Application Facility on Ocean and Sea Ice
PCT	Patent Co-operation Treaty
PPP	Purchasing power parities
QZSS	Quasi-Zenith Satellite System
RAL	Rutherford Appleton Laboratory
Roscosmos	Russian Federal Space Agency
SANSA	South African Space Agency
SBAS	Satellite-based augmentation system
SJAC	Society of Japanese Aerospace Companies
SME	Small and medium-sized enterprise
SRON	Netherlands Institute for Space Research
SSA	Space situational awareness
SSO	Swiss Space Office
UKSA	United Kingdom Space Agency
UN COPUOS	United Nations Committee on the Peaceful Uses of Outer Space
UNOOSA	United Nations Office of Outer Space Affairs
USGS	United States Geological Survey
USPTO	United States Patent and Trademark Office
WAAS	Wide Area Augmentation System
WMO	World Meteorological Organization

ISO country codes

ISO codes for OECD member countries		ISO codes for other economies	
Australia	**AUS**	Afghanistan	**AFG**
Austria	**AUT**	Argentina	**ARG**
Belgium	**BEL**	Armenia	**ARM**
Canada	**CAN**	Azerbaijan	**AZE**
Chile	**CHL**	Bangladesh	**BGD**
Czech Republic	**CZE**	Barbados	**BRB**
Denmark	**DNK**	Benin	**BEN**
Estonia	**EST**	Brazil	**BRA**
Finland	**FIN**	China (People's Republic of)	**CHN**
France	**FRA**	Colombia	**COL**
Germany	**DEU**	Democratic Republic of the Congo	**COD**
Greece	**GRC**	Egypt	**EGY**
Hungary	**HUN**	Fiji	**FJI**
Iceland	**ISL**	India	**IND**
Ireland	**IRL**	Indonesia	**IDN**
Israel	**ISR**	Iran	**IRN**
Italy	**ITA**	Iraq	**IRQ**
Japan	**JPN**	Kiribati	**KIR**
Korea	**KOR**	Lao People's Democratic Republic	**LAO**
Latvia	**LVA**	Lebanon	**LBN**
Lithuania	**LTU**	Madagascar	**MDG**
Luxembourg	**LUX**	Malaysia	**MYS**
Mexico	**MEX**	Micronesia	**FSM**
Netherlands	**NLD**	Myanmar	**MMR**
New Zealand	**NZL**	Namibia	**NAM**
Norway	**NOR**	Nigeria	**NGA**
Poland	**POL**	Pakistan	**PAK**
Portugal	**PRT**	Papua New Guinea	**PNG**
Slovak Republic	**SVK**	Paraguay	**PRY**
Slovenia	**SVN**	Peru	**PER**
Spain	**ESP**	Russian Federation	**RUS**
Sweden	**SWE**	Samoa	**WSM**
Switzerland	**CHE**	Senegal	**SEN**
Turkey	**TUR**	Serbia	**SRB**
United Kingdom	**GBR**	Solomon Islands	**SLB**
United States	**USA**	South Africa	**ZAF**
		Syrian Arab Republic	**SYR**
		Chinese Taipei	**TWN**
		Tanzania	**TZA**
		Thailand	**THA**
		Tonga	**TON**
		Ukraine	**UKR**
		Vanuatu	**VUT**
		Viet Nam	**VNM**
		Zambia	**ZMB**

Executive Summary

Space activities are expanding globally, with a record number of countries and commercial firms investing in space programmes. Ever more down-to-earth activities are derived from satellite signals and data, contributing to new economic activities often far removed from initial investments in space infrastructure. Digitalisation is transforming space manufacturing activities, downstream space applications and even space exploration.

This OECD report *The Space Economy in Figures: How Space Contributes to the Global Economy* documents these emerging trends using original indicators, highlighting the growing importance of space activities for the economy, social wellbeing and science. It further offers lessons learned to policymakers on fostering socio-economic impacts.

The transformation of the space sector

Never before has there been so much interest in the space sector, with satellites in orbit registered in over 80 countries and ever growing public and private investments.

- Public space budgets reached an estimated USD 75 billion in 2017 (a figure expected to grow further in 2018) – their largest amount since the Apollo era in the 1960s. The United States has the highest budget in absolute terms (accounting for more than half of the total), followed by The People's Republic of China (hereafter "China"), Japan and France.
- Promising innovations and new space technology systems are coming of age, attracting much attention and increased public and private capital – small and micro satellites, mega-constellations of hundreds of satellites, small launchers, broadband and internet-of-things from space, commercial human spaceflight, to name a few. In this context, the space economy is projected to grow, although probably at a slower pace than recent years, as markets expand and activities become more interconnected with terrestrial systems and consumer products.
- Start-ups in all segments of the space sector continue to emerge with over 500 small companies, particularly in the United States, but also in Europe, Japan, China and India, created in the past four years. Some of these start-ups aim to provide new launch capabilities, innovative Internet-of-Things services via small satellites, or new forms of data analytics. Although many still need to bring their products to market, one of their strongest impacts so far has been to spur innovation and encourage larger aerospace incumbents to begin to adapt their business practices to the new environment.
- Digitalisation is increasingly impacting the entire space sector, from incumbents to newcomers. Science, research and development (R&D), manufacturing and production processes are all being disrupted. In industry, digitalisation is creating new opportunities, with the introduction of lean manufacturing processes, vertical integration of end-to-end products and services (e.g. from satellites all the way to ground terminals), as well as with the first assembly lines for the mass production of small satellites. The development of 3-D printed components for satellites and rockets are becoming the norm for both large and small aerospace manufacturers. Cost- and time efficiencies are expected to sift into the entire space sector's value chains.

Further shake-ups expected in the space sector

In view of accelerated digitalisation trends affecting all parts of the economy, the structure of the space industry itself seems to be on the verge of a shake-up, with new challenges to overcome:

- Changes in customers' appetites for digital products, from satellite television to geospatial services, could have strong impacts on many existing commercial space service providers if they position themselves correctly. For example, the business models of many of the planned constellations of one hundred plus satellites – key to the space sector's ability to realise the benefits of the continued digitalisation of the rest of the economy – are still to be proven. Despite this launches for at least twenty such constellations are planned in the next six years.

- Stronger competition across the sector may lead to increased concentration and/or multiple exits in certain segments of the value chain, creating both winners and losers. This applies to commercial markets already at the centre of major disruptions such as satellite communications, but also the much larger and traditionally captive institutional space markets in North America, Europe, and Asia.
- Competition from terrestrial providers of services in space downstream markets is becoming more tangible (e.g. fibre and 5G mobile systems with spectrum issues).
- Finally, one crucial unknown in the near future, for all space activities, is linked to the accumulation of debris in orbit, representing millions of objects, where a single accident could have catastrophic cascading consequences for the entire space economy.

Policy actions for a globalised space sector

As the space sector is transformed in the face of continued digitalisation, policymakers play an important role in enabling the transition for existing firms while at the same time fostering innovation and entrepreneurship. In order to reap the full benefits of existing and future space activities and to ensure sustainable and equitable growth, policy actions in four different areas are recommended:

- Increase government use of commercial services, via procurement and co-funding mechanisms. Institutional space budgets still represent a key driver for commercial space activities, with public administrations already acting as funders or anchor tenants of many commercial space services. As capabilities from the private sector grow, government can make more extensive use of commercial space services for increasingly sophisticated tasks.
- Map national space economies in cooperation with national statistical offices, industry associations and/or private contractors. All countries and firms have the opportunity to participate and benefit from the space sector's global value chains. Governments that fund space programmes should better track who is doing what in the space industry and beyond, via regular industry surveys and analysis of existing administrative data. This includes mapping the many actors along the value chains of their national space economies.
- Further address human resources needs of the space sector, particularly in view of current digitalisation trends that will increase competition for talent, and the still significant gender gap in space-related higher education and employment. Programmes to promote fair participation in the space sector would benefit from thorough maps of gender employment, in order to track, evaluate and compare different initiatives.
- Identify solutions to mitigate space debris, through international cooperation, regulation and technology development, especially as the next three years could see a tripling in the number of satellites in orbit.

Key facts and figures on the space sector

- Public space budget have reached their largest amounts since the 1960s and the Apollo era, at an estimated USD 75 billion in 2017, with the United States accounting for more than half of the total budget, followed by China, Japan and France.
- Returns from investments in space programmes take many shapes. In the case of space applications, such as telecommunications and earth observation, top benefits include efficiency gains, cost savings and cost avoidances. Many of these occur in the following domains of application: government services, defence, transport, weather, environmental management and climate change monitoring.
- In view of their positive impacts in developing countries, space applications have become increasingly part of official development assistance (ODA) projects. Top space-related ODA contributors include France, the United States, Japan, The Netherlands, Norway, the United Kingdom, and Canada.
- In Europe and North America, women account for slightly more than 20% of space manufacturing employment and some 10-15% of aerospace engineers. The share of women graduates in aerospace engineering remains low in many OECD countries, despite government and private sector efforts.
- A record number of space exploration missions are planned in the next five years: more than 15 missions to the Moon by eight different space agencies (with even commercial missions), at least six missions to Mars, and two to reach asteroids.
- 2018 saw the highest number of orbital launches conducted since 2000 (114 launches). More than 60% of which took place in either the United States or China. With 21 rockets launched in 2018, SpaceX broke the record of annual launches conducted by one company.
- The past five years have seen exponential growth in the number of launches of very small satellites, with almost 900 satellites launched in the 2014-18 period.
- By 2020, four global navigation satellite systems (GNSS) should be fully operational (US, Russia, Europe, China) and three regional ones are in the process of being rolled out (India, Japan, South Korea). Already more than 60% of devices around the world can receive two or more GNSS signals, and almost all new smartphones are equipped with multi-signal chipsets and receive positioning, navigation and timing information.
- Satellite broadband grew steadily over the last decade. The total number of subscriptions rose from around 1.2 million in 2008 to above 5.2 million in 2017. Developers of several very large satellites constellations aim to provide commercial broadband services to the entire world by 2023-24.
- With cable TV still the leading technology for television broadcasting globally, and new mobile television services being rolled out, around five in every 100 inhabitants worldwide have a satellite TV subscription in 2017, rising from 1.5 in 2008 (with a majority in OECD countries).
- More than 50% of the essential climate variables rely on satellite data. Earth observation and weather satellites contribute information to manage both land and ocean activities, and they provide crucial data for weather forecast models as well.
- At least seven organisations are investing in commercial suborbital and orbital space tourism activities, to start in the next five years. Two companies could be offering their first suborbital activities as early as 2019-20 (Virgin Galactic, Blue Origin).
- Since the start of the space age, more than 5 200 rockets have been launched and 7 500 satellites placed in orbit. Around 1 200 satellites are currently operational today flying in the midst of debris, representing around 29 000 space objects measuring more than 10 centimetres, with an estimated 167 million objects under 10 centimetres.

Chapter 1

THE ONGOING TRANSFORMATION OF THE GLOBAL SPACE SECTOR

This chapter provides an introduction to the ongoing transformation of the global space sector. It first provides a review of institutional and private investments, which are generally on the rise around the world. Governments remain today the main investors in space activities, via procurement and grant mechanisms, but long-term civil space research and development budgets show signs of slowing in some countries. The chapter examines the evolution of the space economy, confronting current hype and market realities. Focussing then on space innovation (using proxies such as bibliometrics and patents), a new landscape of innovative space activities is slowly appearing, demonstrating the ongoing globalisation of the sector. Finally, two policy approaches to better assess and support a transformed space sector are proposed.

The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

Institutional and private investments on the rise around the world

Worldwide, governments are the main investors in space activities, via procurement and grants mechanisms to public agencies, research institutes, universities and the private sector. But in only five years the global landscape for space activities has evolved, with new countries investing in space research and development, and getting involved in global value chains. Private funding of commercial projects has also grown, with unprecedented private capital flows in the space sector from angel and venture capital investments.

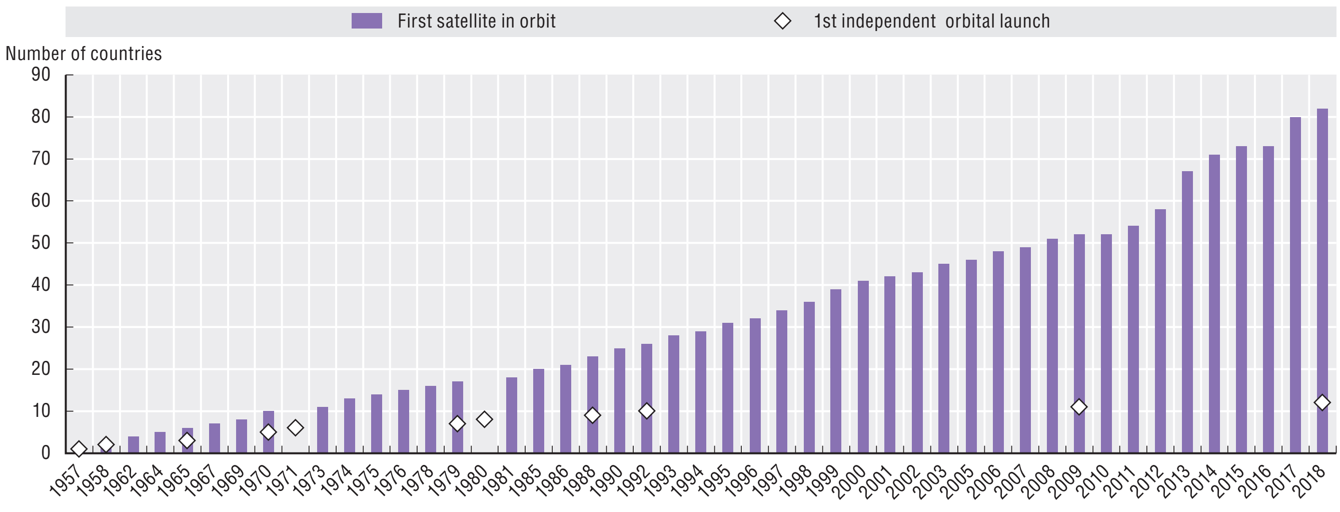
Institutional funding of space programmes

Public investments represent the bulk of funding in space activities, reaching almost USD 75 billion in 2017 (and still growing in 2018), as compared to an estimated USD 52 billion in 2008. Governments invest in space capabilities to support national security and governance objectives (e.g. being able to map and monitor resources from space), but also broad socio-economic motivations, and scientific capacities' development (see Chapter 2 on the impacts of space investments).Countries with space programmes have moved from being a very exclusive club relying on their strong defence and aerospace industries, to a much wider group of developed and developing countries, with very diverse capabilities.

In only a decade, the number of countries with a satellite in orbit have increased from 50 in 2008 to 82 in 2018 (Figure 1.1). The satellites considered are of course very different in their specificities and may involve very little national technical expertise, ranging from large multi-ton telecommunication satellites purchased on the international market to very small cubesats built in local universities. But the possibility to have one's satellite in orbit, registered with one's own national administration, has never been so affordable (OECD, 2016[1]).

Figure 1.1. More than 80 countries with a registered satellite in orbit

Number of countries with a satellite in orbit (launched via a third party or independently between 1957 and April 2018) and number of countries having launched a rocket successfully



Since the first OECD report on the space economy in 2007, some twenty new countries have also started investing in original space programmes and supporting private endeavours, with distinctive and symbolic projects. They include, for example, the United Arab Emirates' planned Mars mission, New Zealand's successful small launcher, Luxembourg's asteroid mining programme, or Israel's lunar mission. Most of these programmes are not starting from scratch (i.e. Luxembourg has been a member of the European Space Agency since 2005 and is the home of the second largest commercial satellite communications operator, Société Européenne des Satellites, SES Global), but some of the recently announced programmes have taken the space community by surprise. This includes Luxembourg's SpaceResources.lu initiative to develop technologies and competencies for the exploration and use of resources found on near earth objects. This has even led to a renewed interest amongst diverse legal expert groups to consider the international implications of space mining. The United Kingdom (UK) has also recently modified its regulatory framework for commercial space activities with the Space

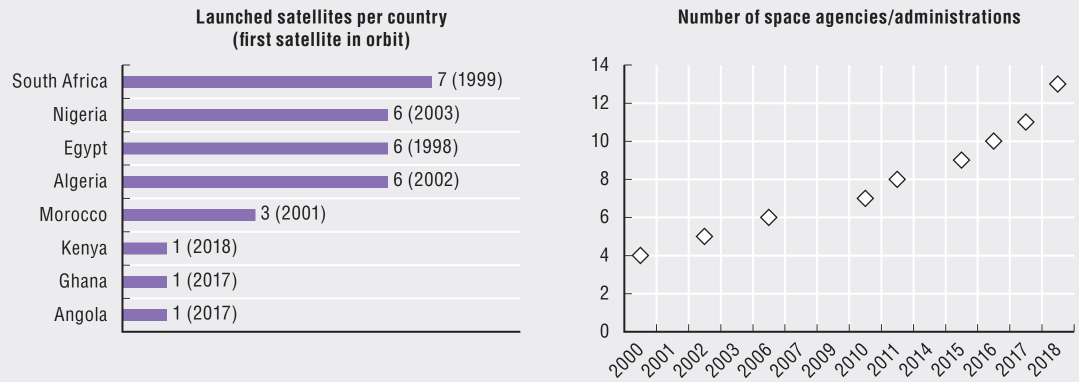
Industry Act 2018. It enables small satellite and suborbital activities to launch directly from UK territory. Several spaceport locations across the UK are under consideration (UK Department for Transport, 2017[2]). Rapid developments are also occurring in Africa, where many countries are developing their own space programmes (Box 1.1).

Box 1.1. Space activities in Africa

Space activities in Africa have picked up significantly since 2000. The continent now counts some 14 space agencies or administrations, half of which were established in 2010 or later. Eight countries, Algeria, Angola, Egypt, Ghana, Kenya, Morocco, Nigeria and South Africa, have registered satellites into orbit (often procured on the international satellite market), with the majority of satellites launched in the last ten years (Figure 1.2).

Figure 1.2. Space activities in Africa

As of March 2019



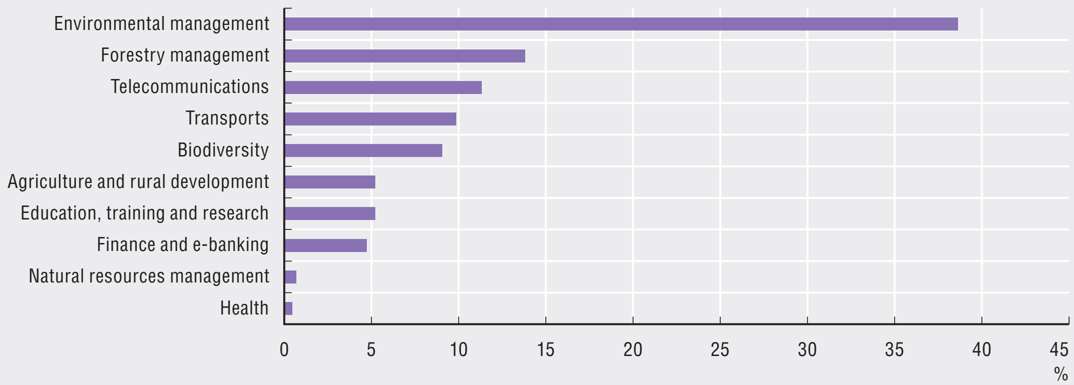
Sources: Based on UNOOSA (2019[3]), *Outer Space Objects Index* and Space in Africa (2018[4]), *https://africanews.space*.

In terms of institutional funding, Nigeria and South Africa have the largest space budgets, estimated in 2017 at some USD 29 million for the Nigerian National Space Research and Development Agency (NASRDA) and USD 23 million for the South Africa Space Agency (SANSA).

Africa is also one of the key recipient regions of space-related official development assistance, with more than USD 200 million committed to projects between 2000 and 2016, mainly addressing environmental management, forestry and telecommunications (Figure 1.3) (see also Chapter 2).

Figure 1.3. Official development assistance projects in Africa

Main purpose of projects, as a share of total space-related ODA commitments to the region.



Source: Calculations based on OECD-DAC database (2018).

A recent development was the 2018 launch of the Africa Regional Data Cube, which provides easily accessible earth observation data for five African countries (Ghana, Kenya, Senegal, Sierra Leone and Tanzania). The data cube was developed by the Committee on Earth Observation Satellites (CEOS) in partnership with several public and private actors.

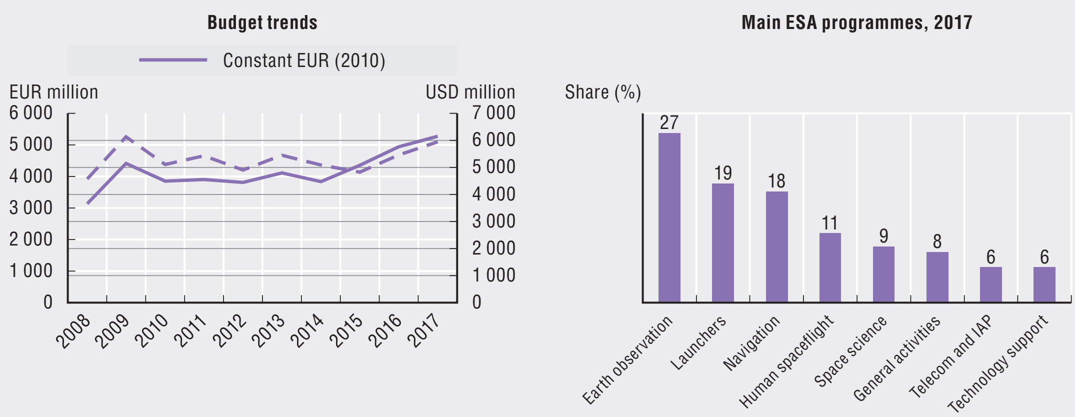
Global institutional space funding in 2017 reached USD 75 billion, a conservative estimate (i.e. based on 49 selected countries with the larger space programmes). Overall, the institutional funding of the largest space programmes remained stable or increased slightly, while most medium and smaller programmes have increased in real terms, and as a share of GDP.

The United States remains the largest space power, building on decades of annual multibillion dollar investments in space programmes. Other countries have developed advanced space programmes, with a wide portfolio of activities, also following decades of investment at much lower levels (e.g. France, Germany, Italy, Canada). In parallel to national programmes, the European Space Agency is an excellent example of how European countries have worked together to build up industrial capacity and create regional value chains for their national space industries (Box 1.2). In the past few years, the European Union via the European Commission has also taken a much larger investor role in the European space industry. Already in charge of the Copernicus earth observation programme and the Galileo navigation satellite programmes, the European Commission is taking a leading role in satellite communications, with the EU GovSatcom initiative. Between 2014 and 2020, it should invest over EUR 12 billion in space activities. With over 30 satellites planned in the next 15 years, the European Union is expected to be the largest institutional customer for launch services in Europe (De Concini and Toth, 2019[5]).

Box 1.2. R&D and innovation at the European Space Agency

The European Space Agency is a major success story in international co-operation. Created in 1973 with ten founding members, it now counts 22 members, and with a 2017 budget of EUR 5.8 billion, including third-party programmes (USD 6.5 billion – almost 0.04% of European GDP), it represents one of the most active space agencies in the world, with a portfolio covering a wide range of space activities, from science, research and development (R&D) programmes to supporting space entrepreneurs (Figure 1.4).

Figure 1.4. ESA's budget at a glance

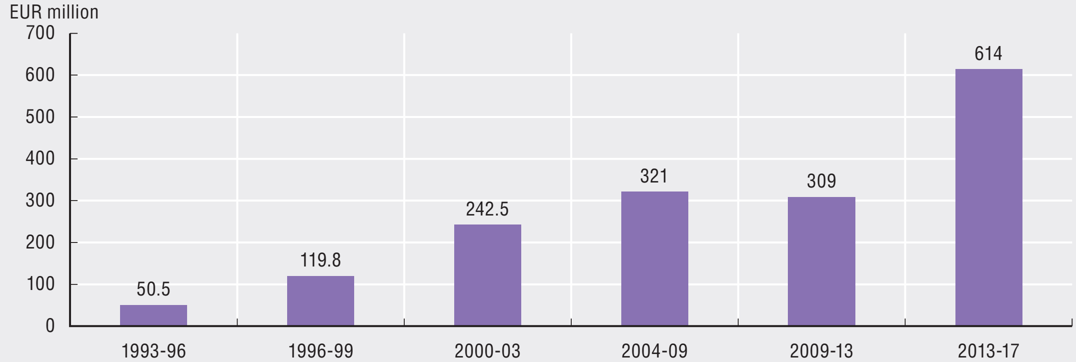


Note: Budgets include third-party programmes.

ESA funds R&D at all stages of technological readiness. Early stage R&D is funded through the Basic Technology Research Programme (about EUR 65 million per year), whereas the General Support Technology Programme (GSTP) and ARTES (telecommunications) programmes aim to convert promising concepts into mature products, working with industry. Funding for the five-year GSTP programme for 2013-17 amounted to more than EUR 600 million (Figure 1.5). ESA is also supporting the emergence of start-ups through its active network of business incubation centres (BICs) in 17 member states.

Box 1.2. R&D and innovation at the European Space Agency *(cont.)*

Figure 1.5. ESA's General Support Technology Programme funding



Source: European Space Agency (2016), GSTP 1993-2017, *http://www.esa.int/spaceinimages/Images/2016/11/GSTP_Infographic*.

Institutional space budgets fund a large range of activities in space research, development and applications in both civilian and military domains. Budgets are often spread across several government agencies, which makes them difficult to track in national accounts. The estimates provided here should therefore be considered as conservative. Figure 1.6 illustrates trends in institutional funding for a selection of OECD countries and partner economies. Although the past five years have generally been a period of tightening government budgets, space budgets have remained relatively resilient to cuts, with growth taking place both in countries with large, established space programmes and in countries with smaller programmes. In Europe, contributions to the European Union programmes Galileo and Copernicus, account for some of these budget increases, but in some cases they also reflect targeted government strategies. Meanwhile, the Russian Federation has seen significant space budget cuts in recent years, following the fall in commodity prices.

Still more growth in institutional funding is expected, although at very different scales depending on national situations. The United States is significantly increasing government funding to both civil and military space programmes. As an illustration, the US Air Force could invest some USD 44 billion over five years in space systems (mainly R&D) between 2018 and 2023 (Erwin, 2018[6]). Luxembourg is setting up an ambitious space programme, investing EUR 238 million (USD 263 million) over the 2017-21 period, half of which will be dedicated to public and private research (Luxembourg Ministry of Finance, 2017[7]). Countries with emerging programmes are also investing in space activities, with New Zealand and Australia, which established space agencies in 2017 and 2018, respectively. New Zealand has set aside some NZD 20-30 million (USD 14-21 million) over the next three years for the space agency and a new space technology research centre. The Australian 2018-19 budget announced funding of AUD 26 million (USD 20 million) over four years to the Australian Space Agency, and AUD 15 million (USD 11 million) to an Australian business support scheme.

Box 1.3. Surfing on the wave of New Space: New Zealand

New Zealand is a new and dynamic actor in the space sector with a focus on harnessing the miniaturisation and lower launch costs that characterise the 'New Space' paradigm shift in order to achieve a range of economic development, science and innovation, and social and environmental goals.

New Zealand is facilitating the creation of a local space industry to help solve some of the world's most pressing issues, such as climate change, illegal fishing and responding to disasters. As well as the spillover benefits of space R&D, New Zealand views space as an opportunity to raise productivity in its traditional sectors – such as through precision agriculture – as well as develop a globally competitive domestic space industry.

Box 1.3. Surfing on the wave of New Space: New Zealand *(cont.)*

To achieve this, New Zealand has established a responsible regulatory regime that balances international obligations and preservation of the space environment while also matching the pace at which the New Space industry is moving. [The Outer Space and High-altitude Activities Act (OSHAA), passed into law in July 2017, regulates orbital launch vehicles, launch facilities and satellites, as well as high-altitude vehicles (excluding high-altitude vehicles used for weather and atmospheric monitoring and educational purposes).]

Already host to the world's first fully private orbital launch facility, New Zealand is committed to facilitating the development of a local space ecosystem. Its priorities are developing its small-sat launch industry, high-tech manufacturing, data analysis and integration, application development, and ground stations, including space situational awareness.

Source: New Zealand Ministry of Business, Innovation & Employment / Hīkina Whakatutuki.

Figure 1.6. Evolution of space budgets for selected countries

Adjusted for inflation with constant national currency and constant 2010 USD, 2008-17

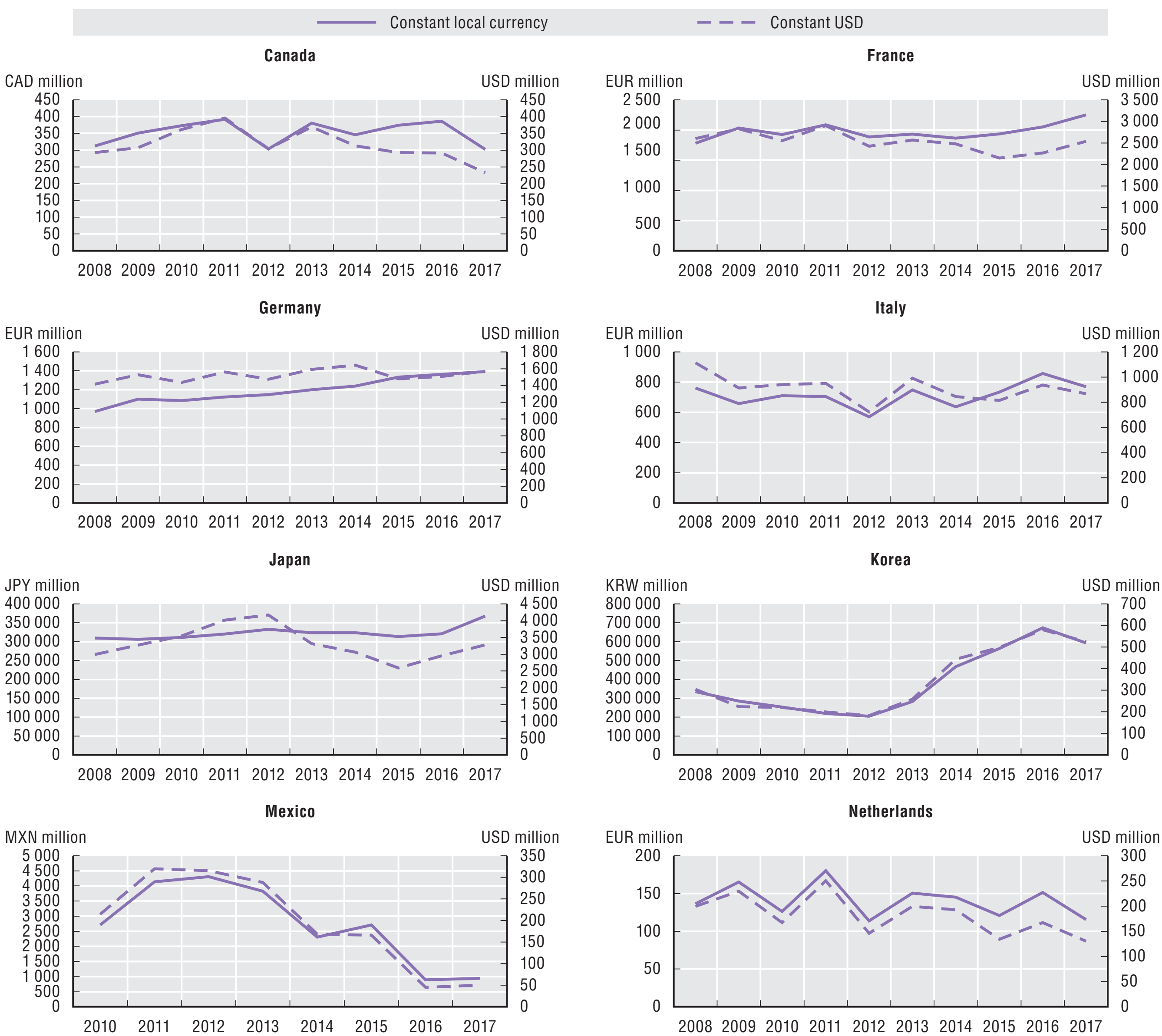
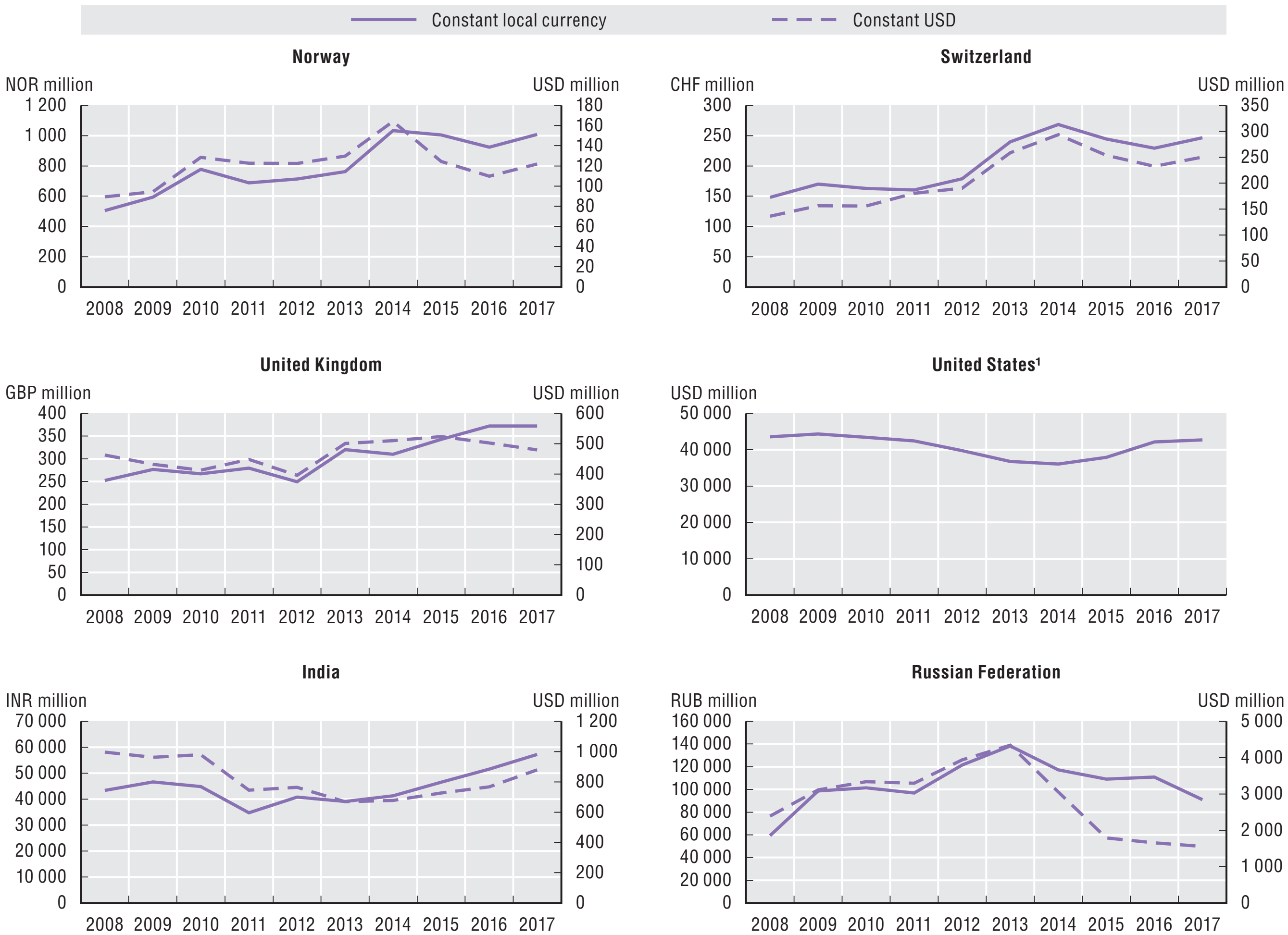


Figure 1.6. Evolution of space budgets for selected countries *(cont.)*

Adjusted for inflation with constant national currency and constant 2010 USD, 2008-17



Note: 1. Conservative estimate for the United States.

Source: Government budget sources and OECD databases (see Box 1.4).

Increasingly, beyond national or federal governments' budgets, more regions are also investing in space programmes via different mechanisms. These investments, albeit often small in scale, are occurring in many parts of the world to attract or retain actors from the space industry (e.g. Canada, Italy, United States). In the United States, there are currently ten licensed orbital and suborbital commercial spaceports, several of which have been constructed in anticipation of possible future developments. Spaceports are often strongly supported by regional policy-makers for local industry development (FAA, 2018[8]; OECD, 2016[1]). As an illustration, the space budget of the state of Florida equals that of a medium-sized European country (USD 30 million in 2016) (Space Florida, 2016[9]).

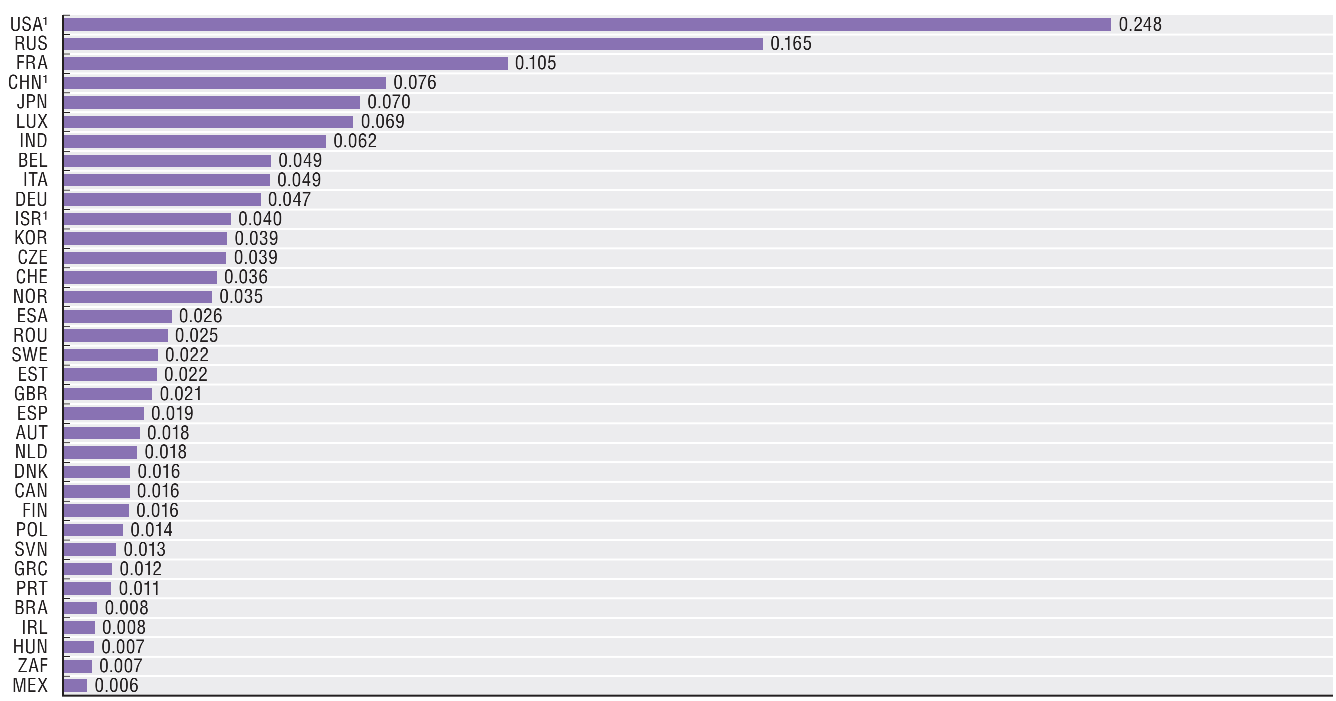
One of the most useful indicators to measure and compare space funding intensity is the ratio of space budget to the national gross domestic product (GDP) (Figure 1.7). In 2017, the budget of the United States accounted conservatively for some 0.24% of national GDP, followed by the Russian Federation at 0.17%, France at 0.1%, The People's Republic of China (hereafter "China") at about 0.08% and Japan at 0.07%. The calculations for the United States, China and Israel are based on conservative estimates. The majority of space budgets constitute less than 0.05% of GDP in 2017 (including civil and military space activities where data are available). Evolutions in a space budget's share in GDP may be affected not only by changes in funding levels but also by rapidly contracting or expanding GDP.

Government budget allocations for research and development (GBARD, previously known as GBAORD) is another indicator which provides interesting insights about the long-term orientations and volumes of government-funded R&D. Data collection for this indicator has been carried out in many economies since the early 1980s. Governments' R&D activities are classified according to 14 different socio-economic objectives, one of which is 'the exploration and exploitation of space'. This category includes both fundamental and applied R&D activities and space-related infrastructure (laboratories, launch systems, etc.). But the data have some limitations, since civil space GBARD excludes all defence-related activities and potentially some of the R&D dedicated to earth observation, meteorology and environment monitoring (categorised under 'exploration and exploitation of earth'). Despite this caveat, GBARD gives an indication of how some space-related R&D budget allocations have evolved, as compared to other national priority areas and over time.

In 2016, civil space R&D (space GBARD) for the OECD members accounted for some 0.4% of GDP and 8% of total government allocations to civil R&D (OECD, 2018[10]), as is shown in Figure 1.8. In the United States, government budget allocations in 2017 for civil space R&D accounted for some 0.07% of GDP and almost 18% of total civil GBARD; followed by Italy (0.05% and 9.3%, respectively), Belgium (0.05% and 8.4%, respectively) and Japan (0.04% and 8%, respectively). In the European Union (EU28), civil space R&D programmes accounted for about 0.03% of GDP and 5% of total civil GBARD (OECD, 2018[10]).

Figure 1.7. Selected government space budget estimates

OECD countries and partner economies, share of GDP in 2017 (%)



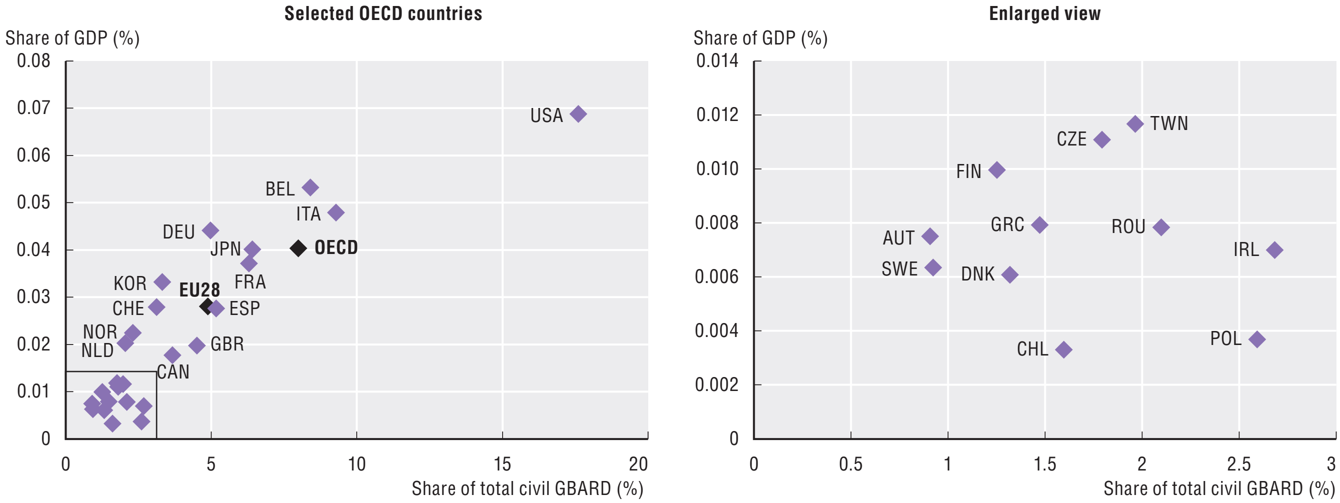
Note: 1. Conservative estimates.

Sources: Government budget sources and OECD databases (see Box 1.4).

When studying the long-term trends of space GBARD (Figure 1.9) over the last three decades, several observations can be made. First, high-spending countries, such as France and the United States, dedicate a decreasing share of their GDP to government civil space R&D compared to the early 1990s, when the share was double what it is today. Second, an increasing number of countries engage in space activities and carry out space R&D. Finally, several countries which dedicate a small or medium share of their GDP to space GBARD have seen a positive growth in the last decade (e.g. United Kingdom, Norway). As a result, space GBARD's share of GDP is converging across the OECD, with ratios stabilising between 0.02 and 0.07%.

Figure 1.8. Civil space GBARD as a share of GDP and total government civil R&D allocations

2017 or latest available year, selected countries

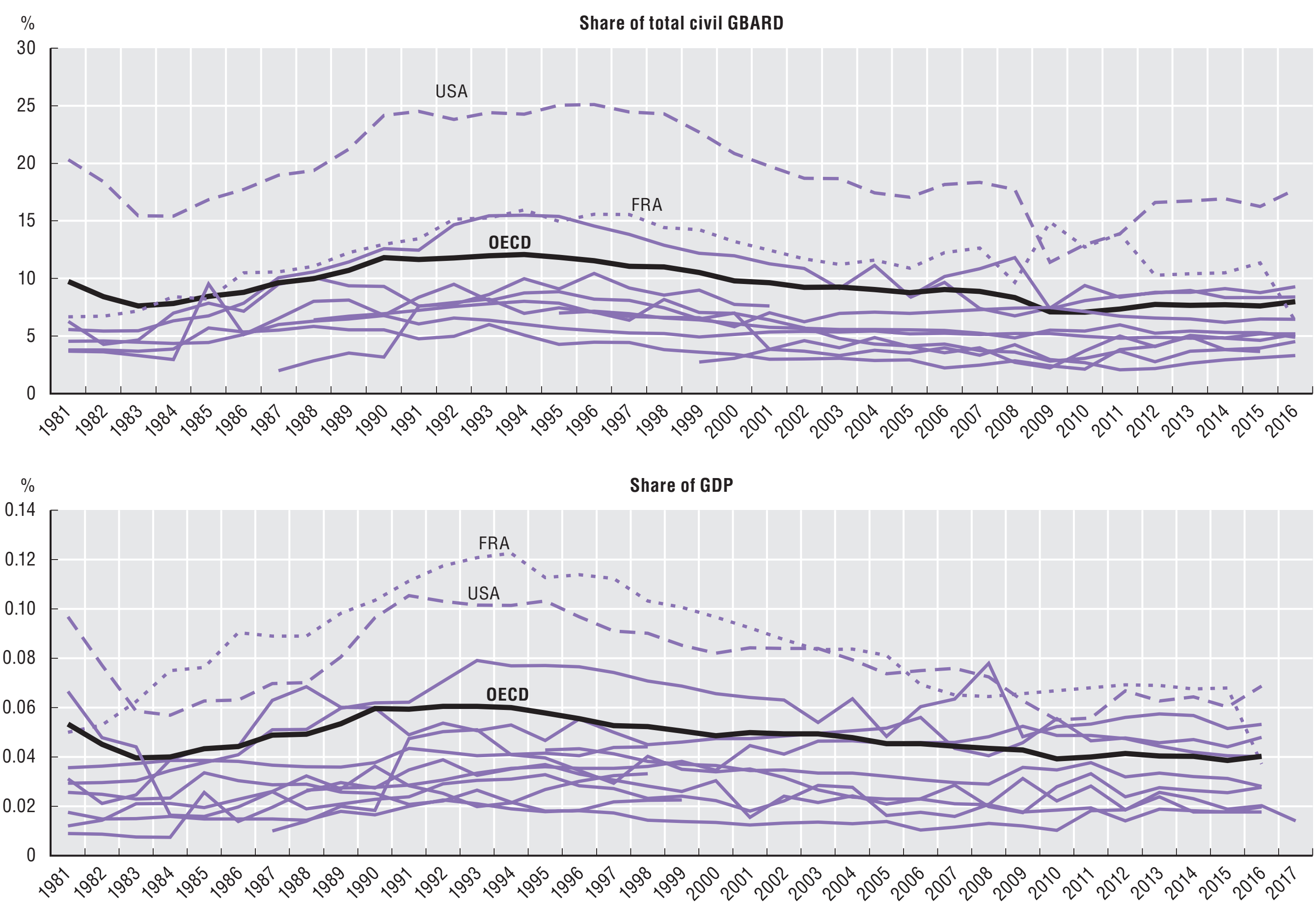


Note: Data from 2016: Belgium, Estonia, France, Greece, Ireland, Italy, Korea, Poland, Spain, United Kingdom, OECD and EU28. Data from 2015: Canada, Chile, Switzerland.

Source: OECD (2018[10]), *OECD Science, Technology and R&D Statistics* (database), *http://dx.doi.org/10.1787/data-00182-en.*

Figure 1.9. Long-term trends for civil space GBARD

1981-2017 or earliest and latest available years, selected countries



Note: Data from 2016: Belgium, Estonia, France, Greece, Ireland, Italy, Korea, Poland, Spain, United Kingdom, OECD and EU28. Data from 2015: Canada, Chile, Switzerland.

Source: OECD (2018[10]), *OECD Science, Technology and R&D Statistics* (database), *http://dx.doi.org/10.1787/data-00182-en.*

Box 1.4. Institutional funding of space activities

International comparisons of institutional budgets for space activities can be affected by many factors, in particular exchange rate issues and data sources. The past seven years have seen many exchange rate fluctuations, making comparisons of national budgets in US dollars (USD) more difficult. Comparing budgets using indices and the ratio budget/GDP based on national currencies still provides the most reliable snapshot of the situation, despite other methodological caveats (e.g. impacts of GDP growth or contraction). When converting national budgets to US dollars to compare budgets, worldwide institutional funding in 2017 is estimated at some USD 75 billion (current) for the 49 economies with the largest space programmes (civil and military). This does not take into account differences in domestic purchasing power, e.g. 1 US dollar does not buy the same amount of space R&D in the United States as in India because of local differences in wage levels, for example.

Government grants and procurement are the most important direct financing instruments for space technology and R&D; they account for the lion's share of institutional space budgets. They are typically channelled through national space agencies and international space organisations (e.g. NASA or ESA), but increasingly through other actors as well, such as the EU Horizon 2020 R&D programme or the European GNSS Agency (GSA). Indirect financing instruments also exist, most notably R&D tax incentives.

If the objective goes beyond R&D support at different technology levels and aims to foster innovation and business development, other financing instruments are important. Loans, loan guarantees, seed grants and similar instruments can be vital for small and young enterprises, which are important sources of new employment and economic growth through innovation (OECD, 2010[11]). Loans can be provided by national innovation agencies and development banks, but are also often provided by local and regional authorities or international bodies (European regional funds). It should be noted that these institutions can also provide other funding solutions. In the last years, innovative financing instruments, such as venture capital and crowd funding have become more common.

Methodological note on institutional budgets: Data are based on government budget estimates for 2017, and actual expenditure for previous years, as identified in national accounts and subject to availability. They include both civil and military space programmes, again subject to availability. Budgets of European countries also include national contributions to the European Space Agency and EUMETSAT. Furthermore, budgets for the Czech Republic, Norway and Switzerland include national contributions to the European Union programmes EGNOS/Galileo and Copernicus. In the cases where contributions to EUMETSAT did not have separate budget entry, estimates are based on the data from EUMETSAT's latest annual report (EUMETSAT, 2018[12]). Budget trends are provided in both constant national currencies and in constant US dollars, to give an indication of the currencies' fluctuations. For calculations, this chapter uses exchange rates (annual averages) from the Finance dataset in the *OECD Main Economic Indicators* (MEI) database (OECD, 2019[13]). The OECD consumer price index (CPI) 'all items' was used to calculate budgets in constant local currencies and USD. The base year of the index is 2010. CPI data were retrieved from the Prices dataset in the *OECD Main Economic Indicators* (MEI) database (OECD, 2018[14]). National GDP comes from the "Main Science and Technology Indicators" dataset in the *OECD Science, Technology and R&D Statistics* database OECD (OECD, 2018[10]).

Private funding of space activities

Private sources of investment for space projects are challenging to track; however, current evidence shows unprecedented investments from angel and venture capital funds in space start-ups and recently established firms, although the amounts still pale compared to public funding.

Commercial satellite telecommunications have paved the way for private financing, as the high profitability of satellite services over the past 15 years has allowed operators to benefit from classic financial schemes (e.g. equity financing, bond issuance) to develop their activities, buy satellites and fund innovation, especially in their distribution networks. Most satellite operators in OECD countries have become publicly traded corporations, and this is also now happening in China, where state-owned enterprises are being restructured (e.g. the operator China Satellite Communications Corp. is due to open its capital; it is a subsidiary of the state-owned China Aerospace Science and Technology Corp., which designs and manufactures many of China's satellites). Operators have also resorted to project financing, with syndicates of banks providing loans. This successful trend in financing satellite telecommunications has led to similar, if limited, experiences in other domains of space activities. For example, in the past ten years, several companies have launched initial public offerings of stocks, using the proceeds to build their next generation of earth observation satellites (e.g. Digital Globe in the early 2010s).

The main sources of funding for new firms are usually the founder's own funds, with investments from family circles, bank loans, equity capital (including from business angels and venture capitalists) and government support. A relatively new source of private capital comes from large aerospace and defence firms, which have all set up their own venture capital funds in the past five years, to invest in start-ups involved in software development, artificial intelligence, augmented reality, sensors and autonomous vehicles in particular. Some of the most active actors include for example Boeing's HorizonX Ventures, Lockheed Martin Ventures, Airbus Ventures, Thales Corporate Ventures, and the Dassault System Venture Fund.

In the space sector, start-up equity investments represented some USD 3 to 3.25 billion in 2018 (Space Angels, 2019[15]; Seraphim Capital, 2019[16]). The number of investment transactions also grew globally, from 200 investment deals in 2011 to over 1 400 in 2017. Space Angels estimates that the 2018 total represented around 16% of all the equity capital invested in space companies since 2009. In China, almost 100 space start-ups have been launched since 2015, following a new national policy to foster space commercialisation (see country profile of China). In 2018, some 30 start-ups involved in rockets, satellite manufacturing and applications raised approximately USD 310 million in venture capital. When including publicly-listed space companies, total private investment amounted to USD 530 million in China (FutureAerospace, 2019[17]). Although these amounts are far from negligible, as a comparison, more than USD 50 billion was invested in artificial intelligence start-ups during the period 2011 through to mid-2018, with some USD 17 billion in 2017 alone (OECD, 2018[18]).

Investments from billionaires in numerous space ventures have also increased in the past five years (Table 1.1). Most of the recent space companies are privately funded (e.g. Space X, Blue Origin) and not publicly traded. Although there are few public data available, their capitalisation is considered important in view of their ongoing large projects (launchers, space exploration modules) and commercial contracts particularly with the US government.

Table 1.1. Selected billionaires' space investments

Billionnaire	Company	Space investment	Activity
Bill Gates	Microsoft	Kymeta	Data
Jeff Bezos	Amazon	Blue Origin	Launch
Mark Zuckerberg	Facebook	SETI	Data
Larry Page	Google	Planetary Resources	Mining resources
Sergey Brin	Google	SpaceX	Launch / data
Li Ka-Shing	CK Hutchinson	Windward	Mining resources
Ma Huateng	Tencent	Moon Express	Launch
Sheldon Adelson	Las Vegas Sands	SpaceIL	Launch
Paul Allen	Microsoft	Stratolaunch	Launch
Elon Musk	Tesla	SpaceX	Launch / data
Eric Schmidt	Google	Planetary Resources	Mining resources
Ricardo Salinas	Grupo Elektra	OneWeb	Data
Richard Branson	Virgin Group	Virgin Galactic	Launch
Lynn Schusterman	Samson Investment	SpaceIL	Launch
Yuri Milner	DST Global	Planet	Data
Marc Benoiff	SalesForce	Taranis	Data

Source: Bryce Space & Technology (2017[19]), *Start-Up Space 2017: Update on Investments in Commercial Space Ventures*.

As a final indication of changes in private financing, new exchange-traded funds, which usually contain various types of investment instruments, are increasingly including stocks from space-related companies. Stocks in aerospace and defence companies have for many years formed attractive portfolios in investment funds, but the specific focus on space is relatively recent. Further interest from the investment community may come if the capital formation of some of the more successful space companies from Table 1.1 eventually moves into the public market.

Despite positive trends, sustained access to finance will remain a challenge for a majority of established and new players in the space sector. Hardened international competition between incumbents, the acceleration of the rollout of new technological solutions, and the apparition of ever-more newcomers with yet unproven business models continue to affect the investment landscape.

Actual returns on investments are still to come for most space ventures that have received capital in the past five years. Long lead times represent an inherent issue for most space activities, as manufacturing processes and launch to orbit take time. These constraints may be increasingly alleviated thanks to major impacts of digitalisation on manufacturing and production processes (impacting satellites, rockets, ground systems) (see Chapter 4). But these are changes still very much in the making. Also the enthusiasm surrounding new space activities may have created possible 'economic bubbles'. Consolidation and buy-outs are expected in the next two years for many competing space start-ups, especially in the small launcher segment where several dozens of actors are currently being financed. The hype concerning the space economy is discussed in the next section.

The space economy: Hype and market realities

In the past five years, many public and private actors have begun investing in space activities. In parallel, some are developing new business proposals, based on the combination of space and digital technologies coming to market (e.g. miniaturised space systems, big data analytics). With new space systems coming of age and stimulating fresh entrepreneurial approaches shaking the industry, a certain hype surrounding the space economy has emerged.

The space sector is indeed facing a new cycle in its development, with mature off-the shelf technologies that can be used by many actors, and new commercial downstream activities derived from satellite signals and data. Although there are many government programmes around the world that support the development of the space economy (via contracts to industry), and a growth of commercial activities in several downstream space segments (e.g. location-based services), available data on the space economy show that the growth of commercial space activities remain modest overall and should not be overestimated. As national administrations and private actors progressively get a better picture of value chains in their national and regional space economy via industry mapping, more evidence on the space economy is expected (see Box 1.6).

Box 1.5. Supporting start-ups and entrepreneurs

Start-ups in the space sector are increasingly supported by public and private programmes (incubators and accelerators).

- Several government initiatives are targeting downstream business and application development, e.g. the UK Satellite Applications Catapult at the Harwell space cluster for British start-ups, and the French Booster programme which supports four dedicated activities in co-ordination with existing technology clusters (OECD, 2016[1]).
- The European Space Agency is supporting business incubation centres (BIC) in its member states, resulting in more than 500 company creations since the launch of the first centres in 2003 (ESA, 2017[20]). The initiative supports on average some 140 start-ups per year (ESA, 2017[20]). The ESA BIC in Harwell reports a company survival rate of 92% since the creation of the incubation centre in 2011 (O'Hare, 2017[21]). The Bavarian ESA BIC, established in 2009, has incubated 130 start-ups, generating 1 800 job creations and EUR 150 million in annual turnover (ESA BIC Bavaria, 2018[22]).
- Space agencies furthermore regularly organise hackathons, prizes and challenges to reach out to non-space users, in particular those in the information and communication technologies (ICT) sector, to identify new ideas and business models (e.g. ActInSpace organised by the European Space Agency and the French Centre national d'études spatiales; the Copernicus Masters and the European Satellite Navigation Competition). In the United States, government procurement programmes support start-ups in satellite weather and cubesat earth observation (US National Geospatial-Intelligence Agency, 2018[23]; St. Jean, 2018[24]).

Government space programmes supporting the space economy

Three overarching thrusts are driving commercial revenue generation in the space sector in all its segments, and will probably continue to do so over the next decade: national security goals; the pursuit of scientific objectives and human space exploration; and the expansion of downstream space applications (OECD, 2016[1]).

The pre-eminence of government objectives, from defence to space exploration, remains a key driver in most space programmes today and will remain for the foreseeable future. Institutional budgets are funding, via procurement schemes and grant mechanisms, a majority of commercial space activities around the world. In addition, in many countries, public administrations play a major role in not only administrating and coordinating space activities, but also in pursuing research and development. Historically, and still today, national agencies, research centres, universities and laboratories (such as test facilities) perform fundamental research, applied research and experimental development in the space sector (see country profiles for illustrations). These research capacities under governmental control have important impacts on employment and public innovation capabilities for the space sector (see Chapter 3 about employment).

This is not a situation unique to the space sector, as major infrastructure and transport activities rely directly and indirectly on sustained public investments (OECD, 2017[25]). But many of these funding schemes in the space sector aim to sustain governmental captive markets, reserved in priority for national industries. This is particularly true for military space programmes, even if recent mergers and acquisitions in North America and Europe have allowed companies to bid for large governmental contracts across the Atlantic.

The growth in institutional demand has so far compensated the downturn in commercial satellite telecommunications markets (see Chapter 6), the traditional leading segment for the European space manufacturing industry. Government programmes represented 59% of European industry's sales in 2017 (EUR 5.1 billion, out of a total of EUR 8.76 billion), with critical procurement from ESA and national space agencies (ASD - Eurospace, 2018[26]). Even when examining exports, a fourth of the European industry sales respond to demand from public agencies, whether civilian or military. In the United States, manufacturers and space launch providers are also benefitting from significant programmes from the US Department of Defense (recent USD 7.8 billion contract for the upgrade of the GPS constellation awarded to Lockheed Martin), while in China the space industry benefits from large scale investments by the Chinese authorities. In the United Kingdom, much of the recent growth in the UK space economy was also driven by recent public investments in launch vehicles and subsystems (London Economics, 2019[27]).

The role of initial and sustained government funding will be essential when looking ahead to further developing the possible "cislunar space economy". This would include commercial human spaceflight in orbit and beyond, the expansion of the human presence in space, or the development of new space missions that may have long-term commercial implications (e.g. space mining). At the core of these missions that are all becoming possible thanks to technological advances, commercial actors will certainly play a determining factor, but with institutional funding support (see also Chapter 5).

Putting different markets in perspective

At a first glance, the space sector seems relatively small and easy to value. Some segments, like space manufacturing, are indeed rather well known, thanks to regular industry surveys that have been conducted for decades (e.g. the Eurospace survey on European space manufacturing). The knowledge base continues to grow internationally and many national and industry associations' efforts are to be commended with annual and bi-annual surveys to map activities and build up datasets to support policy-making (see Box 1.6). However, extensive and comparable microdata to quantify in detail the different segments of the space economy in different countries are still lacking.

In the past five years, much attention has been given to the growth potential of downstream space activities. Downstream activities are very diverse, but they all directly rely on the provision of satellite technology, signals or data to function. Many applications are by definition reliant on space infrastructure set up by public and/or private actors. They include services and products for consumers using satellite capacity, such as communications, satellite television services, geospatial products, meteorology and location-based services (e.g. a navigation device using satellite positioning signals from publicly funded space infrastructure, like the US GPS, the European Galileo or the Chinese Beidou systems). The actual value creation and revenue generation are often far removed from the initial investments.

Box 1.6. Measuring the space economy

International comparability remains limited when examining the space sector's existing statistics, despite much progress overall in terms of data quality and time-series, and the development of national industry surveys in different parts of the world since the first *OECD Handbook on Measuring the Space Economy* was published (OECD, 2012[28]). Statistical perimeters of economic sectors and industries are often defined according to the data needs of different users (e.g. policy-makers at local, regional and national levels, administrations, industry). This results in often different priorities regarding definitions and measurement.

The following working definition formed the starting point of the first *Handbook on Measuring the Space Economy* and is today used quite extensively:

> *The space economy is the full range of activities and the use of resources that create and provide value and benefits to human beings in the course of exploring, understanding, managing and utilising space. Hence, it includes all public and private actors involved in developing, providing and using space-related products and services, ranging from research and development, the manufacture and use of space infrastructure (ground stations, launch vehicles and satellites) to space-enabled applications (navigation equipment, satellite phones, meteorological services, etc.) and the scientific knowledge generated by such activities. It follows that the space economy goes well beyond the space sector itself, since it also comprises the increasingly pervasive and continually changing impacts (both quantitative and qualitative) of space-derived products, services and knowledge on economy and society.*

A second OECD *Handbook* is being produced and tested, with the aim to provide advice, particularly to new actors in the space economy, on how to delineate activities, products and services in the different space economy segments, to inform micro-data level industry surveys.

Commercial satellite telecommunications were indeed first to link with a wide range of businesses with no previous connections to the space community, in order to commercialise satellite capacity mainly for television broadcast. Telecommunications markets are currently facing uncertainties, as space and ground technologies, as well as customer behaviours, are evolving rapidly. There is a current downturn in satellite video, which is starting to impact satellite operators as well as manufacturers. Incumbents and future satellite constellation operators increasingly have to navigate complex telecom ecosystems (more in Chapter 6). Other important downstream actors include the suppliers of devices and equipment supporting consumer markets.

When examining the company Bryce's *2019 State of the Space Industry* report (commissioned by the US Satellite Industry Association), around 87.8% of the estimated USD 277 billion in revenues are generated by activities based on satellite capacity (signals, data), sometimes by actors that are building on investments made by others, much higher in the value chains.

- The bulk of the space economy revenues are considered to come from commercial satellite services with USD 126.5 billion, i.e. 45.6% of the total revenues (with satellite fixed services representing USD 17.9 billion, mobile satellite services USD 4 billion; satellite radio USD 5.8 billion; satellite broadband USD 2.4 billion; commercial remote sensing USD 2.1 billion; and satellite television services representing USD 94.2 billion) (Bryce Space and Technology, 2019[29]) (see Chapter 6 on satellite telecommunications).
- The second largest share of revenues (USD 125.2 billion, 45% of the estimated space economy) consists of devices and chipsets to receive positioning, navigation and timing (PNT) signals (USD 93.3 billion), consumer equipment such as satellite television dishes (USD 18.1), and other network equipment, such as very small aperture terminals and gateways (13.8 billion). Overall these sectors are dominated by consumer electronics companies.

- In comparison, space systems' manufacturing revenues are valued at USD 19.5 billion, i.e. 7% of the total revenues, while the commercial launch industry represents USD 6.2 billion (i.e. 2.2% of the total). These two activities are the foundations for all the others, and are being strongly affected by digitalisation and growing competition from newcomers (see Chapter 4).

When comparing these results with time series and a previous 2014 report, the revenues totalled at that time some USD 246 billion (USD 203 billion in 2014 dollars in the original report). Taking into account discrepancies, the main increase in revenues from 2014 to 2019 comes from the then-strong development of consumer ground equipment, pushed particularly by positioning and navigation equipment (Tauri Group, 2015[30]). A study conducted every two years by the European GNSS Agency, with the estimates usually reused in many other industry report, confirms these trends (European GNSS Agency, 2017[31]). It forecasts that satellite navigation, position and timing devices and related augmentation services could grow by more than 6% annually between 2015 and 2020 before gradually decelerating over the following years. In the United Kingdom, the downstream segment – which has represented the largest segment of the UK space economy via the satellite television direct-to-home and telecommunication markets – has grown since 2014 at a rather slow rate of 1.1% per year (London Economics, 2019[27]).

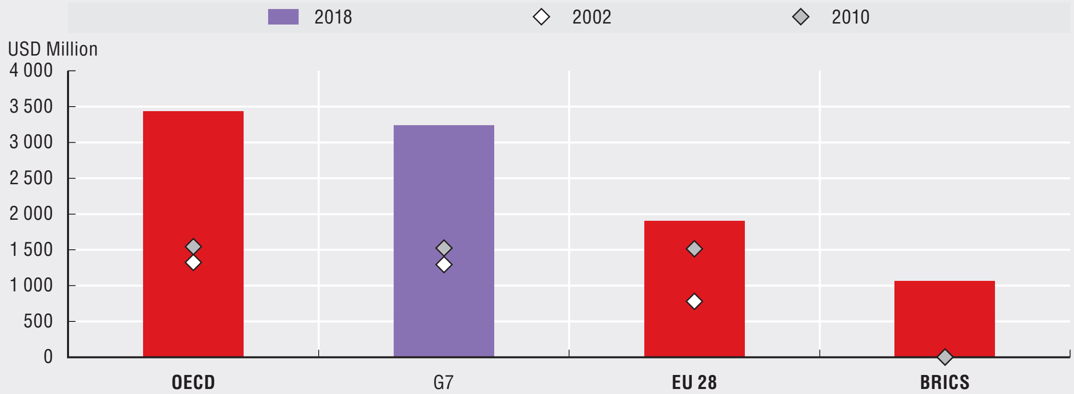
Box 1.7. Trade in selected space products

Imports and exports are useful indicators in today's interconnected world. Still, many commercial space activities are not covered by official statistics, and beyond this limitation, many space products and services are considered strategic in nature and not freely traded. To convene a partial overview of existing trade in the space sector, some conservative data are provided, covering the commodity code "spacecraft (including satellites) and spacecraft launch vehicles" (code 7925) in the International Trade in Commodity Statistics (ITCS) database.

Based on this commodity code, OECD countries are heavy exporters of space products (Figure 1.10). The value of exports almost tripled in fifteen years, amounting to around USD 3.4 billion in 2018. The aggregate for the European-28 region showed a slower growth pace between 2002 and 2018. Exports from BRICS countries experienced growth, booming to USD 1.1 billion in 2018. This suggests a catching-up process in commercial markets, as many Chinese and Indian satellite products are now exported.

Figure 1.10. Exports of selected space products by region

Constant USD million



Note: The figures refer to trade of the product code 880260 of the Harmonised System (HS) for commodity classification. Code 880260 includes: spacecraft, including satellites, and suborbital and spacecraft launch vehicles. The latest available year for Israel was 2017, while the 2009 statistics is reported instead of 2010 for the United States.

Source: Calculations based on UN COMTRADE database and ITC statistics, 2018.

Although they can show only a partial view, snapshots of global exports in 2018 for the code 7925 reveal that France was the leading exporter in 2018 (27.6% of the total exported value), followed by China (22.3%) and the United States (20%). Other actors include Japan (8.1%), Germany (7.9%) and Israel (5.7%).

There is much hype about the space sector and its commercial potential, driving activities in consumer electronics, far beyond space manufacturing and space launchers, with some reason, as it has never attracted so much investment from both public and private actors. Many recent estimates and forecasts from leading consulting firms and investment banks have provided different estimates. This is a challenging exercise, as the space economy encompasses various activities and different value chains (from hardware to digital products far removed from initial space investments). A 2018 report by the investment firm Goldman Sachs predicted that the space economy would reach USD 1 trillion in the 2040s, while a different study by Morgan Stanley projected a USD 1.1 trillion space economy in the 2040s. A third study by Bank of America Merrill Lynch has the most optimistic outlook, seeing the market growing to USD 2.7 trillion within the same timeframe (Table 1.2). As a comparison, revenues from the well-established global commercial airlines amounted to USD 821 billion in 2018 with net profits of around USD 32.3 billion (IATA, 2018[32]).

However, one should remain prudent in forecasts, as downturns may occur in selected downstream markets, notably satellite telecommunications and satellite navigation, position and timing markets, because of strong competition from new terrestrial systems coming online (see Chapter 6). In addition, possible accidents in the space infrastructure need to be taken into account in different scenarios (e.g. satellites remain fragile because of space debris, jamming of signals, etc. see Chapter 5).

Table 1.2. Recent estimates of the space economy

Source	Estimates	Activities and sector(s) included
Space Foundation	USD 383.5 billion in 2017	Includes estimated governments' space budgets, revenues from space products and services, etc.
Morgan Stanley	USD 350 billion in 2016 USD 1.1 trillion in 2040	Government budgets, revenues from ground equipment, consumer TV, etc.
Bank of America / Merrill Lynch	USD 2.7 trillion in 2040	General forecast

Source: Bryce (2018), State of the satellite industry report 2018, commissioned by the Satellite Industry Association; The Space Foundation (2018), The Space Report 2018; Morgan Stanley (2018), Investing in space; Bank of America (2018), The space industry will be worth nearly $3 trillion in 30 years.

As more countries conduct industry surveys to collect relevant micro-data on their space sector's value chains, with the support of national statistical offices or consulting firms, often linking with industry associations, more evidence should become available on the different segments of the space economy. The OECD is already working with many actors to support this effort.

Space innovation is also more globalised

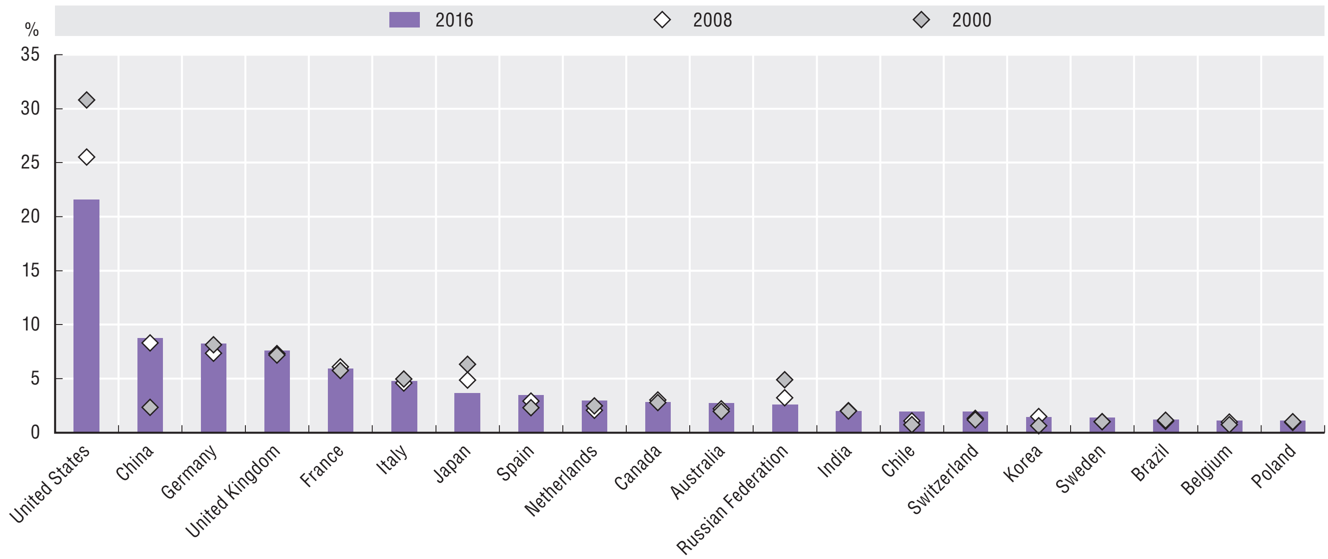
Another major element in the transformation of the global space sector concerns the changing innovation landscape. Space innovation can be examined via proxies such as peer-reviewed scientific publications and patents. Scientific publications convey the research findings of scientists worldwide and provide an indication of the knowledge production in the space sector. Although the numbers are growing, publications and patent applications are still only an indication of innovation, as they often are limited by commercial discretion and confidentiality issues.

Scientific papers on space activities have been published in specialised journals since the late 1950s, but they remained the remit of just a few experts for almost 30 years. Since the 1990s, the multiplication of specialised journals and international conferences has strongly impacted the diffusion of publications on space sciences, technologies and space applications. This trend parallels the growing number of countries involved in space programmes, especially from the BRIICS (Brazil, Russian Federation, India, Indonesia, China and South Africa).

Countries having long-standing space programmes are still leading in terms of scientific publications in space literature, but new countries are emerging (Figure 1.11). The United States has the largest share of publications, accounting for around 22% of the total. China and India saw significant increases. China's scientific production increased ten-fold between 2000 and 2016, making it one of the leading contributors worldwide, which reflects the growing interest in the space sector in China.

Figure 1.11. Top producers in space literature, per country

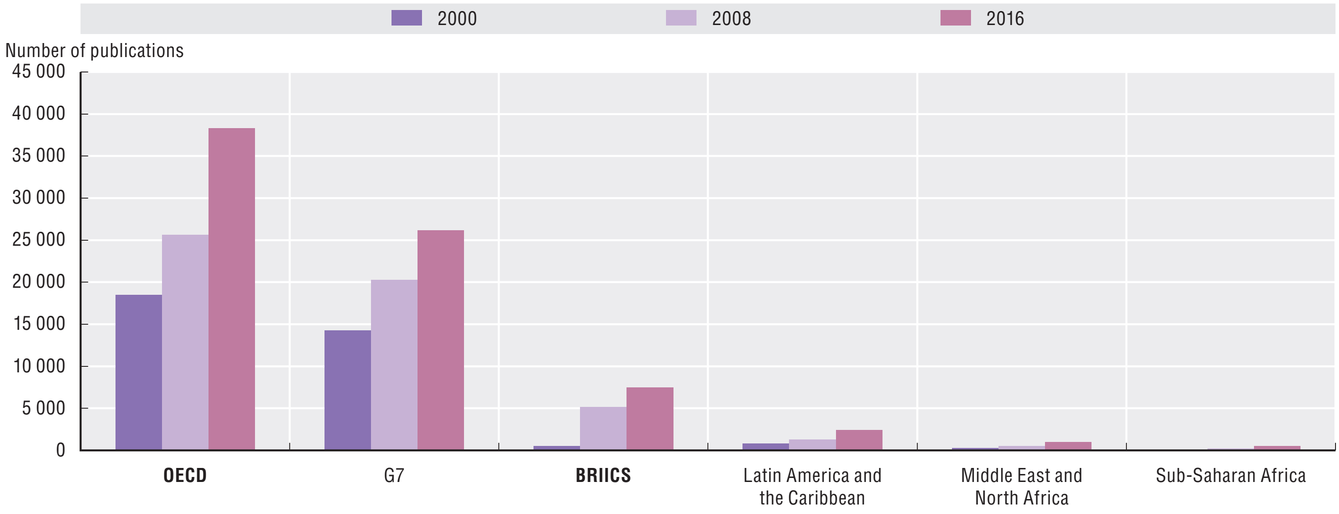
Share of total space-related publications



Source: OECD analysis based on Scopus Custom Data, Elsevier, 2018.

The number of space-related publications increased overall in the OECD area between 2000 and 2016, but the BRIICS economies saw a dramatic increase in their production, with the highest growth rates (Figure 1.12, Figure 1.13).

Figure 1.12. Scientific production in space literature, per region

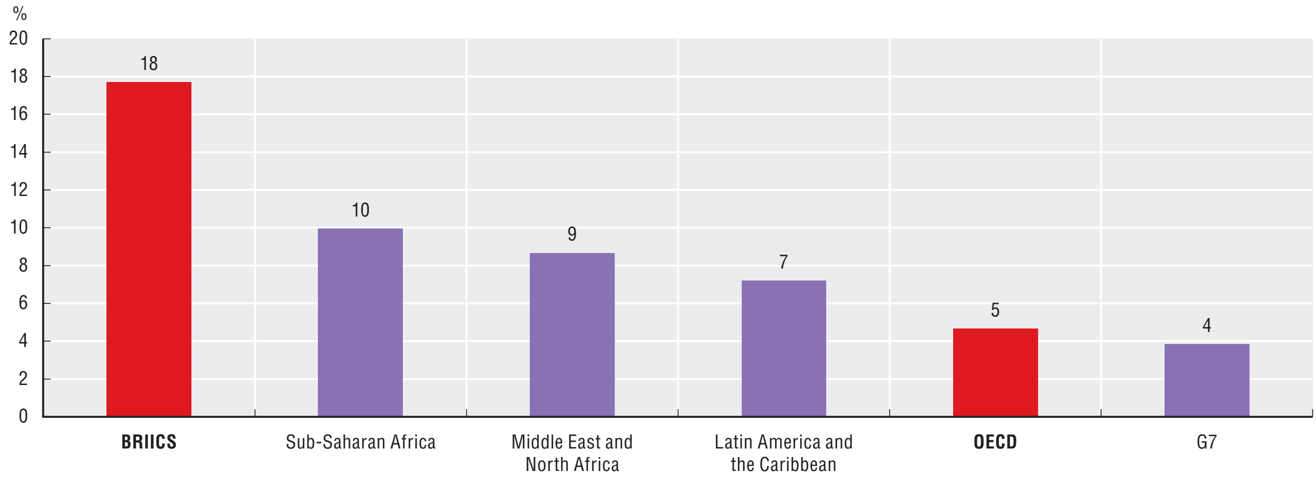


Source: OECD analysis based on Scopus Custom Data, Elsevier, 2018.

The volume of publications on selected "hot topics" (e.g. global positioning system, cubesats and small satellites) also grew significantly, with an increasing number of active countries. The number of countries publishing on subjects related to cube satellites multiplied by a factor of ten between 1999 and 2016, from 7 countries in the 1999-2004 period to 65 in 2011-16. For GPS, the increase was less marked, increasing from 121 countries in 1999-2004, to 159 in 2011-16. Finally, the number of countries publishing publications on small satellites grew from 45 in 1999-2001 to 75 in 2011-16.

Figure 1.13. Growth rates in space literature, per region

Average yearly growth rate in %



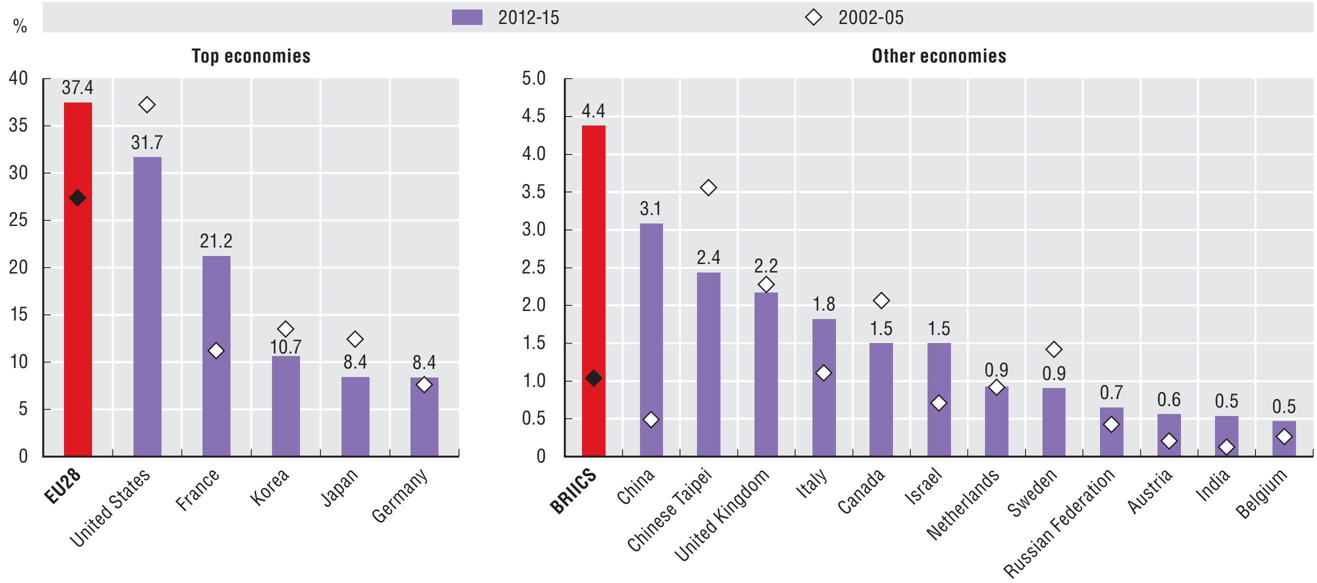
Source: OECD analysis based on Scopus Custom Data, Elsevier, 2018.

As another proxy for innovation, patenting in the space sector is not as common as in other sectors, as commercial discretion and institutional confidentiality are often still priorities for some space systems. There are only a few hundred patents a year. Still, the number of space-related patents has almost quadrupled in 20 years, as revealed by the applications filed under the Patent Co-operation Treaty (PCT). The space application areas (i.e. satellite navigation, earth observation, telecommunications) have also gained in importance in a decade.

When comparing national patent applications for space-related technologies in 2002-05 and 2010-15, the United States still leads but its share has shrunk; while the European Union (EU28) grouping's share has increased (Figure 1.14). Several countries have seen their shares of worldwide patents grow in relative terms, notably France, Korea, Germany, China, and Italy.

Figure 1.14. Patents for space-related technologies per country

IP5 patent families, by priority date and applicant's location, using fractional counts

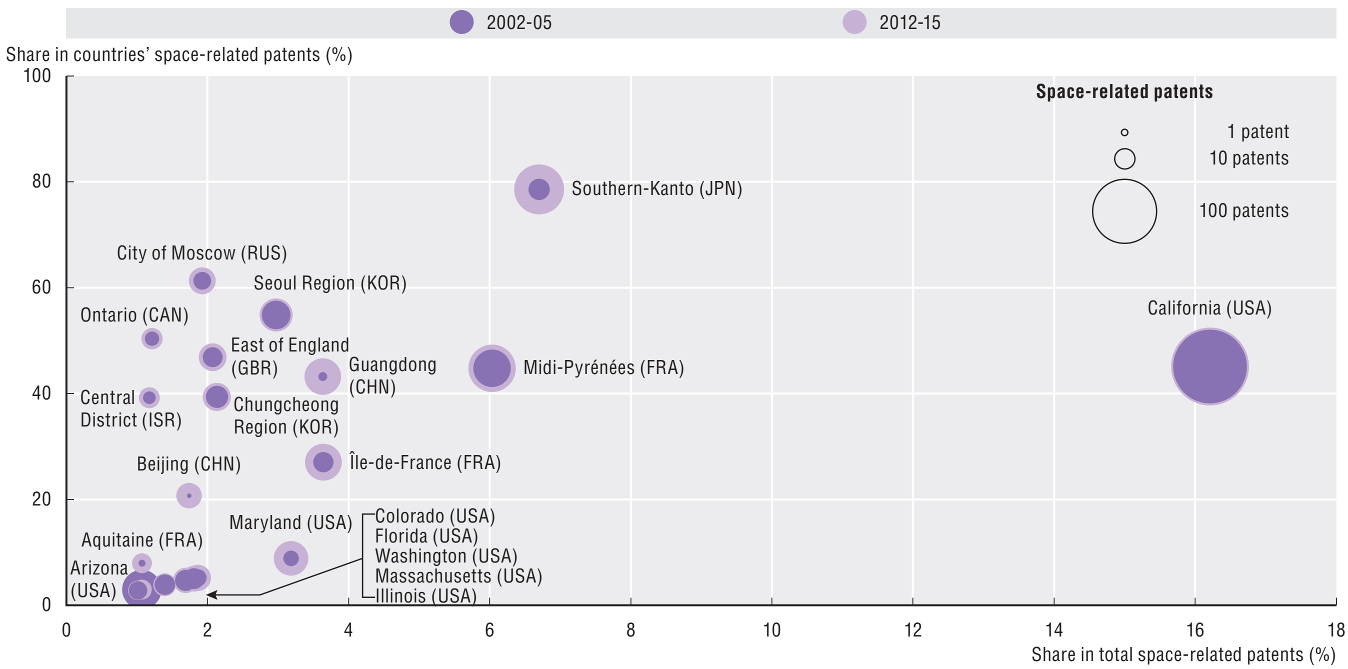


Source: OECD STI Micro-data lab: Intellectual Property Database, *http://oe.cd/ipstats*, March 2018.

When examining space-related patenting on a regional scale (Figure 1.15), the highest shares of patents can be found in a few selected regions, homes to significant space industry clusters. Around 16% of worldwide space patenting occurs in California (USA) (a decrease from 19% in 2002-05), Southern Kanto (JPN) (an increase from 1.6% in 2002-05), and 6% in Midi-Pyrénées (FRA) (an increase from 4.8% in in 2002-05). Other regions with relatively high rates of space-related patenting include Ile de France (FRA), Guangdong (CHN) and the Capital Region (KOR). Shenzhen, a large city in the Guangdong province, is increasingly labelled as the Chinese Silicon Valley, as it hosts many technology firms including public companies developing satellites and space applications.

Figure 1.15. Top 20 regions in space-related patents

IP5 patent families, by priority date and applicant's location, using fractional counts



Note: Data refers to patent applications filed under the Patent Cooperation Treaty (PCT), by inventor's region at Territory Level 2 (TL2) and priority date.

Source: OECD STI Micro-data lab: Intellectual Property Database, *http://oe.cd/ipstats*, March 2018.

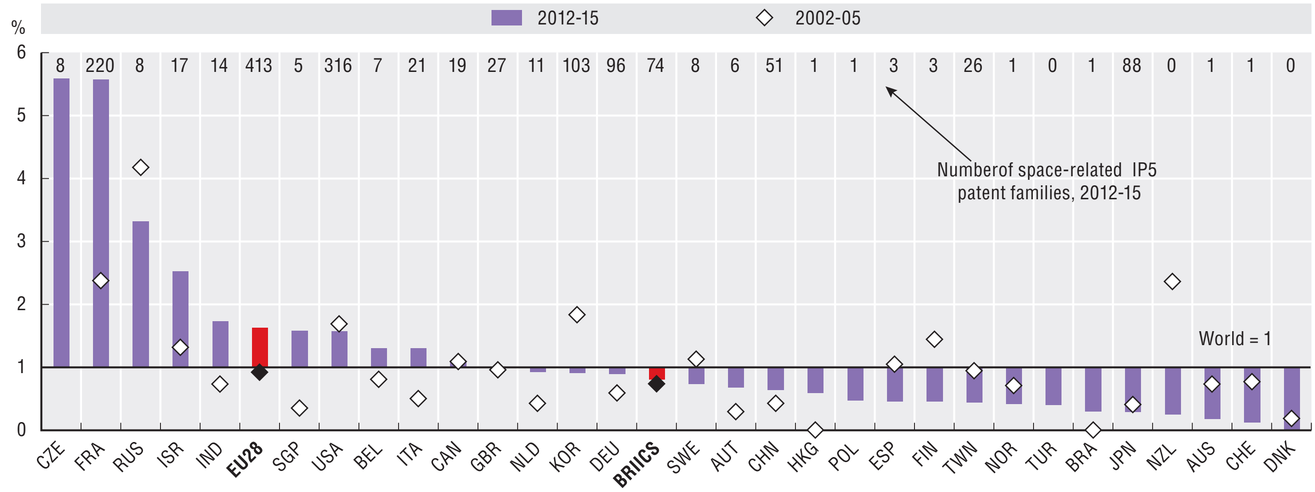
Overall between 2002-05 and 2012-15, several European and Asian regions have seen their patenting activities progress (Midi-Pyrénées, Southern Kanto, Capital Region in Korea), with strong growth in some cases (Ile de France, Guangdong, Niedersachsen, Hamburg, Aquitaine, Ontario).

The revealed technological advantage (RTA) is an index which provides an indication of the relative specialisation of a given country in selected technological domains. The RTA index in space technologies is calculated as the share of patents of a country in space-related technologies relative to the country's share of total patents. Based on the analysis, eight countries demonstrate a level of specialisation in space technologies (Figure 1.16).

The Czech Republic has taken the lead in this indicator for the first time, probably because of its investments in space programmes (particularly satellite navigation), and close links with European organisations. The country joined the European Space Agency in 2008, and its capital Prague is the home of the European Union's European Global Navigation Satellite Systems Agency (GSA) since 2012. The GSA could become after 2021 the European Union's "Agency for the Space Programme", a new space agency running the European Union's space programme. Following the Czech Republic, France, the Russian Federation, Israel, India and the European Union show a relatively large amount of patenting in space activities, compared to other economic sectors.

Figure 1.16. Revealed technology advantage in space-related technologies

IP5 patent families, by priority date and applicant's location, using fractional counts



Note: The revealed technological advantage index is calculated as the share of patents of an economy in space-related technologies relative to the share of total patents belonging to the economy. Data refer to IP5 patent families, by priority date and the inventor's residence using fractional counts. Space-related patents are defined on the basis of their International Patent Classification (IPC) codes. Figures are based on incomplete data from year 2014. Only economies with more than 500 patents in 2012-15 are included.

Source: OECD STI Micro-data lab: Intellectual Property Database, *http://oe.cd/ipstats*, March 2018.

Policy advice to better assess and support a transformed space sector

The ongoing transformation of the space sector raises multiple issues for governments, in particular when it comes to enabling industry competitiveness, encourage further growth and innovation, and ensure some level of returns on investments of publicly-funded space programmes.

While the private sector has played an important role in space manufacturing in many OECD countries since the first space programmes of the 1950s and 60s, private actors are now increasingly leading the way in the use of innovative materials, technologies and processes. This reflects not only the digitalisation of the sector, innovative players, and technologies coming of age, but also strategic shifts in government policy and project management, focusing increasingly on commercialisation and industry partnerships.

Based on lessons learned from other economic sectors, two approaches could be pursued in order to better assess and enable the growth of space activities, while improving returns on public investments:

1. Increased government use of commercial services, via different procurement and co-funding mechanisms. Institutional space budgets still represent a key driver for commercial space activities, with public administrations already as funders or anchor tenants of many commercial space services. As capabilities from the private sector grow, government can make more extensive uses of commercial space services for increasingly sophisticated tasks.
2. Invest efforts in mapping national space economies, in co-operation with national statistical offices, industry associations and/or private contractors. All countries and firms have the opportunity to participate and benefit from the space sector's global value chains. Governments that fund space programmes should better track who is doing what in the space industry and beyond, via regular industry surveys and analysis of existing administrative data. This includes mapping the many actors along the value chains in their national space economy.

As the space sector continues its transformation in the face of unrelenting digitalisation, as the next chapters will demonstrate, policymakers will play an important role in enabling the transition for public agencies as well as for existing firms, while at the same time fostering innovation and entrepreneurship. In order to reap the full benefits of existing and future space activities, and to ensure sustainable and equitable growth, targeted policy actions and further international cooperation will be certainly be required.

Box 1.8. Increased government use of commercial services, via different procurement and co-funding mechanisms

Many public organisations are in the process of reviewing their procedures for space R&D support and procurement, in order to make the best returns on investments. The schemes differ from country to country, but they aim to foster innovation, enable further private sector development, and reduce government costs; they include:

- *Setting up flexible procedures for procurement of commercial space products and services:* Many space agencies and research agencies aim to simplify and accelerate access to funding and facilitate the participation of start-ups and SMEs, through open solicitations or calls, and e-tendering. Some agencies, such as the US Defense Advanced Research Projects Agency (DARPA), use new contract types to reduce companies' administrative burden. Such contract types include, for instance, transaction authority agreements (OTAs) or Space Act Agreements in the United States and simplified contracts for R&D in Europe. DARPA has found that project funding could come through in as quickly as 2-3 months (using OTAs). Interestingly, established actors sometimes are more reluctant to change than the government agency and do not necessarily support the use of new procedures.
- *Co-funding arrangements for R&D and technology development (pre-commercial procurement), including different types of public-private partnerships (PPPs)*. These arrangements are increasingly popular among space agencies. The European Space Agency has a long history of using PPPs in satellite communications (e.g. ARTES programme) and is increasingly using them for larger projects (e.g. Ariane 6) with more applications possible in earth observation and space exploration. Programmes often require that the project participant or a third-party funder contribute 50% of the project cost, but the private sector share may be lower in low-TRL projects or when involving SMEs and start-ups. In the United States, private sector co-payment arrangements are often referred to as public-private partnerships. One recent example is partnerships created between NASA and industry in 2017 to 'Advance Tipping Point Technologies', totalling USD 17 million, where a minimum of 25% industry contribution is required (NASA, 2017[33]). NASA's well-established Commercial Orbital Transportation Services (COTS) programme for developing commercial launchers and orbital capsules has also been key in supporting the development of recent new launchers. It already contributed to strengthening competition and diversifying the services on offer by increasing the number of private sector providers of US transportation services. In Italy, public-private partnerships will play a central role in the national Space Economy Strategic Plan, as one of the main instruments for space technology development in satellite telecommunications, Galileo, Copernicus and exploration.
- *Developing targeted R&D grants:* R&D support programmes in the space sector are increasingly designed to contribute to other policy goals beyond technology development, such as promoting innovation in small and medium enterprises, enhancing collaboration among firms, fostering entrepreneurship, or university-industry collaboration (France Stratégie, 2016[34]). Space agencies play an important role in supporting domestic space manufacturing activities in a more globalised and competitive market, providing funding, facilities and guidance for the use of new technologies. One example is the German Space Components Initiative. This programme by the German Aerospace Space Centre uses a combination of R&D grants, brokering and marketing activities to support component development, production and sales and in this way increase the market share of German industry in off-the-shelf components for satellites (Feddeck and Fischer, 2016[35]).

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Chapter 2

THE SOCIO-ECONOMIC IMPACTS OF SPACE INVESTMENTS

The chapter presents three different approaches on how space investments can be associated with socio-economic impacts. An assessment of the types of benefits derived from space programmes are first provided, based on an original international literature review. In addition, new OECD indicators on the growing role of space applications in official development assistance projects (ODA) are presented for the first time. Finally, the growing relevance of space technology transfers and commercialisation for the wider economy is highlighted.

Introduction

Returns from investments in space programmes are not always evident, immediate or sustained over time. But the evidence is growing on the diverse benefits stakeholders in public and private sectors may get in terms of enhanced operations, skilled jobs, and new products and services born from past or more recent space research and development programmes.

Efficiency and productivity gains derived from the use of space applications are also becoming more visible across very diverse sectors of the economy and society, although experiences in estimating impacts vary across countries. From agriculture to energy, from routine surveillance to timing of financial transactions, institutional actors and private companies are increasingly using satellite data and signals. Satellites also play a key role in providing communications infrastructure rapidly to areas which lack ground infrastructure, contributing to link rural and isolated areas with urbanised centres. The types of benefits one can expect still really depends on the way a space programme or project is run.

This chapter provides three original perspectives on how space investments can have socio-economic impacts:

- First, the results of an international literature survey provide a brief review of the types of benefits that have been documented for the past thirty years, when investing in space programmes. It provides the basis for further evaluation and impact assessments of space programmes;
- Second, a focus on the impacts of space technologies in the developing world is provided, with new OECD indicators on the growing role of space applications in selected official development assistance projects (ODA);
- Finally, a brief review of space technology transfers and commercialisation is presented, as investments in selected space missions or larger programmes can find later applications beyond the space sector.

An original overview of the socio-economic impacts of space programmes

Different types of socio-economic evaluations and impact assesments of space investments have been carried out over the years, and the demand for these studies has been growing. This section presents the findings of OECD research on the existing literature of socio-economic benefits in the space sector. It provides new insights and evidence on how space investments have been tracked so far, illustrating the most common benefits identified and on selected economic sectors affected by space-related investments. It also contributes to detecting some gaps in the literature, pointing out some ways forward in future assessments of space investments.

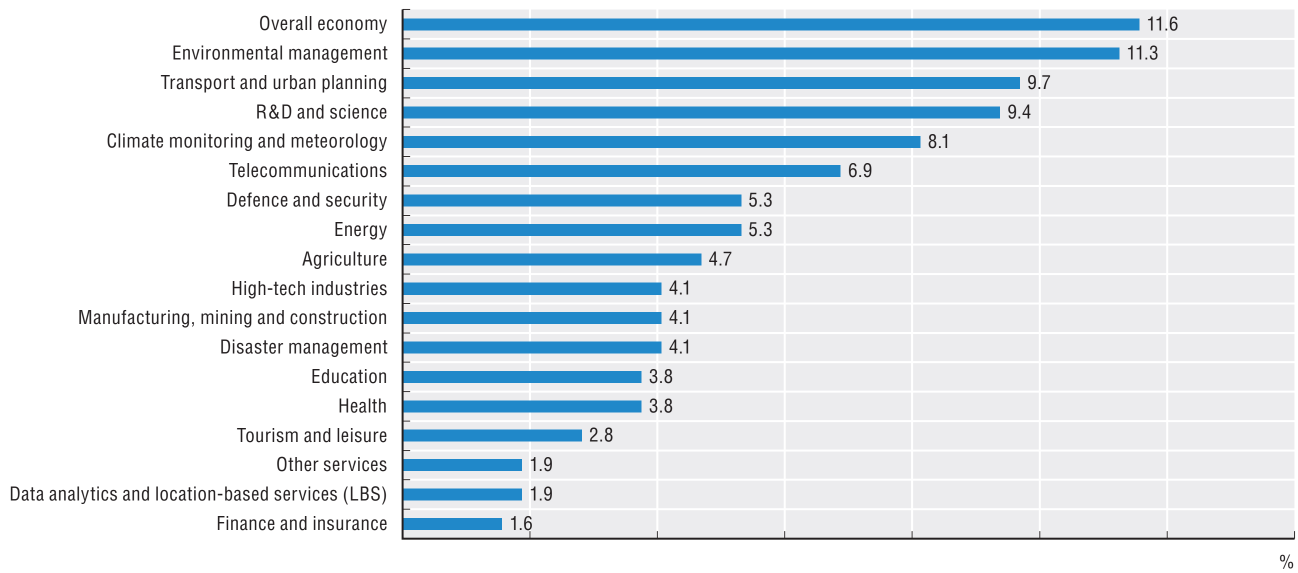
The research is based on a dataset of space-related studies, including 77 publications covering a period ranging from 1972 to 2018. The dataset comprises studies performed internally by space and non-space organisations, as well as academic papers. They include a wide range of studies, analysing national/regional space sectors, space programmes and selected missions. Publications have a wide geographic coverage, analysing the effects of space activities performed at various national, regional and global levels. The largest share of studies focuses on impacts in Europe (22%), in the United States (20%) and more generally at global level (19%). The rest of the studies includes national case studies (e.g. United Kingdom, Canada, the Netherlands, Denmark, Italy and Germany). Very few developing countries are included. Based on this literature review, original indicators were developed after performing a detailed classification of the studies according to the types of benefits and beneficiary sectors.

- In terms of the types of benefits that can be derived from investments in selected programmes, productivity and efficiency gains can often be observed at the firm level (in processes and operations), in the workforce (improvements in workers' skills and know-how) and at the managerial level (organisational benefits such as improved co-ordination and co-operation). Cost savings, cost avoidance, commercial revenues and employment may also occur, in the space sector itself or in other sectors. Depending on data availability, macroeconomic effects of investments can also be tracked, on GDP /value added and tax revenues.
- Beneficiary sectors are the economic sectors that benefit from effects spurred by space activities. As part of the selected categories, they include the overall economy (at national level via GDP); agriculture; health; transport and urban planning; education; environmental management; climate monitoring and meteorology; energy; telecommunications; disaster management; finance and insurance; manufacturing, mining and construction; high-tech industries; defence and security; tourism and leisure; research and development and science; data analytics and location-based services; and other generic services.

With the first institutional investments in large space programmes dating back more than sixty years now, ever-more economic sectors seems to benefit from the socio-economic effects derived from space investments. When examining the literature, several studies assess the impacts of the space sector, of space programmes, or even of the establishment of specific space activities in selected geographic areas, on the local, regional or national economy. More specific studies also analyse benefits of space investments as they spread to sectors such as environmental management, transport and urban planning, R&D and science, climate monitoring and meteorology, and telecommunications. Other sectors include defence and security, energy, and agriculture (Figure 2.1).

Figure 2.1. Selected sectors that benefit from socio-economic effects derived from space investments

Share of total occurrences identified in the literature



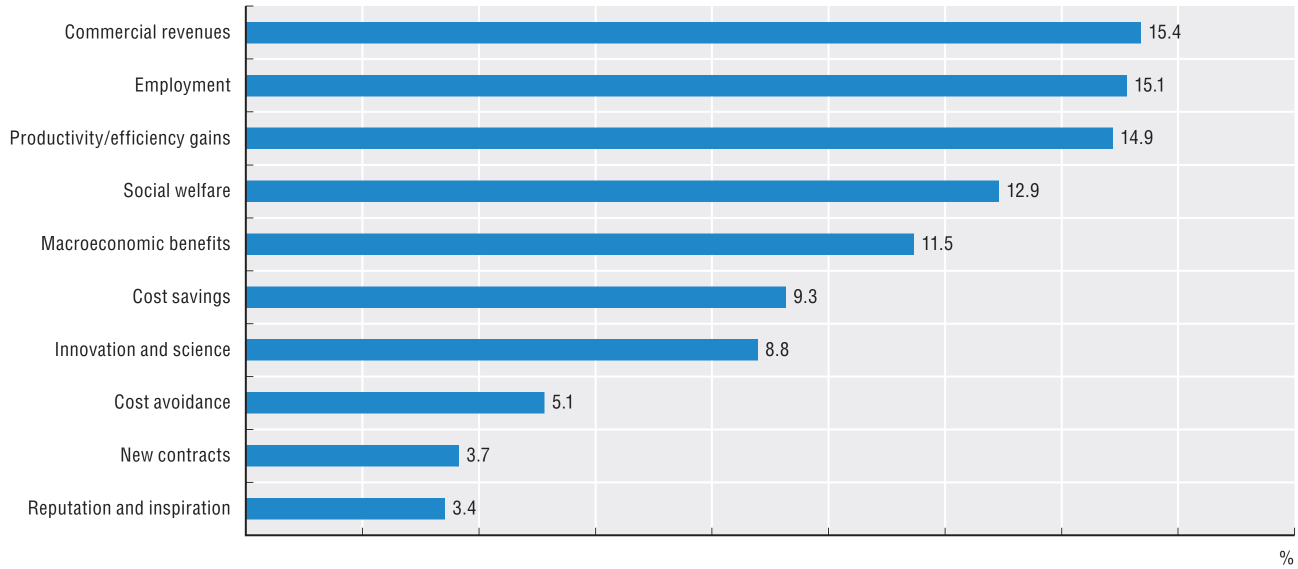
Note: The literature covers 77 impact assessments and programme evaluations published between 1972 and 2018.

In terms of the types of positive effects derived from space investments, commercial revenues represent the top category (Figure 2.2). Several studies found that the implementation of space programmes, technologies or other types of activities created new revenue streams for firms, often beyond the space sector. Commercial revenues are followed by effects on employment, with the creation of new jobs being observed. Productivity and efficiency gains represent another fundamental category of benefits. Many studies assess the socio-economic relevance of space activities at the national, regional or local level, taking a macroeconomic perspective (11.5%), assessing impacts on gross domestic product, value added and additional induced taxation.

The benefits of space do not exclusively impact actors operating in the space sector, as many studies report positive effects in non-space firms and at the broader societal level. This is, for example, the case of cost savings and cost avoidance (Figure 2.3). Around 57% of all cost savings and more than three-quarters of cost avoidance are realised beyond the space sector. Benefits in these categories usually derive from the application of space technologies in other fields, resulting in the reduction of operating costs. Cost avoidance is also highly linked to applications in the context of environmental management, meteorology and disaster management, see also Chapter 7, for example. There, the quality of information provided, often based on satellite data, makes it possible to improve forecasts and decision-making, preventing economic or social costs and losses. On the other hand, positive impacts of space investments on commercial revenues and employment occur more frequently in space firms. Around 59% of effects on revenues and 71% of those on job creation have been quantified in the space sector.

Figure 2.2. Types of positive effects derived from space investments

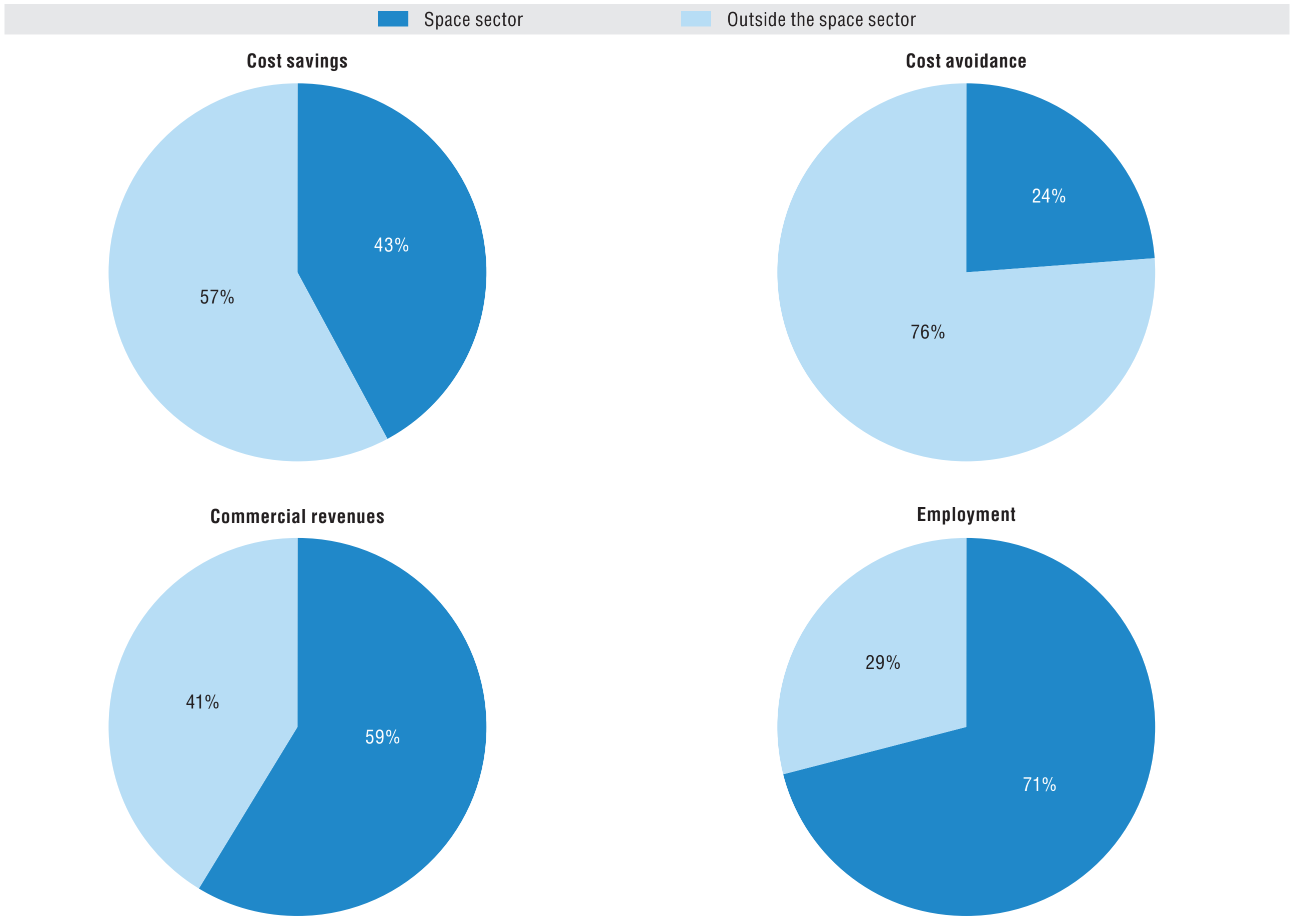
Share of total occurrences identified in the literature



Note: The literature covers 77 impact assessments and programme evaluations published between 1972 and 2018.

Figure 2.3. Benefits in and outside the space sector derived from space investments

As a share of the total listed benefits found in the literature

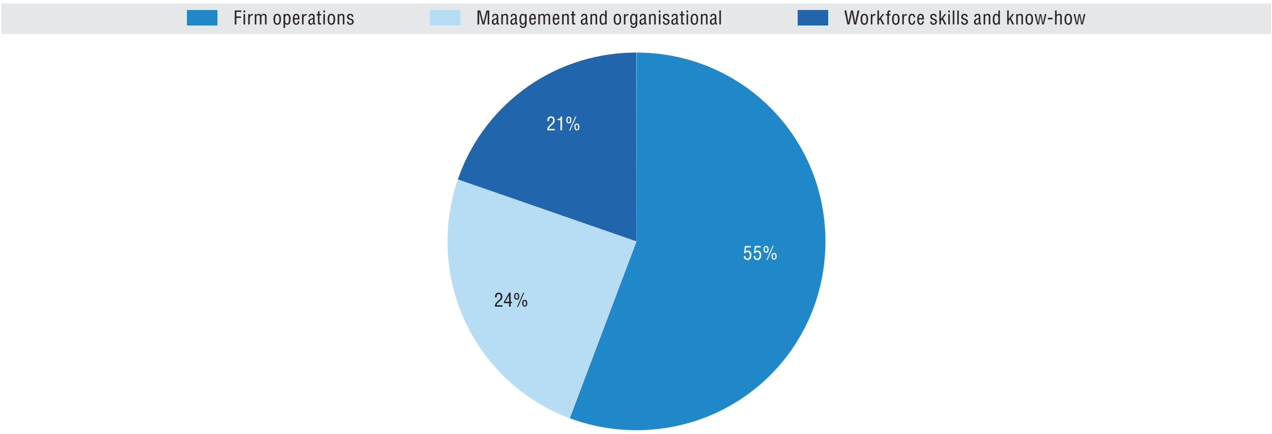


Note: The literature covers 77 impact assessments and programme evaluations published between 1972 and 2018.

The majority of efficiency and productivity gains appear at the level of operations and processes (Figure 2.4). More than half of these benefits (55%) involve better and more efficient production processes and operations that may eventually translate, later on, to cost savings. The rest is almost equally distributed among gains at the workforce (21%) and management (24%) levels. Gains at the workforce level entail boosts of productivity and efficiency resulting from improvements in the workforce's skills and know-how. Gains at the management level comprise all types of improvements coming from better managerial decisions. Improvements include the introduction of more efficient organisational practices, better co-ordination among different business branches and increased external co-operation among firms.

Figure 2.4. Types of efficiency and productivity gains derived from space investments

As a share of the efficiency and productivity gains' benefits found in the literature



Note: The literature covers 77 impact assessments and programme evaluations published between 1972 and 2018.

This international literature review is one useful step in the evaluation and impact assessment of space programmes. Further OECD research will contribute to enhance this growing knowledge base.

Space technologies and the developing world

Despite the daunting challenges facing the developing world, significant, untapped opportunities arise from advances in technology, science and innovation (OECD, 2016[1]). The relevance and take-up of many space applications in developing countries have been growing, thanks to the possibility of accessing many of these information-related technologies more easily and more competitively. This section provides new OECD indicators to track the growing links between development projects and applications of space technologies via official development assistance (ODA) statistics, and then provides some illustrations of existing development projects.

Space technologies and official development assistance

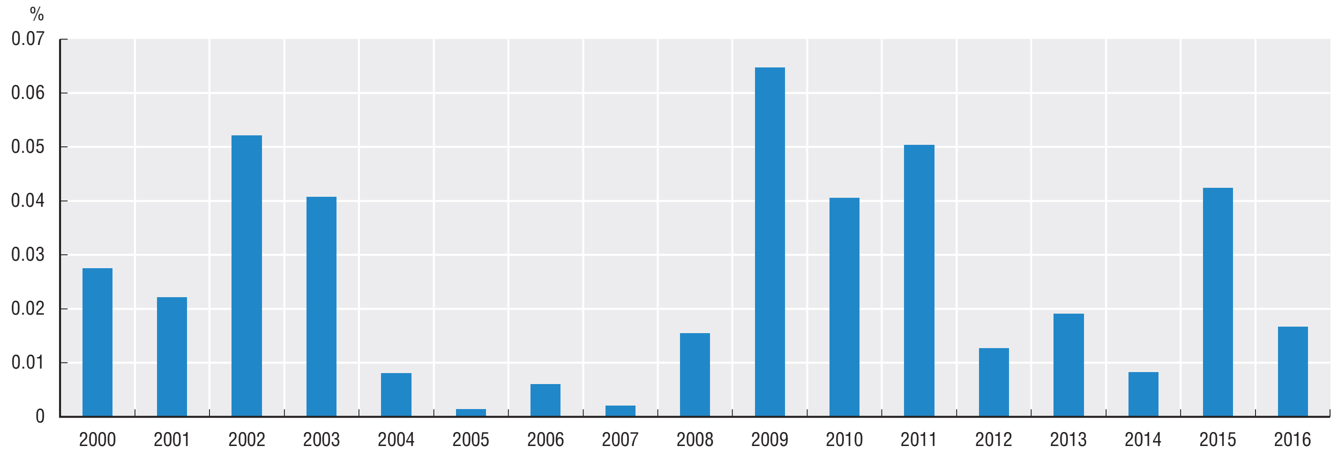
There is growing evidence of the role satellite technologies can play in supporting development objectives. Earth observation (geospatial information, satellite imagery, remote sensing), satellite telecommunication and broadband, as well as global positioning and navigation technologies find many applications specifically targeted for development. They may support the setting up of diverse infrastructure (water, road, transport, telecommunications) or contribute to natural resources management and tackling environmental issues, as in the case of land cover changes and disaster risk prevention and response. Particularly in developing regions characterised by scarce population density and complex urbanisation dynamics, satellite data can improve the implementation of a wide range of development policies at the local, regional and national level. These include public service provision and investment strategies, as well as decentralisation policies (Moriconi-Ebrard, Harre and Heinrigs, 2016[2]). And satellite remote sensing has already been game-changing in several sub-Saharan countries for providing epidemiology information to help contain malaria outbreaks.

In this context, the role of space in official development assistance (ODA) statistics is examined, based on international data curated by the OECD's Development Co-operation Directorate. ODA is today the key measure used in practically all aid targets and assessments of aid performance towards the developing world. The original OECD indicators presented here provide new evidence on the intensifying links between development aid and space applications between 2000 and 2016. Space-related projects were identified using keyword searches in the OECD ODA project database (see Box 2.1), identifying some 2 100 projects over the 2000-16 period. The results are presented in the following paragraphs, identifying some of the most active institutions and countries in terms of funding (via commitments and/or disbursements), main recipient regions, as well as the main fields of application.

Although not negligible, the ODA amounts directed to space-related projects remain modest when compared with overall ODA funding, as illustrated in Figure 2.5. Total overall ODA commitments globally increased from USD 96 billion to USD 188 billion between 2000 and 2016. In comparison, the total committed amounts for space-related official development assistance projects between 2000-16 totalled USD 607.4 million. There are big annual variations, with peaks in 2009 (USD 101 million) and in 2015 (USD 78 million), mainly due to large one-off projects. The 2009 peak is partially explained by a French initiative launched to develop an environment and disaster monitoring small satellite (VNREADSat-1) in Viet Nam.

Figure 2.5. Commitments for space-related official development assistance projects

As a share of total ODA



Source: Calculations based on OECD-DAC database (2018).

Figures 2.6 and 2.7 show ODA project funding statistics for individual donor countries and institutions between 2000 and 2016 (2002-16 for disbursements). Top donor countries generally include countries with big space programmes (United States, France, Japan) and/or countries with dedicated programmes for using space technologies in development aid, including the SERVIR programme of NASA and the US Aid Development Agency, the UK Space Agency International Partnership Programme and Netherlands' Geo-Data for Agriculture and Water programme.

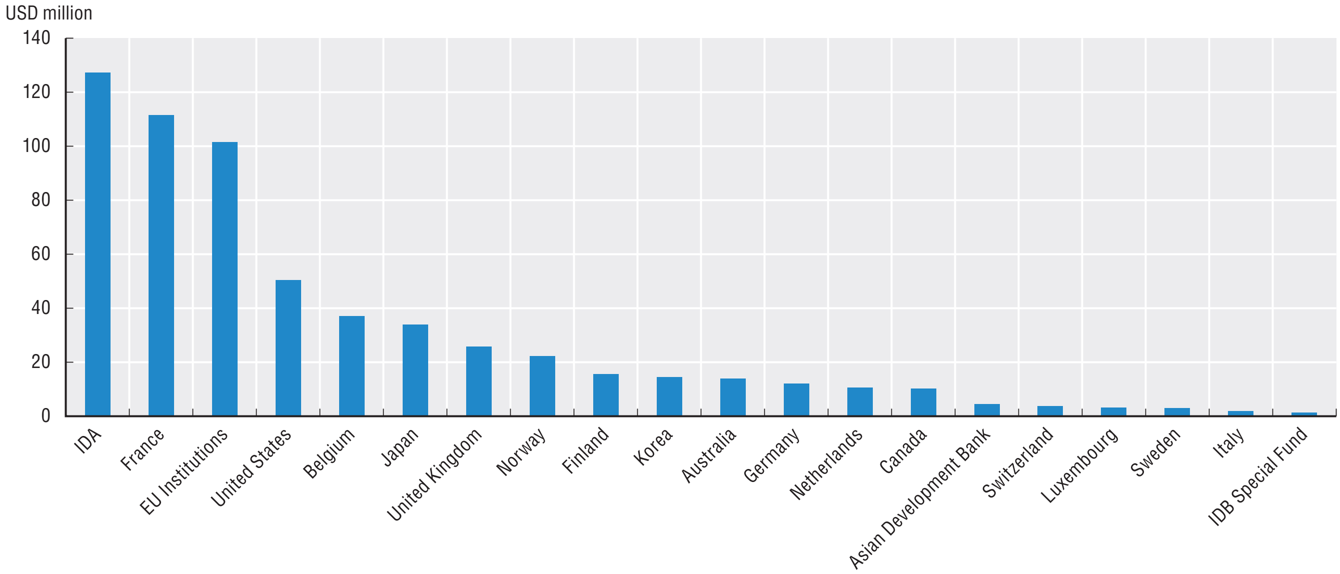
Individual country funding may be channelled either bilaterally or via multilateral organisations (e.g. World Bank/IDA) making funding amounts higher than what is reflected in the figures. Furthermore, the choice of the indicator (ODA commitments or ODA disbursements) may significantly influence the funding amount recorded for a specific year and country. Commitments represent the amount that an actor obliges itself to pay to support a specific project or initiative. In contrast, disbursements represent the amount concretely spent over a determined period (see Box 2.1 for details). Amounts recorded as commitments and disbursements may differ significantly in the short- and medium term, but should normally align in the long run. For instance, it can take several years to fully disburse a commitment. This is due to many concurring factors, including the payment schemes adopted, the nature of the payments and the obligations contracted, as well as their timing, and the selected reporting framework and rules.

If focusing on ODA commitments, the International Development Association (IDA) of the World Bank committed the largest amount of ODA in space projects between 2000 and 2016 (Figure 2.6), followed by

France, the European Union (EU) and the United States. Over the period, the World Bank/IDA committed around USD 127 million, France committed some USD 111.4 million and the United States USD 50.6 million. Among French commitments, one single project accounted for more than half of the total committed amount (USD 65.5 million). This refers to an initiative in Viet Nam, signed in 2009, for the development of an environment and disaster monitoring small satellite (VNREADSat-1), as already mentioned above.

Figure 2.6. Commitments for space-related official development assistance by donor, 2000-16

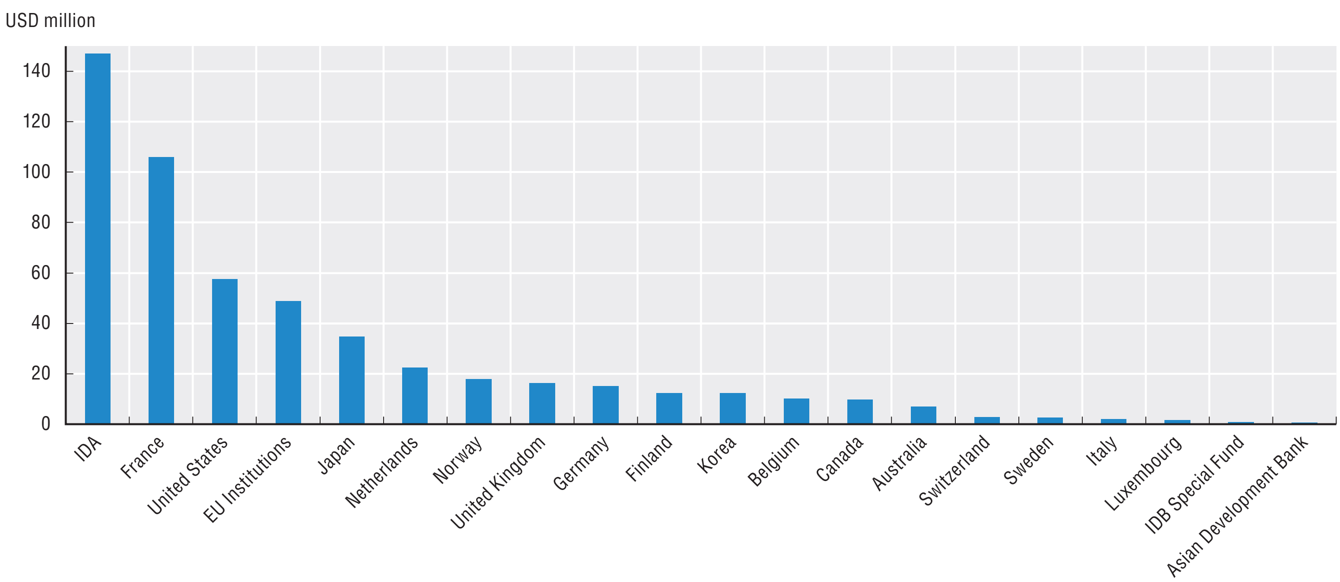
Amounts expressed in constant 2016 USD



Source: Calculations based on OECD-DAC database (2018).

Figure 2.7. Disbursements for space-related official development assistance by donor, 2002-16

Amounts expressed in constant 2016 USD



Note: Due to a change in the reporting guidelines on disbursements in 2002, the figure reports about the period 2002-16 instead of 2000-16 to ensure data robustness.

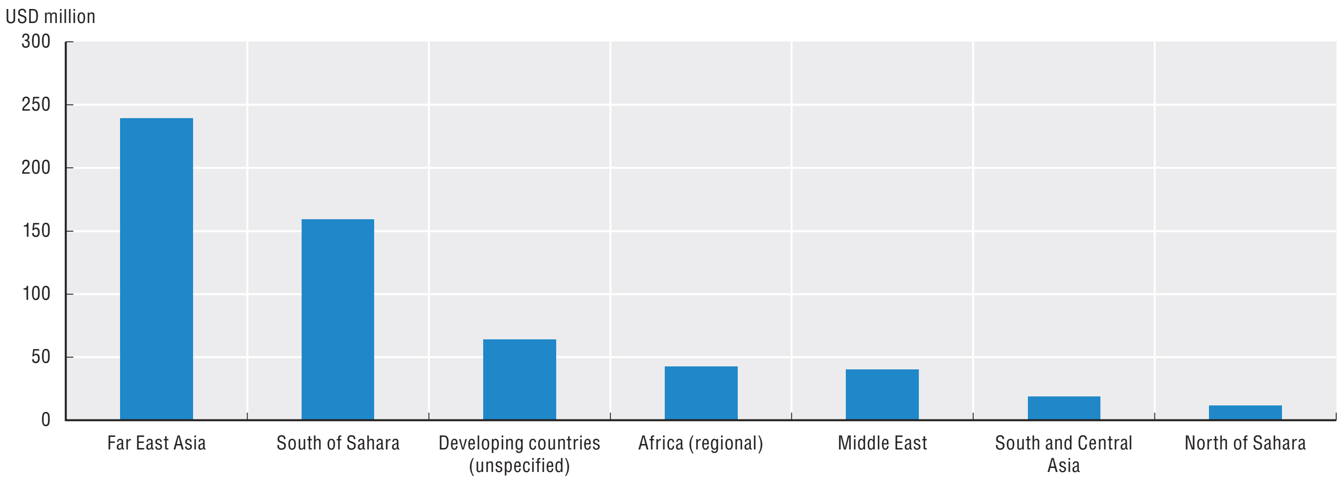
Source: Calculations based on OECD-DAC database (2018).

In terms of space-related ODA disbursements, i.e. money actually spent, IDA, France, the European Union and the United States were the main contributors, followed by Japan (USD 35 million) and the Netherlands (23 million).

Figure 2.8 shows the main regions receiving space-related ODA in the 2000-16 period. The majority of space-related ODA commitments was directed to countries in Far East Asia (East and Southeast Asia), receiving USD 240 million, and Sub-Saharan Africa (USD 160 million). Several projects targeted more than one country, at which case funding was allocated at regional level. The African region has been the target of several such initiatives, receiving USD 43 million in commitments. Several ODA projects do not specify the recipient name or region ('developing countries (unspecified)').

Figure 2.8. Commitments for space-related official development assistance projects by recipient region, 2000-16

Amounts expressed in constant 2016 USD



Note: The category "Africa (regional)" indicates that money was allocated at regional level, targeting more than one country at the same time. The category "Developing countries (unspecified)" is used when no specific recipient was indicated by the ODA project description.

Source: Calculations based on OECD-DAC database (2018).

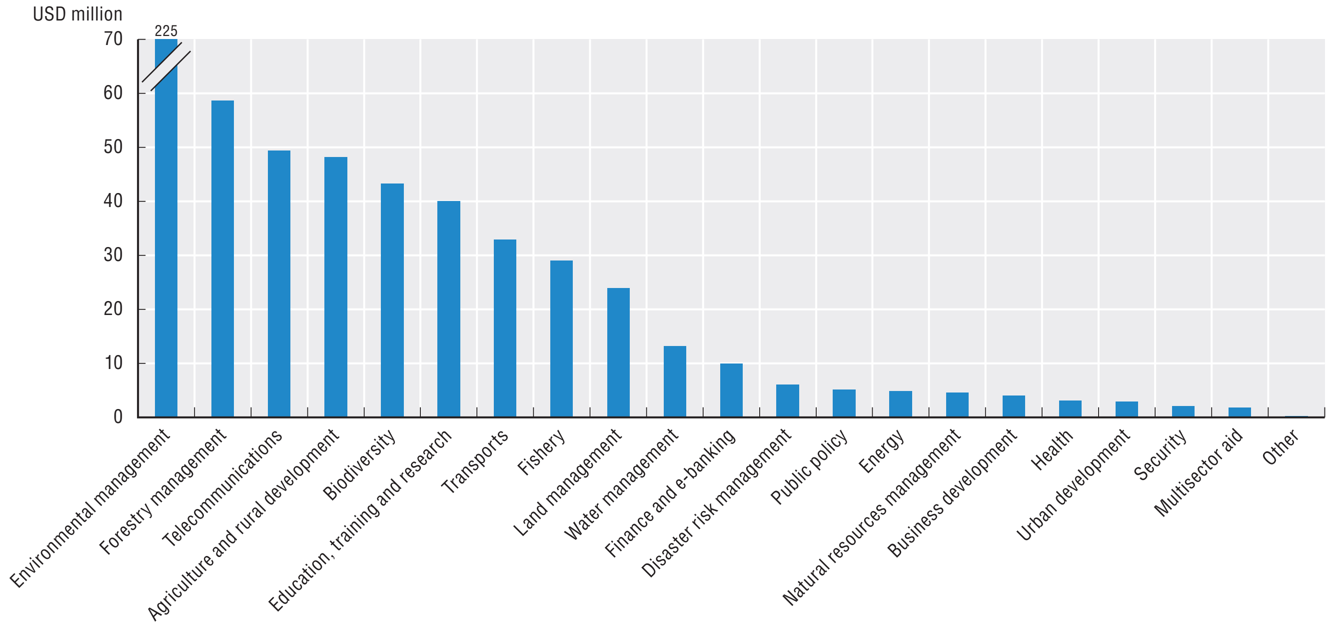
In terms of fields of application, most of the funding has been allocated to projects linked to environmental management objectives (Figure 2.9). Projects in this domain represent USD 225 million between 2000 and 2016. This is followed by forestry management (USD 59 million), telecommunications (USD 49 million) and agriculture and rural development (USD 48 million). A review of the projects included in the datasets finds that:

- Environmental management projects typically adopt satellite technologies to improve the analysis and the use of the environment and related resources, often linked to climate change. Projects tend to be quite large, with a broad regional scope. Satellite remote sensing is used to support and improve decision-making. The bulk of the initiatives are not only aimed at promoting a better use of environmental resources, but also at making environmental monitoring more effective.
- Forestry management projects focus on challenges linked to the sustainable use and conservation of forests. Remote sensing technologies are used to assess the conditions of forests, mapping, gathering data and building databases for monitoring purposes.
- Telecommunications projects deal with the development, or expansion, of regional/national telecommunication infrastructure, involving the provision of satellite broadband and broadcast services. Projects are generally large, aiming to connect remotely located households and communities to the existing telecommunication networks.

Other relevant thematic clusters include agriculture and rural development, biodiversity and education, training and research. Projects listed under 'agriculture and rural development' include all projects exploiting satellite images and data to inform agricultural practices, monitor agricultural resources and assess agricultural productivity. Several initiatives specifically aim at promoting food security as a direct consequence of greater crop production and better functioning of early warning systems and climate condition monitoring. Projects linked to biodiversity protection use remote sensing techniques for biosphere and animal protection. Several applications also include the adoption of GNSS technologies to track species and their dislocation across different geographic areas. Finally, education, training and research projects group the bulk of distance-learning initiatives focusing on the provision of tele-education services to populations living in remote areas.

Figure 2.9. Space-related official development assistance commitments by project purpose, 2000-16

Amounts expressed in constant 2016 USD



Source: Calculations based on OECD-DAC database (2018).

Box 2.1. Official development assistance at the OECD

The OECD's Development Co-operation Directorate has been in charge of measuring resource flows to developing countries since 1961, with particular attention given to the official and concessional part of this flow, defined as "official development assistance", or ODA. In close collaboration with Development Co-operation Directorate colleagues, the OECD Space Forum Secretariat has explored the Development Assistance Committee's databases using keyword searches. The original dataset has been manually checked and cleaned, to identify and retain only the projects dealing with space-related initiatives. Some 2 100 ODA projects featuring satellite applications or technologies were identified over a 16-year period (2000-16).

ODA takes place through transfers of resources, either in cash or in the form of commodities or services. They can be provided in many different ways, usually including privileged loans, grants or even technical assistance.

ODA can be bilateral or multilateral, provided from a donor to a specific recipient or channelled through the action of a development agency. Bilateral aid represents the "flow from official (government) sources directly to official sources in the recipient country". Multilateral aid represents "core contributions from official (government) sources to multilateral agencies where it is then used to fund the multilateral agencies' own programmes". A donor can also decide to charge a multilateral agency with delivering a programme or project on its behalf in a recipient country.

Box 2.1. Official development assistance at the OECD *(cont.)*

ODA is reported in different ways, either as ODA commitments or ODA disbursements.

- An ODA *commitment* is a firm obligation, expressed in writing and backed by the necessary funds, undertaken by an official donor to provide specified assistance to a recipient country or a multilateral organisation. Bilateral commitments are recorded in the full amount of expected transfer, irrespective of the time required for the completion of disbursements. Commitments to multilateral organisations are reported as the sum of (i) any disbursements in the year reported on which have not previously been notified as commitments and (ii) expected disbursements in the following year.
- An *ODA disbursement* is the release of funds to or the purchase of goods or services for a recipient; by extension, the amount thus spent. Disbursements record the actual international transfer of financial resources, or of goods or services valued at the cost to the donor. In the case of activities carried out in donor countries, such as training, administration or public awareness programmes, disbursement is taken to have occurred when the funds have been transferred to the service provider or the recipient. They may be recorded gross (the total amount disbursed over a given accounting period) or net (the gross amount less any repayments of loan principal or recoveries on grants received during the same period). It can take several years to disburse a commitment.

Source: OECD (2018[3]), *DAC Glossary of Key Terms and Concepts*, *http://www.oecd.org/dac/*.

Illustrations of technical assistance projects

A majority of countries with a space programme and private actors operative in the space sector have launched specific technical assistance projects promoting socio-economic development (Table 2.1). They include applications aimed at improving the coverage of the medical system in remote areas, preventing the diffusion of diseases, providing classes and training through tele-education channels and supporting policies for the management of resources and the prevention of natural disasters.

Table 2.1. Selected illustrations of space for development initiatives from around the world

Programme	Organisations involved	Short description	Technologies and domains of application	Geographic focus	Potential benefits
Tele-epidemiology initiatives	CNES (France)	Several projects using earth observation in the area of tele-epidemiology to prevent the diffusion of contagious diseases. Combining environmental variables with satellite imagery, it is possible to draw predictive risk maps able to track the exposure to disease-bearing insects and ideally create widely applicable early warning systems.	Earth observation for tele-epidemiology, health monitoring, disease prevention, agriculture (livestock)	Argentina, Burkina Faso, Chad, China, Mali, Martinique, Mediterranean basin, Senegal	Lives saved, lives improved, cost avoidance (agriculture)
Land subsidence in Jakarta	European Space Agency with World Bank, Jakarta municipal government	Flood risk management project in the Jakarta metropolitan area run by the World Bank. This includes revitalisation of drainage canals and a collection of detailed geospatial information (through COSMO Sky-Med data) concerning flood hazard and an assessment of the existing capacity of the hydraulic networks and investigations of land subsidence patterns.	Earth observation, geospatial information, persistent scatterer interferometry for environmental management, disaster risk management and prevention, urban planning	Indonesia	Cost avoidance, cost savings, efficiency, lives improved
GMES and Africa initiative	European Commission (DG DEVCO) with African Union, GMES Africa Unit	The project facilitates the establishment of systems to receive and process earth observation and geo-data and disseminate relevant information in Africa. It also enables the development of capacities of experts in acquiring wider and deeper knowledge on earth observation techniques and environmental issues.	Earth observation, geospatial information for water management, natural resources management, marine and coastal management	Africa (whole continent)	n.a.

Table 2.1. Selected illustrations of space for development initiatives from around the world *(cont.)*

Programme	Organisations involved	Short description	Technologies and domains of application	Geographic focus	Potential benefits
Telemedicine programme	Indian Space Research Organisation with local governments	The programme started in 2001 with the goal of using satellite communications in the provision of health services to people living in remote areas. The goal of the project is to connect remote college hospitals and mobile telemedicine units to major specialty hospitals in cities and towns through Indian satellites. Thanks to satellite links it is possible to provide medical diagnosis and consultation by specialist doctors to patients located in remote and rural areas.	Satellite broadband for telemedicine	India	Lives saved, lives improved
SERVIR	National Aeronautics and Space Administration (NASA) with US Agency for International Development (USAID)	Partnership between NASA and USAID exploiting earth observation for environmental management purposes in more than 30 developing countries. The goal is to help local governments improve their response to natural disasters, tackle food security, safeguard human health, and manage water and natural resources.	Earth observation, satellite imagery, geospatial information, science applications for environmental management, land use and land cover, disaster risk management and prevention, water management, agriculture, food security	Hindu-Kush region (Himalayas), Lower Mekong River basin, eastern Africa, southern Africa	Environmental effects, lives saved, lives improved, cost avoidance (agriculture)
Geodata for Agriculture and Water (G4AW)	Netherlands Space Office (NSO) with local partners in each country	Using EO data and satellite broadband to provide developing economies with information on climate, weather and hazards and help food producers and other stakeholders. The goals are to: improve the output of the agricultural, pastoral and fishing sector; reach a minimum 10% increase in sustainable food production; help achieve a 10% more effective use of inputs; and promote sustainable improvement and increase of food production.	Geospatial information, satellite broadband for agriculture	Bangladesh, Burkina Faso, Ethiopia, Indonesia, Kenya, Mali, South Africa, Tanzania, Uganda, Viet Nam	Increased agricultural productivity, increased agricultural turnover
International Partnership Programme (IPP)	UK Space Agency with different partners according to country and programme	The IPP is a five-year GBP 152 million programme which seeks to maximise the practical impact on the lives of those living in developing countries by partnering with these countries to use space solutions to solve their specific development challenges. The programme is delivered through a series of calls run by the UK Space Agency's IPP team. Several projects are registered under the IPP umbrella in many regions and countries in the world.	Earth observation, geospatial information for health, education, deforestation, disaster response, land-use monitoring, maritime sector, renewable energy	Sub-Saharan Africa, Latin America and the Caribbean, South East Asia	Environmental effects, lives saved, lives improved

Illustrations for three domains of space applications are provided below: health, education, and natural resources and land-use management.

Health

The national health system represents a crucial sector for developing economies, and the use of specific satellite technologies have been demonstrated over the years to tackle specific challenges. This includes reaching populations living in remote areas to provide them with basic medical services, consultations and the sharing of patients' data with specialists. Epidemiology is another promising field using satellite imagery to track the diffusion of diseases and disease-bearing insects (e.g. malaria).

The Indian Space Research Organisation (ISRO) is very active in applying satellite technologies, and broadband in particular, to provide health services to its very widespread population. ISRO's Telemedicine Programme started in 2001 with the goal of using satellites to provide health services to people living in isolated areas. The goal of the project is to connect remote college hospitals and so-called mobile telemedicine units to major specialty hospitals in cities and towns through Indian satellites. Thanks to satellite links, it is possible to provide medical diagnosis and consultation by specialist doctors to patients which otherwise could not be reached. The network includes 384 hospitals, with 60 specialty hospitals connected to 306 remote college hospitals and 18 mobile telemedicine units. The latter are operative in the areas of ophthalmology, cardiology, radiology, diabetology, mammography, general medicine, and women's and children's health (ISRO, 2017[4]).

Private actors are also increasingly playing a significant role in the health sector, making available their assets and expertise for the provision of services. Inmarsat launched an e-health project in collaboration with the charity SOS Children's Villages in Benin (Inmarsat, 2014[5]). The initiative makes it possible for rural community health clinics to send patients' medical information to doctors in urban hospitals via Inmarsat`s broadband data service infrastructure. About 1 350 children and their families have been helped thanks to improved health monitoring and early diagnosis of conditions.

As another illustration, the French space agency (Centre national d'études spatiales, CNES) is currently running several projects using earth observation in the area of tele-epidemiology to prevent the diffusion of contagious diseases. CNES has developed a deterministic approach based on the relationship between climate, environment and health relationships, to monitor, predict and prevent epidemics (Vignolles, 2011[6]). Combining environmental variables with satellite imagery, it is possible to draw predictive risk maps able to track the exposure to disease-bearing insects. This concept is currently applied to track the diffusion of malaria (Argentina, Burkina Faso, Chad, Mali and Senegal), bilharzia (The People's Republic of China), vibrio (Mediterranean basin) and dengue (Argentina and Martinique). The idea is to develop early warning systems applicable to a wider array of diseases in other places with different environmental characteristics.

Education

Similarly to telemedicine, education also benefits from satellite connectivity as a means to reach populations living in remote areas thanks to tele-education. In some countries, mobile learning centres as well as schools are increasingly equipped with ground stations transmitting via satellite different types of learning services, including classes, courses, interactive exercises and trainings. In 2004, ISRO launched a tele-education initiative, the EDUSAT programme, aimed at bringing education to every corner of the country. EDUSAT is the first satellite entirely used in the country for the provision of education services. They are delivered through a wide range of interactive educational channels like one-way TV broadcast, video conferencing, computer conferencing and web-based instructions (ISRO, 2017[7]). The established network includes two types of terminals, namely satellite interactive terminals and receive-only terminals. As of December 2012, 83 networks had been implemented connecting to 56 164 schools and colleges (4 943 satellite interactive terminals and 51 221 receive-only terminals) covering 26 states and 3 union territories of the country. Estimates indicate that about 15 million students benefit from the EDUSAT programme every year.

Satellites are also very useful for civilians in the case of conflicts that make entire regions impossible to access for long periods of time. For example, Inmarsat, partnering with Télécoms Sans Frontières, used satellite broadband to provide classes to children caught up in the conflict in Iraq (Inmarsat, 2014[8]). Services were provided through mobile e-learning centres located in refugee camps. The centres allow children to access the Internet via Inmarsat's broadband global area network (BGAN) service using digital tablets.

Natural resources and land-use management

Natural resources and land-use management are two areas which are particularly suitable for the application of satellite earth observation. Different types of satellite imagery integrated with other data sources are now commonly used to better inform decision-making processes and disaster management processes, monitor land cover and land-use change, as well as water, and to control the use of resources to promote food security and sustainable development. Even in the case of setting up cadastral information and urban agglomerations maps, satellite data play an increasing role, as demonstrated by ongoing activities of the OECD Sahel and West Africa Club (Box 2.2).

In order to help local governments improve their response to natural disasters, tackle food security, safeguard human health, manage water and natural resources, the SERVIR initiative was set up in 2004 as a then very original partnership between the National Aeronautics Space Administration (NASA) and the US Agency for International Development (USAID). The programme uses satellite-based earth monitoring, imaging and mapping data, geospatial information, predictive models, and science applications to help improve environmental decision-making in co-ordination with agencies in developing economies (NASA, 2017[10]). The initiative now runs in more than 30 developing countries. Within the programme, NASA partners with leading regional organisations in eastern and southern Africa, the Hindu-Kush region of the Himalayas, and the lower Mekong River Basin in Southeast Asia. In the Himalaya region, earth observation data are used to detect forest fires, monitor land-use and cover changes as well as water resources. In Africa, the main target of the initiative is flood forecasting, monitoring the impact of frost on regional agriculture and again assessing land cover and land-use change. Activities in the Mekong region focus instead on disaster risk reduction and response, together with water and food security, landscape management to reduce greenhouse gas emissions, and sustainability of the river basin.

Box 2.2. Africapolis, an initiative from the OECD Sahel and West Africa Club

Combining census data with satellite imagery to build a homogenous, independent and verifiable database on urban agglomerations in Africa.

Africa is set to have the fastest urban growth rate in the world in the coming decades, with the number of people living in cities and towns projected to double over the next 20 years. Cities are and will increasingly be a defining feature of Africa's social, economic and political landscape. There is a need to understand urbanisation – what it looks like, what it means and what it might mean in the future. More complete and up-to-date data are crucial in order to document and analyse the ongoing dynamics of urbanisation and to provide the evidence base for a wide variety of public policies.

The Africapolis database produced by the OECD Sahel and West Africa Club is a unique database on cities and urbanisation dynamics in Africa. The 2018 edition covers 51 countries and provides information on the number of inhabitants, the size of built-up areas and geolocation for 7 500 urban agglomerations with more than 10 000 inhabitants between 1950 and 2015. The uniqueness of the Africapolis database comes from a combination of features that make it comparable across countries and time, rendering it independent of national definitions and verifiable.

The methodology combines census data and other official population counts, with satellite and aerial imagery and other cartographic resources. In many African countries, censuses are carried out infrequently, during different years, are based on country-specific definitions and provide different levels of detail. The integration of satellite imagery is therefore necessary for building a homogenous database. The application of a morphological definition to an urban agglomeration is verifiable – it is observable on the ground, and it allows for the detection of a number of key features such as urban sprawl, connectivity, the formation of metropolitan areas and the emergence of new agglomerations. Given the pace of urbanisation dynamics in Africa, these features are particularly important for policy analyses and design, ranging from provision and accessibility of basic public services to accessibility to jobs, public transport provision and funding needs, resource efficiency and sustainability, and the design of appropriate governance structures and agencies.

Source: OECD Sahel and West Africa Club (SWAC) (2018[9]).

Other space agencies and organisations are using earth observation for development purposes, often partnering with aid agencies and institutions in various parts of the world (Table 2.1). The Japan Aerospace Exploration Agency (JAXA) is collaborating with the Asian Development Bank on projects in the region where space applications serve mainly agriculture and rural development (ADB, 2013[11]). The UK Space Agency's International Partnership Programme (IPP) is a GBP 150 million multiyear programme launched in 2015. The explicit goal is to use space expertise and knowledge to deliver socio-economic benefits to underdeveloped economies (UK Space Agency, 2017[12]). Within it, several cross-sectoral projects have already been implemented in partnership with local governments, aid organisations and private actors in the area of land-use and natural resources management. Other initiatives include the one by the European Commission and JRC boosting the use of Copernicus data in Africa (European Commission Joint Research Centre (JRC), 2017[13]), and the Netherlands Space Office's Geo-Data for Agriculture and Water programme (G4AW) (Netherlands Space Office, 2016[14]).

Impacts of space technology transfers

The process through which a technology originated in one sector finds an application in another sector is called technology transfer. The term indicates every "movement of know-how, skills, technical knowledge, procedures, methods, expertise or technology from one organisational setting to another" (Roessner, J, 2000[15]). Studying this mechanism sheds light on the path followed by ideas and knowledge from the moment they are created to the moment when they are transferred and find a concrete application in the marketplace.

Technology transfers and their commercialisation contribute to foster broader socio-economic development, thanks in particular to their impact on innovation in different sectors (OECD, 2017[17]). Technology transfers act as a strategic channel to stimulate and trigger innovation creation and propagation mechanisms, by means of knowledge spillovers through industryscience collaborations and technology transactions among various actors (OECD, 2016[18]); (OECD, 2017[17]). They do so primarily by inducing direct economic benefits to industry, for example, by boosting productivity and increasing the number of jobs created, but also by improving people's well-being and addressing critical societal challenges.

The interest for technology transfers from the space sector to other sectors of the economy has been growing over recent years, reflecting the increasing focus on space applications and their potential for generating socio-economic benefits beyond space missions, for the economy and society (Jolly and Olivari, forthcoming[16]). Space technology transfers have moved from being often accidental by-products of space research, to new ways to multiply the value of original space R&D. Promoting the diffusion of space technologies is becoming a significant task in space agencies' programme of work in many countries.

Technology transfers and commercialisation (TTCs) aim to extend the benefits of space R&D investments and maximising their returns. When the transfer is timely and well organised, technology recipients may reduce the costs necessary to introduce new advanced technologies, in terms of time and funding (ESA, 2017[19]). They may benefit from enhanced productivity and efficiency in production processes and may be able to offer a larger portfolio of more competitive products. These newly developed goods and services can lead to new markets. For the general public, such transfers are also very useful, as the space R&D can appear as contributing other socio-economic benefits beyond initial space missions, building a case for increasing public and private space investments.

This virtuous process is not automatic and depends on several concurrent factors and strategic decisions. The likelihood of TTCs taking place depends on the characteristics of the technology to be transferred, of the objectives of the R&D programme where the technology has originated and of the R&D network of actors receiving it. In addition, policy makers have a fundamental role to play in creating the right environment and institutional framework which facilitate the diffusion of technologies. The recipients of new technologies are also important, in particular in the commercialisation phase. Their vision is crucial in disclosing the potential of the assets they receive. This includes testing them in specific applications, adapting and upgrading them to respond to the needs of the market they serve or aim to serve, and getting a monetary value out of the process.

Assessing the effects of space TTCs

Assessing the effects of commercialised technologies is a difficult task, particularly in the space sector. In order to make the effects generated identifiable and therefore allowing for a more immediate evaluation, some indicators of impact of space TTCs can be identified, and generally include: jobs created, revenues generated, productivity and efficiency gains, lives saved/not lost and lives improved (Table 2.2).

Table 2.2. Selected benefits derived from space technology transfers

Category of benefits	Measurement
Jobs created	Number of people hired to produce or use a space-derived product or service.
Revenues generated	Estimation of revenues generated by a company producing or offering a product or service that is a spin-off of space technology.
Productivity/efficiency gains	Quantification of saved and/or avoided costs due to the use of space-derived products or services, either by the company or by its customers.
Lives saved/not lost	Number of lives not lost as a result of a product or service that is a direct application or spin-off of space technology.
Lives improved	Number of people whose lives have been extended, enhanced and/or improved by a product or service that is a direct application or spin-off of space technology.

All of these can generically be defined as indirect effects from space programmes and be further classified in:

- *Technological effects*: effects produced by the direct application of the new space-related technology by the recipient actors.
- *Commercial effects*: can appear as network effects – i.e. impact of the space programme on the network in which the recipient actor operates – and reputation effects – i.e. boost in an actor's relative prestige and reputation within its network.
- *Organisational effects*: increased experience and know-how, as well as learning, derived from the collaboration between space and non-space actors in developing and exploiting new technologies.
- *Work factor effects*: impacts on employees acquiring new skills, capabilities and expertise with the potential of feeding that into other departments of the organisation for which they work.

Traditional assessment frameworks, involving macroeconomic modelling, econometrics, input-output multipliers and cost-benefit analysis, are not always suitable to measure such impacts. For instance, assessing the effects of transfers must often rely on ad hoc analysis to control for case specificity and subjectivity at a micro level. The relevant TTCs' effects are often evident from the firm and user perspective, rather than in the economy at large. Particular attention must be given to: the identification of causality linkages, the use of ad hoc methodologies and the definition of the right units of measure through which to quantify the effects of TTCs.

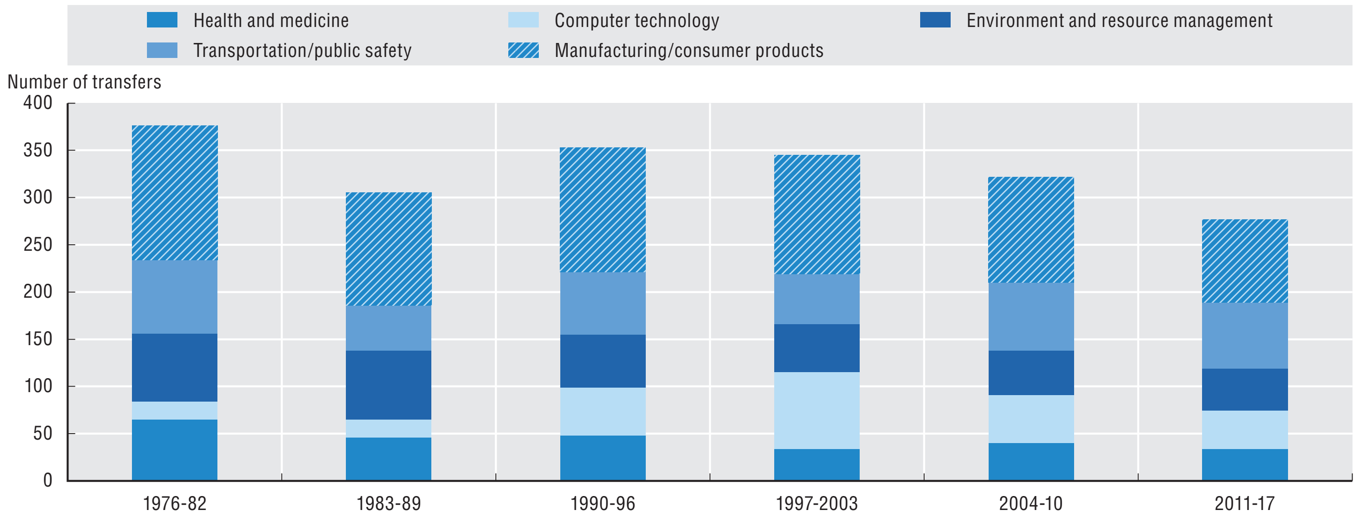
Examples of successful transfers from the space sector

Several examples of technology transfers exist and are recorded, as space organisations are increasingly tracking positive transfer stories. Successful use cases can be found in areas like health, transportation, consumer goods, air quality control and public safety, just to name a few (summarised in Table 2.3). In some cases, technologies are developed within space programmes with the predetermined goal of addressing clear needs in a specific sector. In others, opportunities of application and commercialisation appear later, with unexpected uses arising in different fields. The Space Shuttle programme, for example, is a leading illustration of this second group (see Box 2.3). The programme was able to influence several sectors in different moments during the decades following its first launch. Many of the technologies developed for the Shuttle, and to serve its operationalisation, spurred over the years and impacted a number of areas ranging from health to transportation and consumer goods.

The National Aeronautics and Space Administration (NASA) in the United States has documented nearly 2 000 commercial products and services successfully developed between 1976 and 2018. The majority of them have been recorded in the sectors of manufacturing and consumer products, with an average of 18 products per year over the 41 years analysed by NASA (Figure 2.10). Other relevant socio-economic sectors of application are transportation and public safety (nine per year), environment and resource management (eight), health and medicine (seven), and computer technology (six). As an illustration, a cardiac imaging system developed commercially by the medical industry in 1990, derived from camera technologies on board NASA Earth resources survey satellites. The benefit was, at the time, significantly improved real-time medical imaging, with the ability to employ image enhancement techniques to bring out added details while using a cordless control unit (NASA, 2018[20]).

Some twenty year ago, the European Space Agency mapped the sectors developing the highest number of commercial products based on space technologies. This included software solutions, engineering, energy, medical applications, transports and safety and security (ESA, 1999[21]). An analysis of transfers recorded in the ESA Business Incubation Centres' programme from 1990 to 2006 showed that transfers from both the space sciences and launchers programmes produced the highest number of new commercial products, followed by human spaceflight and telecommunications (Szalai, Detsis and Peeters, 2012[22]). More recent documented ESA applications of space technology transfers to different sectors include, for instance, air purification systems in hospital intensive care wards, radar surveying of tunnel rock to improve the safety of miners, and enhanced materials for a wide variety of products from racing yachts to running shoes (ESA, 2016[23]).

Figure 2.10. NASA technology transfers to different economic sectors



Source: OECD calculations based on NASA spin-offs database (2018).

Overall, there are many recorded examples of space technology transfers to medical applications in different space agencies. Based on ultrasound probes developed during the first French human spaceflights in the early 1980s, innovative echocardiography probes were developed and commercialised by a still very active spin-off firm, with cumulated sales representing around EUR 200 million (CNES, 2014[24]). Recently, the German Aerospace Center's Institute for Robotics and Mechatronics licensed space technologies used on the International Space Station to a large medical equipment company to develop commercial robotic arms for surgery (DLR, 2016[25]).The Italian Space Agency (ASI) has supported several technology transfer projects over the years as well. The Microfluidics and the Mach-Zehnder projects are just two examples where ASI promoted an "earth-space-earth" technology cycle: assets developed in a non-space sector have been initially applied and upgraded in space, to be finally adapted and patented for commercial uses in down-to-earth applications (Verbano and Venturini, 2012[26]).

Table 2.3. Selected examples and applications of space technology transfers

Space programme	Technologies transferred	Applications outside space	Areas of application
NASA investments in life sciences research	Investments in life sciences research and development of related technologies	Development of more efficient medical and research equipment and research activities	Health and medicine
Italian Microfluidics project	Micro-propulsion system to control and regulate a satellite's tilt	Technologies for healthcare and membrane filtration and research activities	Health and medicine
Italian Mach-Zehnder project	Microinterferometer, technology to analyse planetary gases	First: technology for the monitoring of air quality and the presence of atmospheric pollutants Second: technology for monitoring fermentation and various chemical processes in wine production	Environmental monitoring and agriculture and food sectors
Research from the Max Planck Institute for Extra-terrestrial Physics (MPE) on ROSAT X-rays	Mathematical algorithm (SIM) used to analyse data from X-ray satellite ROSAT	Development of a computer-aided early recognition system (MELDOQ) to recognise melanomas through digital image analysis	Health and medicine
ESA work on robot calibration	Creation of a new system, the so-called Rodym, exploiting multiple cameras to measure the movement of infrared LED markers on space robots	Rodym is now part of many car manufacturers` production lines to enhance precision, with significant returns in terms of higher production rates and better quality control	Transports and manufacturing
DLR Institute for Robotics and Mechatronics work on remotely controlled robots for the International Space Station (ISS)	Development of robots remotely controlled from Earth or from the ISS giving the operator the impression of being there (e.g. telepresence)	MIRO is a robot remotely controlled by doctors to perform a surgeon's movements with high precision through numerous sensors via partial or total automation	Health and medicine
ESA's Rosetta mission	Technology used in the Ptolemy Instrument for analysing comets	Development by a UK company of a detector that enables the hospitality industry to reproducibly and accurately monitoring for the presence of bed bug infestations	Hospitality industry

Table 2.3. Selected examples and applications of space technology transfers *(cont.)*

Space programme	Technologies transferred	Applications outside space	Areas of application
CNES human spaceflight	Ultrasound probes tested by universities during the first French human spaceflights	Development of innovative echocardiography probes	Health and medicine
Canadian Space Agency's technology tested on the International Space Station (ISS)	Portable Canadian technology that analysed cells and hormones in blood or other biological samples.	Microflow could be used to perform rapid, real-time testing and analysis anywhere in the country, including areas with limited medical equipment, such as remote communities or those affected by natural disasters	Health and medicine
Carré Technologies of Montreal, Quebec, developed Bio-Monitor for the Canadian Space Agency (CSA)	A new wearable technology has been designed to fit into an astronaut's daily routine aboard the International Space Station (ISS) while monitoring and recording vital signs.	An early version ca improve the performance of sport athletes. The next ones have the potential to help Canadians who are bedridden, housebound, or living in rural communities with limited access to medical support. It can also be worn by workers in dangerous environments such as mines, industrial sites, or factories.	Heath and medicine/Sports

Box 2.3. Examples of technology transfers from the Space Shuttle space programme

Initially conceived for uses only within the space sector, the Space Shuttle has produced many benefits thanks to technologies spurred in the process. At least seven areas have been affected, namely health and medicine, transport, public safety, consumer goods, environmental management, computer technology, and industrial productivity (Lockney, 2010[27]). Some examples include:

- *Transport*: In the 1970s, studies on the Space Shuttle's aerodynamic structure inspired a new design for trucks able to reduce aerodynamic drag and boost efficiency through improved fuel autonomy. In 1994, NASA commissioned the development of a new lubricant for the Space Shuttle, safer for the environment, to Sun Coast Chemicals of Daytona Inc. The company also started an entire line of racing products incorporating environmental benefits. In addition, a Florida-based company collaborated with NASA on the development of a new type of foam to be used in the manufacturing of acoustic and thermal insulation. The result was a new flame retardant, which was licensed and also applied as an insulator for NASA cryogenic propellant tanks.
- *Public safety*: Video surveillance technologies used to improve the quality of the Space Shuttle's launch have been exploited in image stabilisation systems widely used in the law enforcement industry and for military missions. That is the case, for example, of video surveillance, crime scene footage, sting operations and several more specific military applications (Lockney, 2010). In addition, infrared cameras used on the Space Shuttle are now adopted to scan for fires, as well as for night vision, early warning systems, navigation and weather monitoring, among others.
- *Consumer goods and services*: A number of parts and tools used in the Space Shuttle have been integrated by companies to develop new goods and services. Examples range from new insulation materials for homes and clothing; cabin flight simulators for exhibits, museums or other events; simulation devices for exhibits; lubricants for hunting and fishing equipment and many others.

The role of policies

Policy and legal frameworks play a key role in initiating, supporting and boosting transfers from the space sector to other fields. Policy-makers are encouraged to mitigate information asymmetries and ensure legal certainty, by defining clear property rights and legal frameworks; strengthen R&D networks using research grants, matching grants and tax incentives, as well as other available policy instruments; promote the role of technology transfer intermediaries, including innovation centres, incubators and technology parks, by using gap funds and mentoring and networking programmes and supporting start-ups; and make transfers a built-in goal of space programmes by acting on public procurement policies.

Given their strong R&D focus with pre-existing portfolios of technologies, software and patents, facilities and expertise, space agencies are uniquely placed to support technology transfers and commercialisation. Several agencies already have online catalogues of patents available for public or commercial use and propose a range of connected services. One example is the NASA Patent Licensing Programme. NASA's patent portfolio which contains more than 1 200 patents that are available for different types of exclusive and non-exclusive licenses. Start-ups can license a selection of these patents with no initial fees (NASA, 2015[28]). Potential applicants may further have the opportunity to observe a technology demonstration or talk to the inventor at different NASA centres.

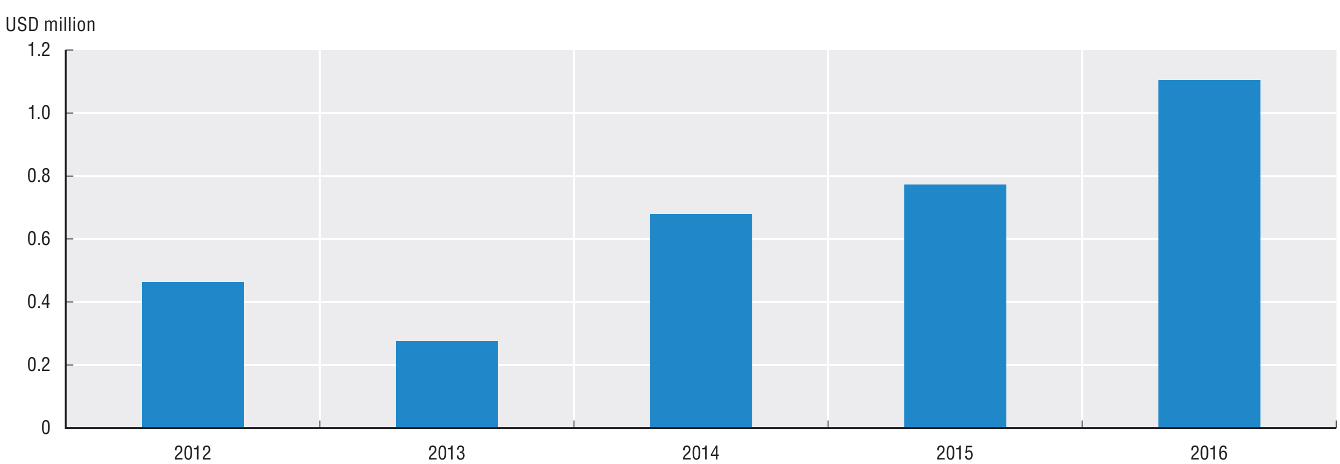
Mentoring programmes providing commercial and technical guidance tend to be a separate, but closely connected activity, which encourages the development of space-related start-ups and strengthens the relationship with private and academic actors. For instance, the technology marketing office of the German Aerospace Centre (DLR) provides substantial support to both in-house and external entrepreneurs who want to commercialise DLR technologies. This includes helping with the business plan, finding suitable financing and granting access to existing DLR infrastructure and equipment. ESA business incubation centres provide similar services. With the STAR Exploration Programme, the Korean Aerospace Research Institute supports around ten entrepreneurial projects every year with USD 35 000 granted per project. After project selection, the agency offers consulting and support for the commercialisation phase, as well as monitoring and help with the follow-up stages (Park, 2017[29]).

As the space sector evolves, so does the role of space agencies and that of their technology transfer offices. There is an ever-growing focus on downstream activities and the transfer of space technologies to different sectors. Space agencies' role in technology commercialisation and marketing has in some cases been upgraded from mere brokers to active "helpers" and market makers. Feasibility studies in Canada for a space business incubation centre emphasise the importance of depending on existing organisations for business and commercialisation support, with the space agency keeping responsibility for technology development (Phan, 2017[30]).

With such a variety of TTC objectives, programmes and institutions, it is essential to continue the efforts to identify, monitor, track and, finally, measure the impacts of the transfers of space technologies and their commercialisation in non-space sectors. This is closely aligned with the need for better economic accountability in the sector as a whole. Several agencies already keep track of patent and licensing activities. NASA has witnessed a 293% annual increase in the number of licences released over the last six years (NASA, 2017[31]). On the same line, DLR registered an increase in revenues from licenses from EUR 2.3 million in 2015 to EUR 6.65 million in 2017 (DLR, 2018[32]). Similarly, the Korean Aerospace Research Centre (KARI) has recorded a notable increase in licensing revenues since 2012, accounting for some USD 1.2 million in 2016 (Figure 2.11). The same year, KARI made 23 licensing contracts (Park, 2017[29]).

Figure 2.11. Increase in Korean Aerospace Research Institute (KARI) patents' licensing revenues

Amounts expressed in current USD



Source: Adapted from Park (2017[29]).

The work done by agencies on technology transfers is starting to bear fruit with more returns expected in the coming years. The OECD Space Forum will continue to work with space agencies and technology transfer offices to track developments in space TTC in order to better measure the impacts of space investments on societies and the economy.

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Chapter 3

REMEDYING THE GENDER GAP IN A DYNAMIC SPACE SECTOR

This chapter provides a brief overview of employment in the space sector. It also presents one of the first exercises at the international level to produce indicators to evaluate the space sector from a gender perspective. It provides exploratory indicators on government space agencies, higher education institutions and the private sector as well as female tertiary education enrolment and graduation statistics in space-related fields.

The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

State of employment in the space sector

The space sector is home to highly skilled professionals around the world, mainly technicians, scientists and engineers, with other ancillary professions ever more represented (e.g. business, legal). The gender gap that has been strong in the sector for decades may be narrowing, pushed by corporate actions, but also by the prospects offered by new generations of trained professionals coming into the market. In order to track, compare and evaluate different initiatives, gender participation in the space sector needs to be thoroughly mapped.

The global space sector employed around 1 million persons around the world in 2017. To give orders of magnitude, around 350 000 full-time employees are active in the United States, 200 000 in the Russian Federation and around 60 000 in Europe. These are only estimates, as detailed official statistics are not available for every country.

Space-related employment includes jobs in public administrations with responsibilities for managing space activities and publicly funded research and development programmes (space agencies, space departments in civil and defence-related organisations), the core space manufacturing industry (building rockets, satellites, ground systems), direct suppliers to this industry and the wider space services sector (mainly commercial satellite telecommunications). Not included in this estimate are other major actors that play a direct or indirect role in space programmes, such as universities or military personnel.

Space manufacturing employment has been stable or increasing in most OECD countries over the last ten years (Figure 3.1). Workers tend to be highly qualified. For instance, in Japan almost 50% of the space manufacturing workforce are engaged in R&D activities (SJAC, 2018[1]). In Europe, some 34% of the workforce have university degrees (Eurospace, 2018[2])

The sector is currently undergoing significant reorganisation in different parts of the world. Chinese and Russian government agencies are seeking to consolidate their state-owned enterprises and optimise production and processes (People's Republic of China State Council, 2016[3]; Roscosmos, 2017[4]) while companies in the OECD area are restructuring their space business after multiple mergers and putting in place vertical integration of their activities. Important investments are also being made in new digitalised facilities with less need for manpower.

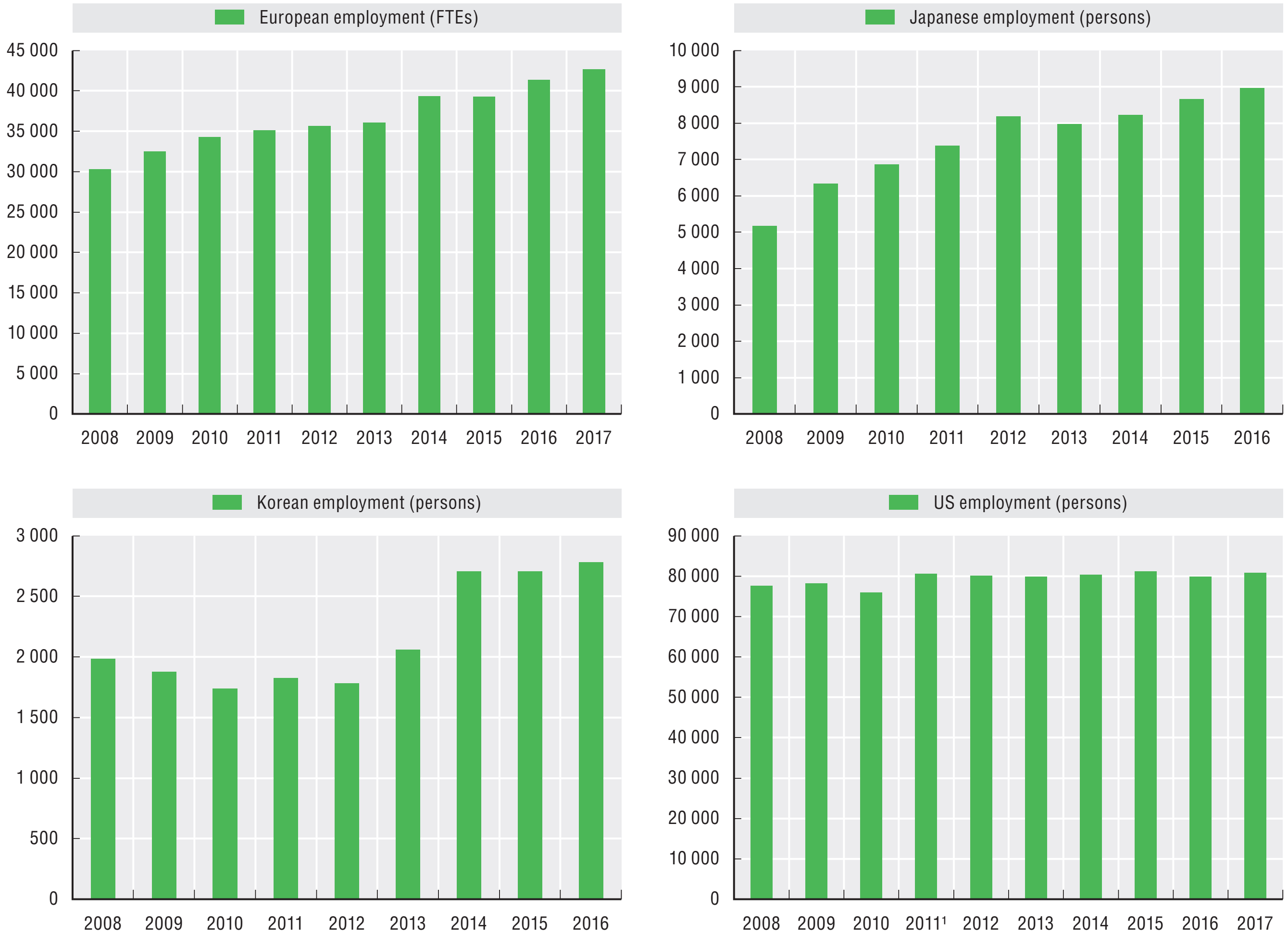
Figure 3.1 shows how space manufacturing employment has evolved in selected countries and regions with space activities in the last ten years. In Europe, space manufacturing employment has grown continuously over the period, reaching almost 43 000 full-time equivalents in 2017 (Eurospace, 2018[2]). In North America, US employment levels have remained stable over the period, with 80 000 people employed in space manufacturing in 2017, whereas the Canadian upstream sector employed almost 5 000 people in 2017 (AIA, 2018[5]; Canadian Space Agency, 2019[6]). In Asia, some 9 000 employees work in space manufacturing in Japan and almost 3 000 in Korea, for both countries a considerable increase since 2008 (SJAC, 2018[1]; KARI, 2017[7]). In the People's Republic of China (hereafter "China"), one of the countries with the largest space programme in the world, data on employment are not easily accessible. According to the Chinese National Bureau of Statistics, some 26 000 people are employed in Chinese space manufacturing in 2016 in state-owned enterprises (Chinese National Bureau of Statistics, 2017[8]). This represents a small change compared to 2008, and probably a much under-evaluated estimate, when considering the number of organisations involved in the extensive Chinese space programme.

Employment in the space sector is affected by different trends, some specific to national situations, others more general in the context of changing demographics and a growing digitalisation of the economy:

- Like for most sectors, the number of baby boomers retiring in many large OECD countries and partner economies is creating a slow generation change. This does not automatically translate into a younger workforce in space agencies or companies, but the middle management is currently changing in many organisations around the world, opening up opportunities for younger staff in some cases.
- In parallel, many emerging economies have launched space programmes, drawing in experienced experts, some often having worked abroad, but also younger qualified staff, educated onsite, and/or in large aerospace engineering and scientific universities. For example, the Mohammed Bin Rashid Space Centre in the United Arab Emirates, established in 2005, employs today some 200 people, with an average age of 28. Some 40% of its engineers and scientists are women.

Figure 3.1. Space manufacturing employment in selected OECD countries

2008-17, or latest available year



1. The US Aerospace Industries Association has changed their methodology for data from 2011 onwards.

2. Data on space-related human capital are very fragmented. Official employment statistics on the sector are often poor, lacking in both quality and detail. To some extent, the gaps can be filled by micro-data coming mainly from industry associations' surveys, which usually focus on the space manufacturing industry, while the larger services sector is not included.

- The next production revolution and digitalisation trends will have effects on employment that are yet to be fully captured in the different value chains of the space sector. While it is too early to see any general effects on space manufacturing employment, growing automation may affect future job creation. The announced number of manufacturing jobs created by some of the most recent entrants in the space sector is at this stage quite low (e.g. 200-300 jobs per facility for OneWeb). Other large industry players are adapting their digitalisation strategies all along the different value chains, to improve their processes and reduce costs in a highly competitive international environment. The impacts of automation on employment is currently leading to more research.
- The gender gap, or the under-representation of women in science and engineering occupations and management positions in public and private space organisations and companies, and the persistently low percentage of girls and women pursuing studies in space-related fields of education, has been evident for decades, as in other high-technology fields. Overall, women are still under-represented in all segments of the space sector, from government sector administration and research to private sector manufacturing and services provision, irrespective of fields. There are some differences between the public and private sector, as well as variations across industrial segments. The following sections will study this in more detail, looking at employment in government space organisations, in higher education institutions and the private sector.

Employment in government and higher education organisations

This section focusses on the employment of women in government organisations and higher education organisations in the space sector. The past decade or so has seen some positive changes occurring in many countries.

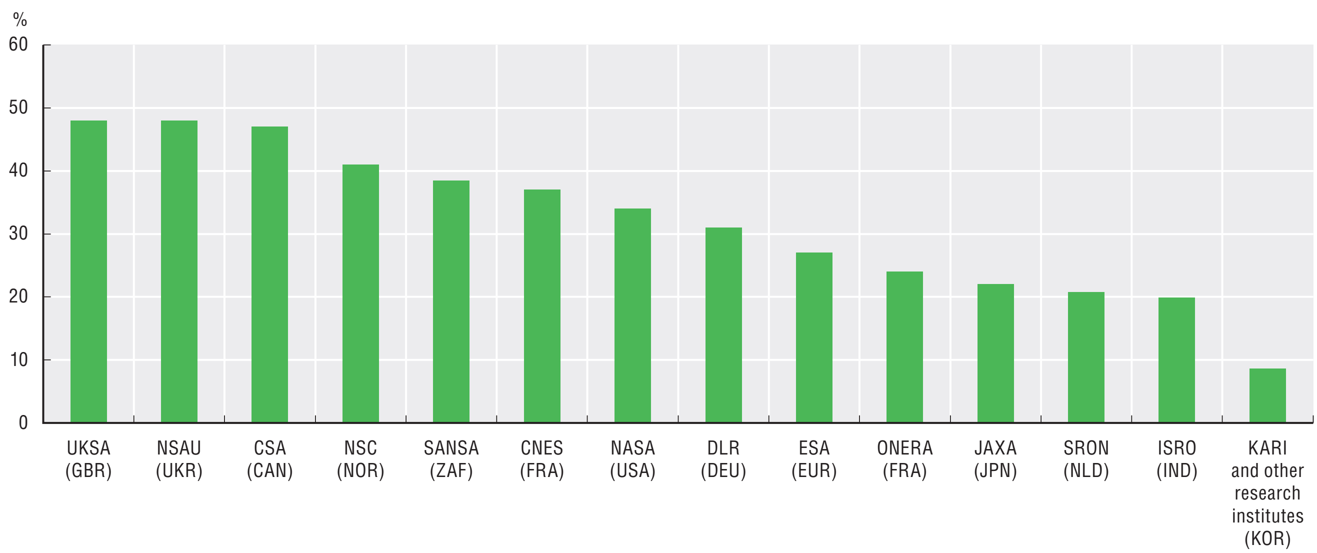
Female employment in government organisations

Female employment rates in government space organisations vary quite significantly according to the work areas of public administrations and across countries. Female employment rates tend to be higher in agencies with a more administrative and project management role, such as the UK Space Agency or the Norwegian Space Centre (NSC) and lower in agencies with large research and manufacturing activities, such as the French Centre national d'études spatiales (CNES) or the National Aeronautics and Space Administration (NASA).

One exception is the National Space Agency in Ukraine, which maintains a high share of women employees (48%) despite including in its statistics not only the agency staff, but also the dependent state-owned manufacturing enterprises, totalling almost 2 000 persons (State Space Agency of Ukraine, 2016[9]). Figure 3.2 gives an overview of the share of female employment in a selection of space agencies and space-related research organisations.

Figure 3.2. Share of female employment in selected space agencies and research organisations

2017 or most recent year



Note. Data refer to 2014 for CNES. DLR, KARI and ONERA include other research areas than space.

Across all organisations with available data, the share of women in non-administrative or non-clerical occupations, i.e. mostly science and engineering occupations, is significantly lower than the share of total employment. For instance, at the German Aerospace Center (DLR), women account for 32% of total employment and 20% of the "scientific" staff (DLR, 2018[10]). Similarly, while in 2014 women at the CNES accounted for 37% of total staff, 26% of the engineers were women (CNES, 2015[11]). Equally, at NASA, women currently account for some 34% of total employment and 23% of "science and engineering" occupations (NASA, 2018[12]). In some cases, this gap is much smaller. At the South African Space Agency (SANSA), women account for 39% of employment and 37% of engineering and scientist/researcher staff (SANSA, 2018[13]). Table 3.1 summarises some of these findings.

Table 3.1. Share of female employment in different types of occupations, selected space organisations

Latest available year

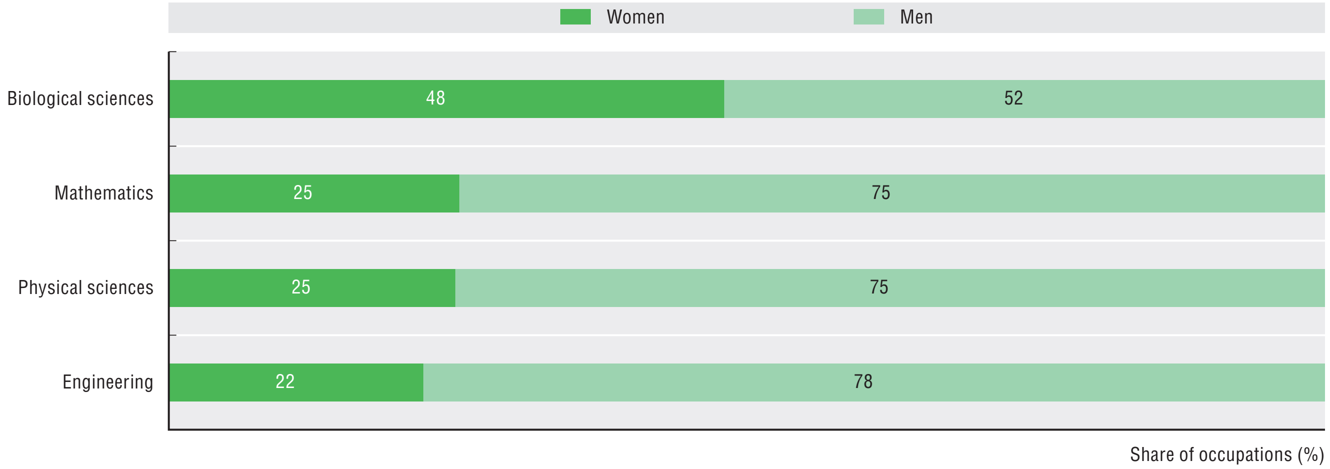
	CSA, CAN (2017)	SANSA, ZAF (2017)	CNES, FRA (2014)	NASA, USA (2017)	DLR, DEU (2017)	ESA (2016)	JAXA, JPN (2015)	ISRO, IND (2017)
Share of total staff	47%	39%	37%	34%	32%	26%	22%	20%
Share of "non-administrative and/ or non-clerical staff"[1]	23% (scientific and professional positions)	37% (engineers and scientists/ researchers)	26% (engineers)	23% (science and engineering occupations)	20% (scientific staff)	21% (executive staff, translators and "off-scale", e.g. directors, staff)	12% (researchers)	16% (science and technology occupations)

Note. 1. This category typically refers to women in science and engineering occupations, but definitions and data availability vary across organisations.

There are also significant differences in women's participation within the science and engineering employment category. At NASA, women account for almost half (48%) of staff in biological sciences, but only 22-25% of the occupations in engineering, physical sciences and mathematics (NASA, 2018[12]), as is shown in Figure 3.3.

Figure 3.3. Occupations in selected science and engineering fields at NASA, by gender

Office of Personnel Management occupational classifications, January 2018



Source: NASA (2018[12]), "Workforce Profile Cube", *Workforce Information Cubes for NASA*, *https://wicn.nssc.nasa.gov/wicn_cubes.html*.

Women also generally hold a lower share of management positions than men in government space organisations. At DLR, women occupy 19% of management positions (DLR, 2018[10]), while at the Canadian Space Agency, this share is 33%. At the European Space Agency (ESA), only 9 % of the top management are women, or some 25 out of 295 positions including division heads and above, the same share as in 2011 (ESA, 2017[14]).

Box 3.1. Women and spaceflight

Human spaceflight, the most emblematic and mediatised of all space activities, is heavily male-dominated. By the end of 2017, 560 people (depending on the definition of spaceflight, see note below Figure 3.4), including 60 women, have flown to space as test pilots, astronauts, cosmonauts, taikonauts (i.e. Chinese astronauts), payload specialists or tourists (WorldSpaceFlight, 2018[15]). This includes 46 women from the United States; four from the Russian Federation/USSR; two each from Canada, China and Japan; and one each from France, Italy, Korea and the United Kingdom, as presented in Figure 3.4. The first woman in space was the USSR cosmonaut Valentina Tereshkova in 1963.

While the United States has sent the greatest number of women into space, this still accounts for only 13% of the total number of US astronauts in orbit, whereas the proportion of women for the Russian Federation/USSR is 3%. Several countries (Canada, China, Italy, Japan, Korea and the

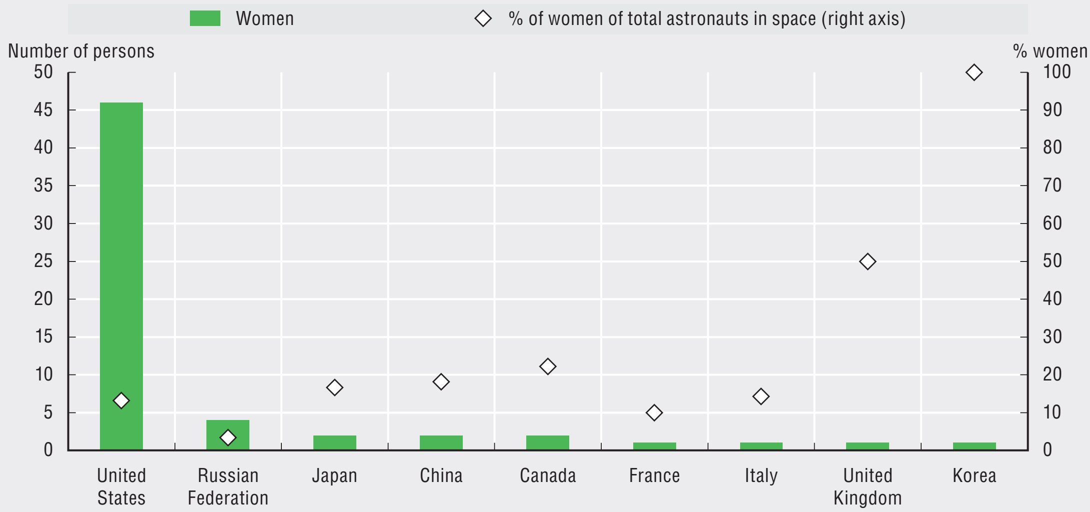
Box 3.1. Women and spaceflight *(cont.)*

United Kingdom) have a higher proportion of women. Both Korea and the United Kingdom sent a woman as their first citizen into space (Yi So-yeon, flying on Soyuz mission TMA-11 in 2008, and Helen Sharman, travelling to the Mir space station in 1991).

The number of women space travellers has increased steadily over the last decades. The two last NASA astronaut candidate classes in 2013 and 2017 had a 50-50 gender distribution (NASA, 2017[16]).

Figure 3.4. Women in space

Number and share of women astronauts by country, as of April 2018



Note: This list includes persons who have crossed the von Karman line at 100 kilometres altitude.

Source: Adapted from WorldSpaceFlight (2018[15]), *Astronaut/Cosmonaut Statistics*, *https://www.worldspaceflight.com/bios/stats1.php*.

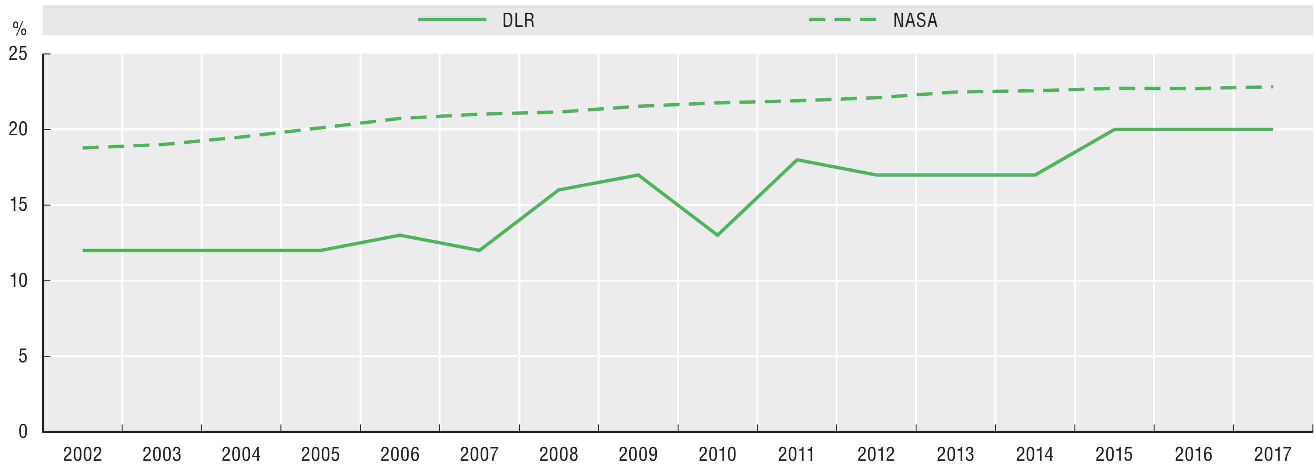
Most of the organisations studied in this section have seen an increase in the share of female employment in the last decade and, where data are available, in the share of women science and engineering staff. At NASA, the share of women in science and engineering occupations increased by four percentage points, from 19% to 23%, between 2002 and 2018, but growth was faster at the beginning of the period (NASA, 2017[17]). Meanwhile, the share of women working as scientists at the DLR increased from 12% to 20% during the same period (DLR, 2018[10]), as illustrated in Figure 3.5.

Employment of women in higher education institutions in space-related fields

This section looks at women employed in higher education institutions engaged in teaching, holding an academic rank, and/or engaged in R&D activities as researchers or technicians in space-related fields of education, such as aerospace engineering, geosciences or astronomy. Country examples are included from France, Korea and the United States, which are some of the few countries with readily available data on this topic.

As already observed in the previous section on government space organisations, women are under-represented among the academic staff and researchers, but with great variation across disciplines and countries. In Korea, higher education institutions and individual university departments report employment and gender data in the annual Korean *Space Industry Survey*. The institutions are divided into two categories: “space” (e.g. aerospace engineering and IT systems, astronomy and space sciences) and “space-related” (departments of physics, mechanical engineering, electric engineering, etc.) In 2016, women in the “space” institutions and departments accounted for some 9% of the academic staff in the reporting institutions (KARI, 2017[7]). Only 6 out of 127 professors (5%) were women, but the share among postdoctoral fellows was much higher (37%, 7 out of 19), which could indicate future higher female participation in the sector.

Figure 3.5. Share of women in science and engineering fields at DLR and NASA

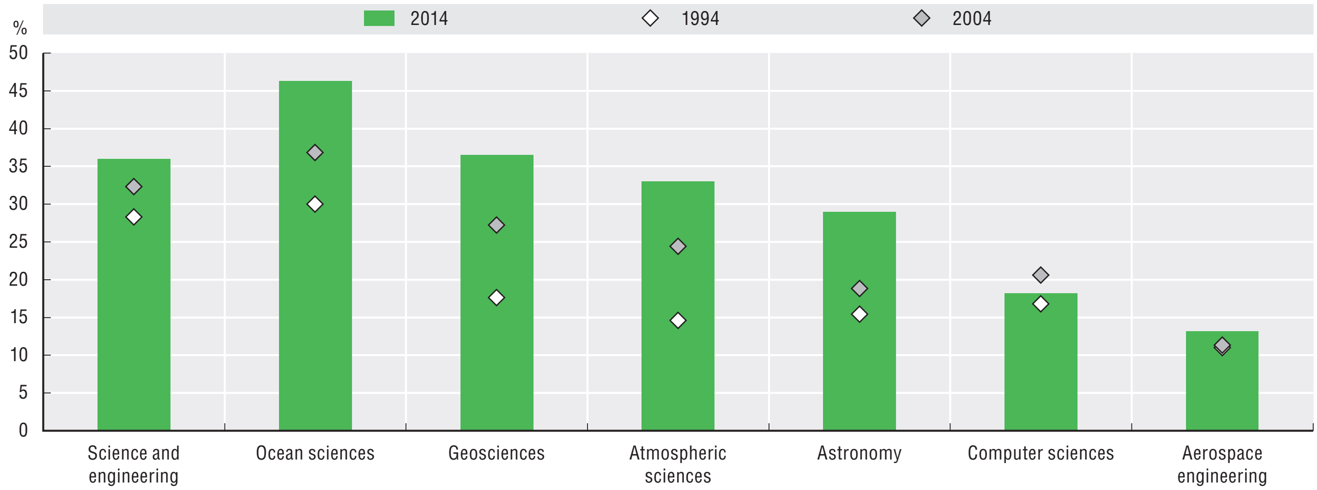


Note: DLR's and NASA's occupation categories are not directly comparable. DLR's activities also include other research areas than space.

In France, space-related academic research is carried out both at universities and engineering schools. One of the most important research actors is the CNRS (National Centre for Scientific Research), whose Institute for Earth Sciences and Astronomy (Institut national des sciences de l'univers, INSU) employs more than 2 000 people at different universities and laboratories across France (CNRS, 2018[18]). In 2016, women accounted for 34% of INSU's permanent research personnel, 29.6% of researchers (*chercheuses*) and 37% of technicians (*ingénieures* and *techniciennes*) (CNRS, 2018[18]). This is a small improvement compared with 2009 (the earliest comparable year following a reorganisation of the CNRS institutes), with women accounting for almost 33% of the research staff, 27.5% of researchers and 36% of technicians (CNRS, 2010[19]).

The United States has highly granular data on specific fields of education and several decades of time series on the share of women in postdoctoral fellowships in academic institutions. Figure 3.6 shows how several space-related fields of education are increasingly populated by women scientists. In 2014, women accounted for more than a third of postdoctoral fellows in ocean sciences (46%), geosciences (37%) and atmospheric sciences (33%), a significant growth since 1994. In contrast, women accounted for only 13% of fellows in aerospace engineering in 2014, a 2 percentage point increase since 1994, and 17% in computer sciences, the same share as in 1994 and a decrease compared with 2004 (US National Science Foundation, 2017[20]).

Figure 3.6. Female share of postdoctoral fellowships by field, United States



Source: US National Science Foundation (2017[20]) *Women, Minorities, and Persons with Disabilities in Science and Engineering: 2017, http://www.nsf.gov/statistics/wmpd/* and equivalent reports for previous years.

Gender diversity in the space industry

In the private sector, gender disparity levels vary significantly across different space industry segments. There is a big gender gap in space manufacturing, whereas downstream applications and services tend to have a higher share of women employees.

Available data for selected OECD countries show that female employment in space (and/or aerospace) manufacturing hovers around 20% in Europe and the United States, with a lower rate of employment in science and engineering occupations (e.g. science and engineering professionals and technicians). Meanwhile, in the Russian Federation, the female employment rate in the space manufacturing sector ("rocket and space industry") in 2016 was 46% (Roscosmos, 2017[4]). Similarly, as already noted above, 48% women were employed in the space sector in Ukraine in 2016, including government-owned enterprises and the space agency, (State Space Agency of Ukraine, 2016[9]).

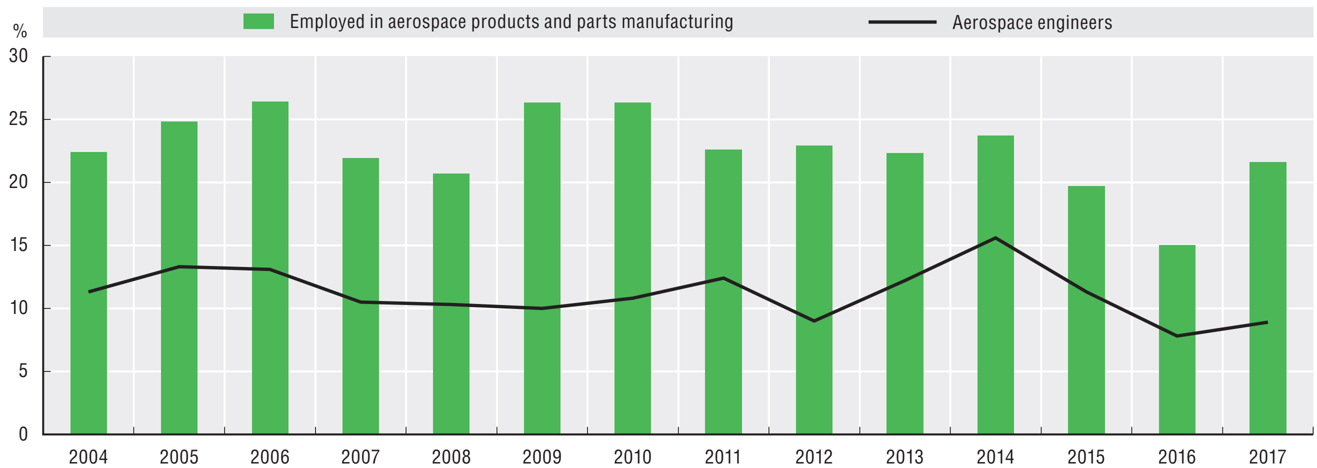
The latest data for Europe for 2016 show that women accounted for 21% of employment in space manufacturing, and 15% of highly educated staff (four to five years and more of tertiary education (Eurospace, 2017[21]). There has been little or no evolution since 2012 (Eurospace, 2013[22]).

Aerospace workforce statistics in North America show similar findings. Figure 3.7 shows that in 2017 women accounted for 22% of the aerospace manufacturing workforce (data not available for space manufacturing), while women's share of the total number of aerospace engineers was much lower, at 9% (US Bureau of Labor Statistics, 2018[23]; US Bureau of Labor Statistics, 2017[24]). Women's share of employment in US aerospace manufacturing has evolved very little since the early 2000s. The share of women aerospace engineers has also remained stable, although slightly declining in the last years (US Bureau of Labor Statistics, 2017[24]). As an illustration, at Space Exploration Technologies (SpaceX), the female employment rate is 14%, according to a Silicon Valley compensation survey (PayScale, 2018[25]).

In Canada, women accounted for about 20% of the workforce in aerospace manufacturing and 12% of aerospace engineers in 2016 (Statistics Canada, 2018[26]).

Figure 3.7. Female employment rates in US aerospace manufacturing

Share of total employment



Sources: US Bureau of Labor Statistics (2018[23]), "Employed persons by detailed industry, sex, race, and Hispanic or Latino ethnicity", *Labor Force Statistics from the Current Population Survey*, *https://www.bls.gov/cps/cpsaat18.htm, US Bureau of Labour Statistics* (2017[24]), "Women in the labor force: A databook", Bureau of Labor Statistics, *https://www.bls.gov/opub/reports/womens-databook/2017/home.htm*.

In the services and geosciences-oriented downstream segments, female participation tends to be higher. In Korea, women's share of employment is higher in downstream industries than in space manufacturing. Women accounted for 20% of employment in earth observation and 16% in both telecom and satellite navigation in 2016, compared to 5% in satellite production (KARI, 2017[7]). Recent data from the European earth observation sector indicate that some 33% of employees are women (EARSC, 2017[27]).

It should be noted that the growing importance of information and communication technologies (ICT) for data processing and analysis may negatively impact female employment in this segment, as ICT remains a male-dominated field in the OECD. For example, in 2015 women accounted for 19-20% of tertiary ICT graduates in the OECD (median and average values) (OECD, 2017[28]).

Preparing the next space workforce

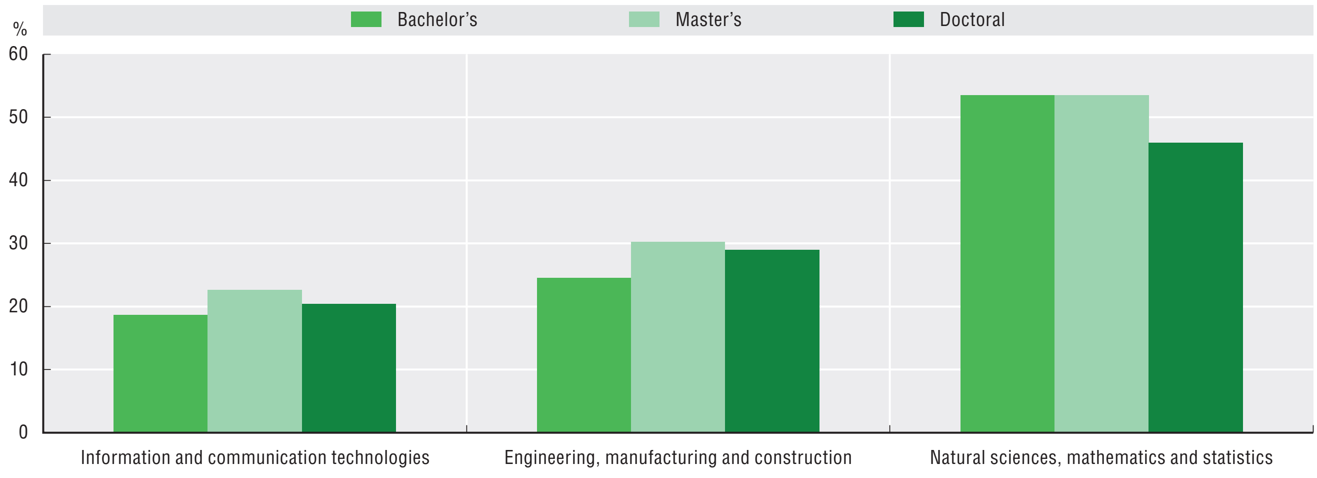
This section looks at female tertiary education enrolment and graduation statistics in space-related fields of education such as aerospace engineering, earth sciences and astronomy. Tertiary education data are key to understanding and predicting short- and medium-term employment trends and to evaluating the effect of school and university-level policy initiatives to address the space sector gender gap.

Before looking specifically at space-relevant fields of education, it is useful to get a general overview of the distribution of women graduates in some of the broader science and technology fields that are of relevance in the OECD.

Figure 3.8 shows the OECD average for the distribution of women tertiary graduates in ICT; engineering, manufacturing and construction; and natural sciences, mathematics and statistics in 2015, and how this share evolves according to the levels of education. In natural sciences, mathematics and statistics, women accounted for more than 50% of bachelor's and master's graduates, and 46% of doctoral graduates (OECD, 2017[28]). In ICT, women accounted for 19% of bachelor's, 23% of master's and 20% of doctoral graduates. In engineering, manufacturing and construction, women accounted for 25% of bachelor's, 30% of master's and 29% of doctoral graduates (OECD, 2017[28]). While the share of women is considerably lower in engineering and ICT than in natural sciences, the share remains stable when moving higher up the educational ladder, i.e. master's and, in particular, doctoral graduates.

Figure 3.8. OECD average distribution of women graduates in selected fields of tertiary education, 2015

Share of women graduates in bachelor's, master's and doctoral or equivalent degrees (ISCED 2011 Levels 6, 7 and 8)



Note: OECD averages calculated without data from Greece. No data for Japan in information and communication technologies. No data for the Netherlands for doctoral graduates.

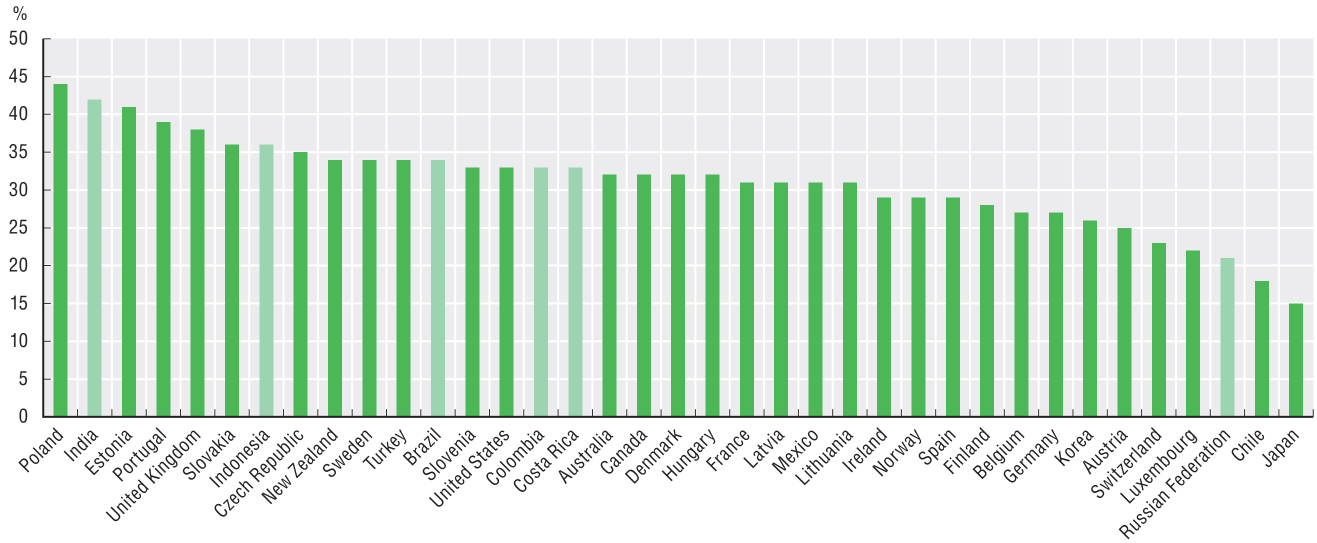
Source: OECD (2017[28]), *Education at a Glance 2017: OECD Indicators*, *http://dx.doi.org/10.1787/eag-2017-en*.

These averages hide considerable country differences. Figure 3.9 shows the distribution of women graduates in science, technology, engineering and mathematics (STEM) in 2015 for OECD countries and selected partner economies for total tertiary education (bachelor's, master's and doctoral graduates). In three countries (Poland, India and Estonia) women accounted for more than 40% of STEM graduates, while in two countries (Chile and Japan), they accounted for less than 20% of STEM graduates (OECD, 2017[28]).

Examples from Korea and the United States provide some country insights about the number and share of women entrants and graduates in space-related tertiary fields of education.

Figure 3.9. Distribution of women graduates in science, technology, engineering and mathematics, OECD countries and selected partner economies

Share of women tertiary graduates in 2015, total tertiary education (ISCED 2011 Levels 5-8)



Note: OECD averages calculated without data from Greece, Israel, Italy and the Netherlands. No data for Japan in information and communication technologies.

Source: OECD (2017[28]), *Education at a Glance 2017: OECD Indicators*, *http://dx.doi.org/10.1787/eag-2017-en*.

In Korea, data from the national *Space Industry Survey* record the number of enrolled male and female students in "space" fields of education, mainly aerospace engineering and space science and "space-related" fields in participating institutions (KARI, 2017[7]). In 2016, women accounted for 17% of both doctoral and master's students in "space" fields of education in Korea (KARI, 2017[7]). Graduation data from the United States equally show relatively low female participation rates in aerospace engineering and astronomy, but there are some interesting long-term trends (Figure 3.10). On the one hand, the share of women doctoral graduates increased in all the studied space-relevant education fields in the two decades between 1994 and 2014, indeed, in aerospace engineering, the share of women doctoral graduates tripled, from 5% to 16% (US National Science Foundation, 2017[20]). In ocean sciences, there is now a majority of women among both master's and doctoral graduates.

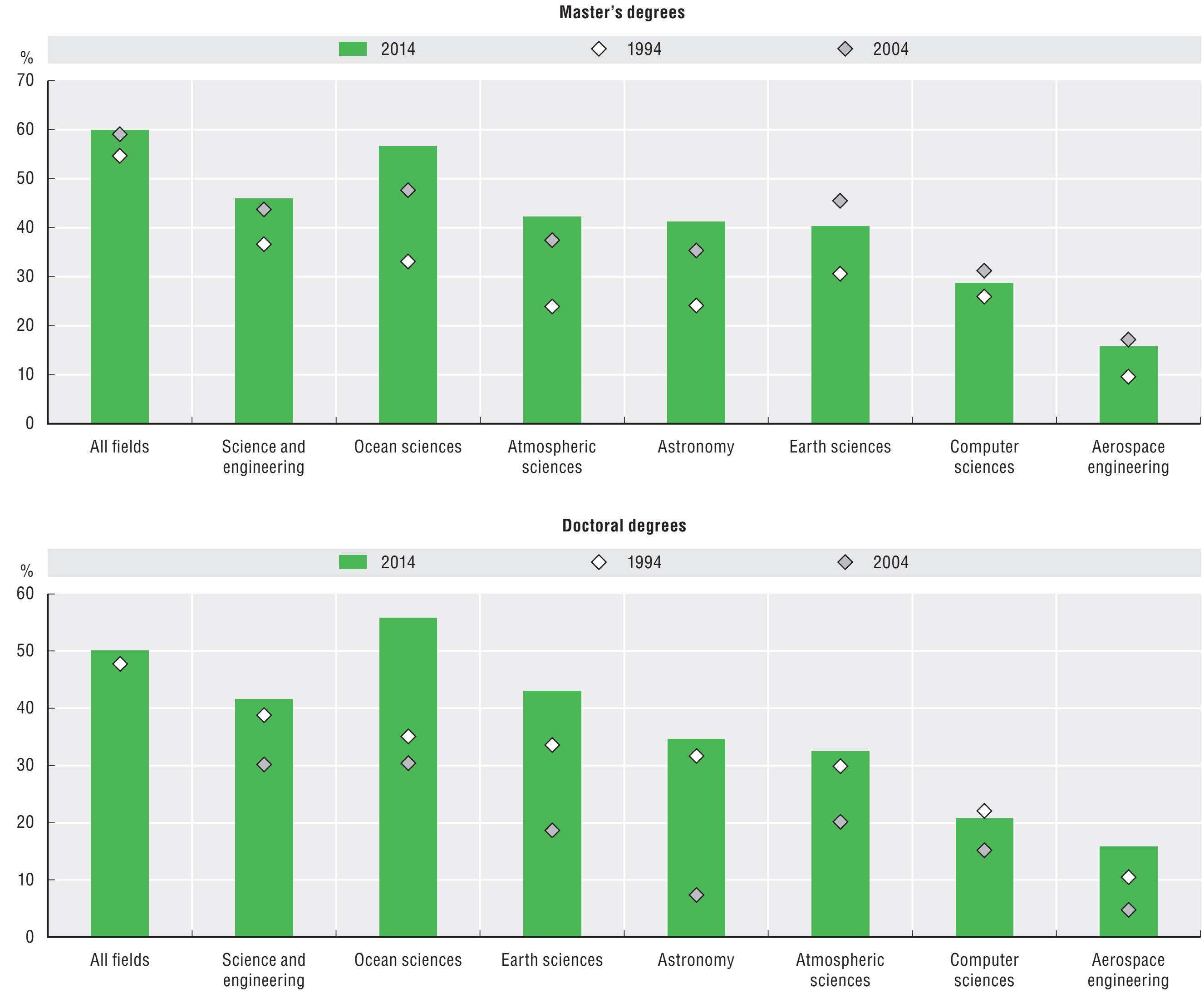
On the other hand, the rapid growth in the share of women master's graduates in aerospace engineering between 1994 and 2004 has flattened in the last decade and accounted for 16% of all graduates in 2014, well below the average for science and engineering as a whole. In computer sciences, women accounted for 29% of master's graduates and 21% of doctoral graduates in 2014, a small decrease compared with 2004, and only a small increase compared with 1994 (26% and 19%, respectively) (US National Science Foundation, 2017[20]).

Reducing the gender gap in the space sector is increasingly seen as an opportunity to bring in new talents and innovators. It has been a priority at government, agency and company level for more than a decade, with long-established diversity policies and equal opportunity offices in several space agencies (e.g. NASA Diversity and Equal Opportunities Strategic Implementation Plan (NASA, 2016[29]), the 2002 ESA Equal Opportunities and Diversity Policy (ESA, 2005[30]). In the private sector, companies such as Airbus, Thales and Safran are increasingly proactive and have set recruitment targets for women for the next five years (33% of new recruits at Airbus and 40% of all new recruitments and 30% of managers by 2023) (Dubertrand, 2017[31]).

This issue is also receiving increasing high-level political attention. In 2017, UNOOSA and UN Women arranged Space for Women, a three-day expert workshop, in connection with the UN COPUOS thematic priority "capacity-building for the 21th century" for the implementation of UNISPACE +50. The main topics of discussion were STEM education and gender, women's involvement in the space sector, with a particular focus on developing countries, and the role of space technologies in fulfilling the Sustainable Development Goal on gender equality (UNOOSA, 2017[32]).

Figure 3.10. Women graduates in space-related fields of education, United States

Share of master's and doctoral degrees awarded to women



Source: US National Science Foundation (2017[20]) *Women, Minorities, and Persons with Disabilities in Science and Engineering: 2017*, *http://www.nsf.gov/statistics/wmpd/* and equivalent reports from previous years.

Public and private space organisations tend to concentrate their efforts in the following broad areas of action, separately, or in accordance with existing government frameworks on gender equality and STEM education.

- Increase awareness and engage decision-makers at a high political level (conferences, workshops)
- Address gender bias at an early age and inspire girls in primary and secondary education (e.g. present role models and stimulate interest; educate teachers)
- Attract women to space-related higher education (e.g. make available dedicated scholarships and grants; provide guidance and mentoring)
- Promote gender equality in a professional setting (e.g. recruitment objectives at entry level and for management positions; prevent gender bias; mentoring schemes and networks; work-life balance schemes)
- Promote gender equality in entrepreneurship and innovation activities.

Selected initiatives are summarised in Table 3.2.

Table 3.2. Selected policy instruments and organisations promoting gender equality

Policy objective/audience	Initiatives	Selected activities and organisations
Increase awareness and engage decision-makers at a high political level	High-level conferences and workshops	Space For Women (UNOOSA/UN Women); 3G IDEA (International Astronautical Federation)
	Gender and diversity awards	Diversity Excellence Award (International Astronautical Federation)
Address gender bias early and inspire girls in primary and secondary education	Female role models in school visits, printed and online material	Gender mainstreaming in communications materials and publications (NASA); *Space Girls Space Women* photo exhibition and website (ESA); #ENSEMBLE photo exhibition (Airbus); Women@NASA website (NASA); NASA/Lego NASA women figurines, NASA/American Girl astronaut doll
	Teacher training	BEST (Beginning Engineering Science Technology Educators) with emphasis on underserved / underrepresented student populations (NASA); European Space Education Resource Office (ESA)
	Facility tours	Speed networking events between local school girls and women engineers (Thales UK); ELLES du FUTUR (Airbus and Toulouse school district); Girls Day (DLR), visits to Le Bourget with mentors (Elles bougent)
	Partnerships with youth organisations	NASA and Boys and Girls Clubs of America Partnerships; NASA/Girl Scouts Partnerships
	Girl camps	Summer Institute in Science, Technology, Engineering and Research (SISTER) (NASA Goddard)
	Social media content for girls	NASA Hidden Figures Tour on Google Expeditions app (NASA); NASA Boys and Girls (virtual mentoring through Skype or Google chat by NASA employees); Aspire2Inspire (career information website, NASA)
Attract women to space-related higher education	Scholarships	Scholarships (Women in Aerospace Foundation); Amelia Earhart fellowships for women aerospace doctoral degrees (Zonta International Foundation)
	Mentorships, networks	Brooke Owens Fellowship; career mentor directory for aeronatics and space (Elles bougent), Women in Aerospace
	Dedicated internships	Integrated Recruiting Internships (NASA); diversity objectives for scholarships (NASA); Brooke Owens Fellowship
Promote gender equality in a professional setting	Addressing gender bias in managers and employees	Gender bias training sessions (NASA; JAXA ; etc.) Increasing female participation on interview panels (ESA)
	Recruitment and career progression policies	Career mentoring schemes (JAXA, NASA, DLR) career re-entry schemes (JAXA, DLR)
	Work-life balance schemes	Child care facilities (DLR, ESA, JAXA, NASA) Child care and long-term care leave (JAXA, DLR, ESA) Teleworking (JAXA, DLR, NASA) Flexitime (JAXA, DLR, NASA) Career re-entry procedures (JAXA, DLR)
	Professional networks	Women in Aerospace, Elles bougent
Promote gender equality in entrepreneurship and innovation	Research funding targets	JAXA (double the competitive research funding obtained by women researchers)
	Scientific output targets	JAXA (increase the number of submitted articles and patents by 1.5 times)
	Public procurement policies	Special attention given to women-owned small businesses in the procurement of R&D and other products/services (US federal agency procurement policy, including NASA)

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Chapter 4

DIGITAL (R)EVOLUTION IN MANUFACTURING AND IN THE PRODUCTION OF SPACE SYSTEMS

This chapter examines how digitalisation is affecting the space sector, with a focus on key developments in manufacturing and production in space systems, particularly satellites and space launchers. The chapter reviews some of the new production processes and changes in supply chains; it also introduces current developments in the space launcher and satellite markets particularly the rise of small satellites; and examines possible emerging activities (space tourism, in-orbit servicing, space mining and resources extraction).

The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

Introduction

As demonstrated by the large-scale OECD Going Digital project, all sectors of the economy are starting to be impacted by digital technologies and data flows (OECD, 2019[1]). Not only is digitalisation accelerating research and innovation cycles, but it also allows more open and collaborative innovation, while in many cases radically changing competition dynamics and business models (OECD, 2019[2]). In this context, it is not surprising that the space sector is entering a new paradigm, mainly driven by digitalisation. The impacts of the digital revolution in space manufacturing and in the production of space systems are still hard to measure, although they will probably have strong implications in the next five years on both the structure of space industry itself and on several policy-making aspects, related to space activities' research and development funding and regulations.

These rather sudden changes in the space sector are taking place against the backdrop of broader evolutions in science, technology and innovation, largely driven themselves by digitalisation (OECD, 2018[3]). The development of the space sector follows five distinct cycles, each lasting some 10-15 years and illustrating the evolutions of space technology and applications and their uptake in society (Table 4.1).

Table 4.1. Cycles of space development

Cycles	Dates	Description
Pre-space age "-1"	1926-1942	First rockets (from Goddard to the V2)
Pre-space age "0"	1943-1957	Military race for intercontinental ballistic missiles, first satellite on orbit (i.e. Sputnik)
Cycle 1	1958-1972	Space race (from Sputnik to the end of the Apollo era), beginning of military applications (e.g. spy satellites), first humans in space, robotic space exploration
Cycle 2	1973-1986	First space stations (Skylab, Salyut) and shuttles (US space shuttle, Buran), further development of military applications (GPS, Glonass), beginning of civilian and commercial applications (earth observation, telecommunications), emergence of new actors (Europe, Japan, China)
Cycle 3	1987-2002	Second generation of space stations (Mir, ISS), stronger role of space applications in militaries, further development of civilian and commercial applications (Landsat, Spot Image, satellite television), with more actors entering markets, and many space technology transfers at the end of cold war
Cycle 4	2003-2018	Ubiquitous use of space applications in various fields thanks to digitalisation (strong rise of downstream activities), new generation of space systems (small satellites) prompted by integration of breakthroughs in micro-electronics, computers, and material sciences, globalisation of space activities (large and very small national space programmes coexist, development of global value chains)
Cycle 5	2018-2033	Growing uses of satellite infrastructure outputs (signals, data) in mass-market products and possibly for global monitoring of treaties (land, ocean, climate), third generation of space stations, extensive mapping of solar system and beyond thanks to new telescopes and robotic missions, new space activities coming of age (e.g. new human-rated space launchers, in-orbit servicing)

Source: Adapted from OECD (2016[4]), *Space and Innovation, https://dx.doi.org/10.1787/9789264264014-en.*

The first two cycles of space development, during the 1960s and 1970s, were heavily dominated by public-oriented missions, with an emphasis first on defence projects followed by space exploration missions (e.g. Apollo programme), and civilian applications. The third cycle, from the 1980s onwards, saw the development of the first commercial space applications, in particular in telecommunications, with large satellite operators being privatised. From 2000 onwards, digitalisation and miniaturisation have been key drivers of new downstream space applications and new generations of (smaller) space systems, prompted by ever-increasing computing power capabilities and breakthroughs in micro-electronics, computing and material sciences. The year 2018 marked the verge of a fifth cycle of space development, where data and signals from satellites feed directly into mass-market consumer products, and are routinely used in government and commercial operations. This may also be the beginning of a new era of space exploration and in-space activities, as the sector has never seen such a diversity of actors getting involved, as funders and developers of space systems.

The drivers for this transformation are multiple and complex, and can be found in both the upstream and downstream segments of the space sector. This chapter will particularly focus on key enabling activities and developments in manufacturing and space launch. The following sections review some of the new processes for production and supply chains; discuss important developments in the space launcher and satellite markets; and look at some of the maturing technologies on the horizon. The evolutions in space exploration and in telecommunication markets that are driving much of the commercial growth in the space sector are treated separately in dedicated chapters (Chapters 5 and 6).

New production and supply chain management processes

Building on decades of research and development, much of the innovation in the space sector still originates in countries with long-standing and well-funded institutional space programmes. But new and disruptive groups of actors, production processes and digital technologies are starting to change where, what and how space systems and products are being developed as compared to less than a decade ago. The next sections review selected technical evolutions in space manufacturing, as well as ongoing adaptations in supply chain management.

Evolutions in space manufacturing

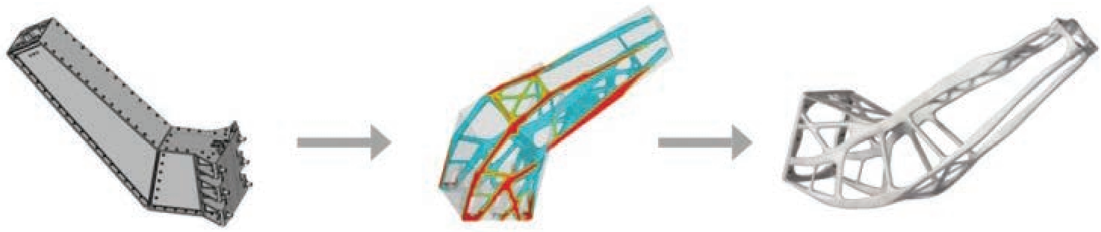
The next production revolution in manufacturing refers to the increased use of digital technologies in industrial processes (OECD, 2017[5]). It has profound impacts on productivity, on employment levels and required skill sets, on industry demographics, etc. The first mover advantages of big companies may also be reinforced by large investments in digital technology, with an increased probability of "winner-takes-most" scenarios due to the scalability of intangible digital assets (OECD, 2017[5]; 2017[6]; Haskel and Westlake, 2018[7]; OECD, 2019[2]).

In this context, where aerospace and defence industry players tend to benefit the most from large institutional space programme contracts in both OECD countries and partner economies, digital manufacturing technologies are already gradually transforming the space sector. Several incremental technologies, such as data analytics, additive manufacturing and robotics, contribute to reducing material costs and production times for many different types of missions. These missions include one-off platforms for government science missions for example, and more standardised satellite buses for commercial earth observation or telecommunications. In particular, incremental technologies pave the way for mass production of both satellites and launchers, something which is closely related to the planned broadband constellations of thousands of communications satellites in the 100-400 kg range (see chapter 6) and requiring space manufacturers to produce and assemble satellites at an unprecedented scale and speed.

Several of these process innovations were introduced to the sector by newcomers, but incumbents are following suit. SpaceX was one of the first companies to adapt experiences and data from high-volume industries, such as the automotive industry, to space manufacturing. Other companies are also heavily investing in new technologies and facilities. The company Thales Alenia Space is building a EUR 20 million automated production facility for photovoltaic assemblies in Belgium, with several new techniques such as robotised panel assembly, digital data management and traceability, online tests and inspections, as well as augmented reality (Mouriaux, 2017[8]; Thales Alenia Space, 2017[9]). The satellite manufacturing company OneWeb Satellites, a joint venture between the broadband satellite company OneWeb and European manufacturer Airbus, opened a new facility in Toulouse (France) in 2017 and is finalising the main production facility in the Kennedy Space Center Exploration Park in Florida, which will have two assembly lines (Bauer, 2017[10]; Richardson, 2017[11]). The estimated cost of the 10 000 m^2 Florida facility is some USD 85 million and it will employ about 250 people (Richardson, 2017[11]). The venture aims to produce up to 15 satellites per week (OneWeb Satellites, 2018[12]). The US company Blue Origin is equally investing some USD 200 million to build a new 70 000 m^2 (750 000 ft^2) production facility for its New Glenn launcher in the Kennedy Space Center Exploration Park, employing some 330 people (Richardson, 2017[13]), as well as a new facility in Alabama for its BE-4 engines, capable of producing 30 engines per year (Foust, 2017[14]). "Moving" assembly lines have also been introduced for the production of Ariane 6 first- and second-stage engines, inspired by similar practices in aeronautics manufacturing (Meddah, 2017[15]).

The uptake of additive manufacturing in space manufacturing has accelerated in the last years, especially with the advances made in metal additive manufacturing. 3D-printed metal satellite components (e.g. antenna brackets and supports) were first sent to orbit in 2015-16 (Arabsat-6B) (Russell, 2017[16]). Figure 4.1 shows the redesign process of an antenna bracket on the Sentinel satellites, with the final 3D-printed aluminium alloy bracket 25% lighter, more performant and with half the production time (down from ten weeks to four or five weeks) than the original bracket (EOS, 2016[17]). For some satellite parts, the weight gain is even higher. 3D-printed dual antenna arrays for mobile satellite communications can be up to five times lighter than more conventional products (Swissto12, 2019[18]).

Figure 4.1. Additive manufacturing of satellite antenna bracket



Source: Adapted from EOS (2016[17]), "Additive manufacturing of antenna bracket for satellite", *Customer case studies*, *https://www.eos.info/case_studies/additive-manufacturing-of-antenna-bracket-for-satellite*.

3D-printed components and parts are also increasingly used in launchers, in particular for engine components. SpaceX made its first launch with a 3D-printed engine part (the main oxidiser valve body) in 2014 (SpaceX, 2014[19]). Currently, several manufacturers are using additive manufacturing for producing engine parts. The US/New Zealand company Rocket Lab uses additive manufacturing for all "primary components" of its Rutherford engine, including the combustion chamber, injectors, pumps and propellant valves (Rocket Lab, 2015[20]). Table 4.2 summarises these findings and shows a selection of 3-D printed engine parts among space manufacturers.

Table 4.2. Selected 3D-printed parts in space launcher engines

Space vehicle	Company	Type of part	Material(s)	Main subsystem	First launched
Falcon 9 launcher	SpaceX	Main oxidiser valve body	Inconel (nickel-chromium based alloy)	Merlin 1D engine	2014
Electron launcher	Rocket Lab	All primary engine components (e.g. combustion chamber, injectors, pumps and main propellant valves)	Titanium	Rutherford engine	2018
Vulcan launcher	Blue Origin	Housing, turbine, nozzles, rotors	Aluminium; nickel-based alloy	BE-4 engine	In development
Ariane 6 launcher	ArianeGroup	Injector head (all-in-one design, 248 elements reduced to only 1)	Nickel alloy	Upper stage Vinci engine	In development
Ariane 6 launcher	ArianeGroup	Gas generator	n.a.	Vulcain 2.1 engine	In development
	Aerojet Rocketdyne	Preburner	Mondaloy 200 (nickel-based alloy)	AR-1 engine	In development

Additive manufacturing is also used in small satellite and cubesat manufacturing. While previously mainly adopted for the production of secondary structural parts, experiments are now carried out with primary structures (NASA, 2018[21]). The PrintSat picosatellite (0.1-1 kg), whose structure was entirely 3D-printed at Montana State University using a carbon-fibre reinforced composite, was lost in a launch failure in 2015 (Montana State University, 2015[22]).

Adaptations in supply chain management

The changes in space manufacturing processes and the increasing development of small satellite and cubesat constellations in low-earth orbit increasingly influence the management of space manufacturing supply chains. Several trends can be identified, such as the vertical integration of production and increased internationalisation of supply chains, with a growing reliance on off-the-shelf components. Advances in additive manufacturing (3D-printing) and autonomous systems are also making certain in-space assembly, repair and manufacturing activities increasingly feasible.

Leaning towards more vertical integration

The increased reliance on serial production and automation lowers the cost of production and reduces the need for outsourcing. It is estimated that more than 70% of each Falcon launch vehicle is manufactured at the SpaceX production facility, in Hawthorne, California (OECD, 2014[23]). This has made it possible to quickly scale up productions and to shorten research and development lead times (e.g. the rapid transformation of Falcon 9 to address the commercial geostationary market, increased reusability). Other companies, such as Blue Origin and Rocket Lab, also rely on vertically integrated, in-house production. Blue Orbital's Florida facility for its New Glenn launcher will accommodate manufacturing, processing, integration and testing (Calandrelli, 2016[24]). In a similar vein, ArianeGroup, the joint venture of Airbus and Safran, which is producing the future European Ariane 6 and the small launcher Vega-C with Arianespace, is also consolidating its production supply chain, previously spread across 25 different European industrial sites, by focusing more on site specialisation and mass production of standardised parts and components (OECD, 2016[4]; Meddah, 2017[15]).

Increased internationalisation and use of off-the-shelf components

Other manufacturers, in contrast, are spreading out their supply chain, using more affordable international suppliers to cut costs, despite higher risks of delay (US Department of Commerce, 2013[25]). As very small satellite and cubesat constellations become more efficient and commonplace, the relatively low cost and rapid satellite turnover makes technology solutions more "expendable", with increased room for experimentation with off-the-shelf technologies and components sourced from other, faster moving non-space industries (e.g. electronics).

Examples include the early adoption of technologies such as flat lithium-polymer cells for cubesat energy storage or off-the-shelf technologies used for on-board computing system (NASA, 2018[26]; 2018[27]). Table 4.3 shows a selection of battery and battery cell providers for cube- and nanosatellites identified in NASA's report *State of the Art Small Spacecraft Technology*. The list includes both specialised aerospace/defence manufacturers (ABSL/EnerSys, Clyde Space, GomSpace, EaglePicher) and electronics manufacturers such as Canon, Molicel, LG and Samsung.

Table 4.3. Selected cubesat batteries and their manufacturers

Product	Manufacturer	Energy density (Whkg-1)	Cells used	Technological readiness level (TRL)
COTS 1865 Li-ion Battery	ABSL	90-243	Sony, Molicel, LG, Sanyo, Samsung	TRL 8
BP-930s	Canon	132	Four 18650 Li-ion cells	TRL 9
Li-Polymer, 8.2 V, 1.25-20 Ah	Clyde Space	150	Clyde Space Li-Polymer	TRL 9
Li-Polymer, 32 V, 6.25 Ah	Clyde Space	150	Clyde Space Li-Polymer	TRL 8
Rechargeable space battery (NPD-002271)	EaglePicher	153.5	EaglePicher Li-ion	TRL 7
NanoPower BP4	GomSpace	160	GomSpace NanoPower Li-ion	TRL 9
NanoPower BPX	GomSpace	157-171	GomSpace NanoPower Li-ion	TRL 9
Li-ion battery block VLB-X	Vectronic	..	SAFT Li-ion	..

Source: Adapted from NASA (2018[26]), "Power", in *State of the Art of Small Spacecraft Technology*, *https://sst-soa.arc.nasa.gov/03-power*.

The same mix of specialised (aerospace/system critical) and general electronics manufacturers can be found among providers of cubesat on-board electronic systems, as illustrated in Table 4.4.

Table 4.4. Selected manufacturers of cubesat on-board computing systems

Mainly system-critical and harsh environment (aerospace/defence) industries	Mainly electronics industry
BAE Systems	STMicroelectronics
BroadReach/Moog	Texas Instruments
C-MAC Microtechnology	3D Plus
Cobham (Aeroflex)	Xilinx
Intersil	Arduino
Maxwell Technologies	BeagleBone
Space Micro, Inc.	ATMEL
	Honeywell
	Intel
	Freescale/NPX
	Microsemi/Microchip

Source: Adapted from NASA (2018[26]), "Power", in *State of the Art of Small Spacecraft Technology*, *https://sst-soa.arc.nasa.gov/03-power*.

Additive manufacturing for space habitation and exploration

Additive manufacturing is a particularly interesting technology for space habitation and deep space exploration, making it possible to produce spare parts when needed in space, instead of transporting voluminous parts from Earth.

The technology, using aerospace-grade composites, has already been tested on the International Space Station since 2014, and the permanent Additive Manufacturing Facility on the station can print tools, components and other hardware. Made in Space, the same company that has developed the additive manufacturing facilities for the International Space Station, recently won a NASA grant to develop a hybrid composites/metal printer for microgravity, capable of producing precision parts of aerospace-grade metals, such as housings for life support systems, and components that consist of multiple materials (Made In Space, 2018[28]).

Another potential application of additive manufacturing is the provision of human shelter in space. NASA's printed-habitat for Mars challenge has been running for several years in separate stages, each time focusing on different aspects of the habitat, such as design and materials. The latest stage of the challenge required the digital representation of a 90 m^2 (1 000 f^2) habitat sustaining four astronauts during a year combining living space with critical life survival systems such as life support, plumbing and rover hatches (NASA, 2018[29]).

From rockets to satellites: More changes are coming

Incumbent satellite and launcher manufacturers are facing competition from a growing number of international and commercial actors. Markets are also diversifying, with new niche products such as small and inexpensive satellites for rapid technology testing and prototyping, small satellite launchers and cubesat constellations. At the same time, government and commercial large-scale launchers for lunar exploration are getting closer to completion. The following sections take a closer look at these developments.

A crowded landscape of rockets

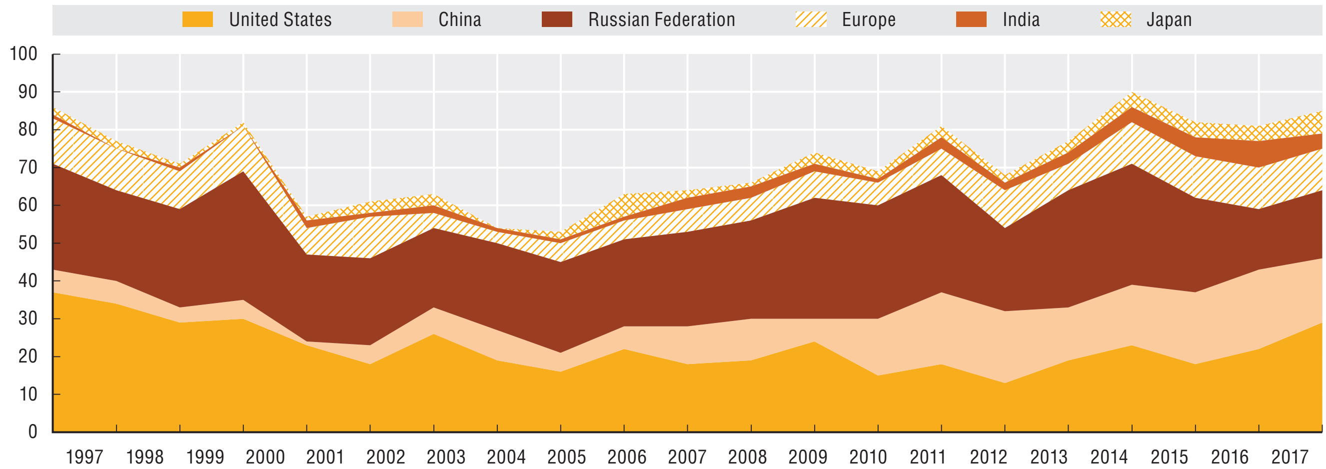
The space launch market has traditionally been closely aligned with the 10-15 year replacement cycles of telecommunication satellites, and annual launch patterns have not evolved significantly since the late 1990s (see Figure 4.2). But there have been important recent changes in the composition and type of launch providers, and more changes are coming, driven by the new manufacturing and production trends described in the previous sections, affecting particularly commercial telecommunications satellites.

The capability to carry out an orbital space launch and to manufacture and maintain a fleet of launchers remains limited to a small number of actors, which in 2019 includes ten countries (the People's Republic of China (hereafter "China"), India, the Islamic Republic of Iran, Israel, Japan, Korea, New Zealand, the Democratic People's Republic of Korea, the Russian Federation and the United States) and the European Space Agency (ESA). Six of these actors can launch to the geosynchronous orbit at some 36 000 km altitude, home to crucial telecommunications and weather satellites (China, India, Japan, the Russian Federation, ESA and the United States).

Global space launch activity has picked up since 2010, and 2018 saw the highest number of launches since the late 1990s. This growth is mainly due to significant launch activity increases in China and the United States. But launch activity has also increased in several other parts of the world (e.g. Europe, India and Japan), and with new entrants (New Zealand). Only the Russian Federation has seen a decrease in its launch activity since 2010, with launch activity in 2016-18 representing the lowest number of launches in 20 years.

In 2018, there were 111 successful space launches and 3 failed launches globally (FAA, 2018[30]). China had the highest number of successful space launches (38), followed by the United States (31), the Russian Federation (19), Europe and India (7) and Japan (6). Europe, China and the Russian Federation had one launch failure each. A small number of these launches (22), were commercial launches, e.g. privately financed or internationally competed.

Figure 4.2. Number of successful space launches for selected actors, 1997-2018



Note: This figure only counts successful or partially successful launches, i.e. the payload(s) was delivered to a usable orbit.

Source: Adapted from FAA (2018[30]), *The Annual Compendium of Commercial Space Transportation: 2018*, *https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2018_AST_Compendium.pdf* and equivalent reports for previous years.

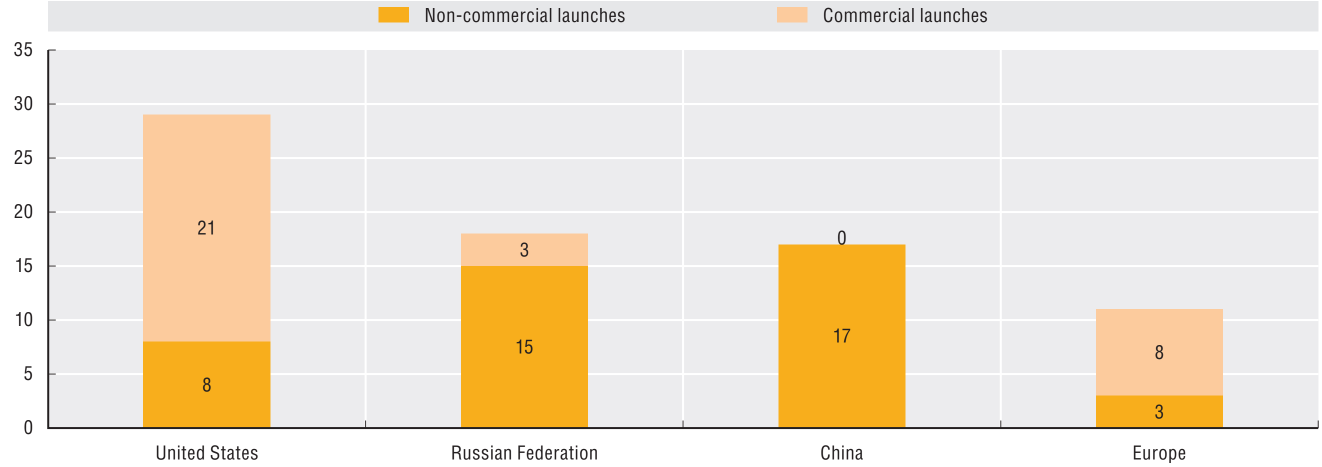
The majority of commercial launches were carried out in the United States (14 launches), followed by Europe (six launches), and New Zealand (two launches), as shown in Figure 4.3. China is seeing a considerable growth in launcher start-ups targeting commercial markets, and in October 2018, the private company Landspace made the first private (commercial) orbital launch attempt with its Zhuque-1 launcher.

Commercial launch revenues accounted for some estimated USD 3 billion in 2017 and were mainly generated from the launch of telecommunications satellites for the geostationary and low-earth orbit, as well as commercial resupply missions to the International Space Station. The launch of many small and very small commercial satellites that are launched as secondary payloads will not necessarily be recorded under this definition, if the primary payload is non-commercial. Revenues were divided between the United States (57%), Europe (36%) and the Russian Federation (6%), as shown in Figure 4.4 (FAA, 2018[30]).

Commercial launch revenues are starting to be affected by the looming crisis in satellite telecommunications, which will be further described in Chapter 6.

Figure 4.3. Commercial and non-commercial space launches in 2018

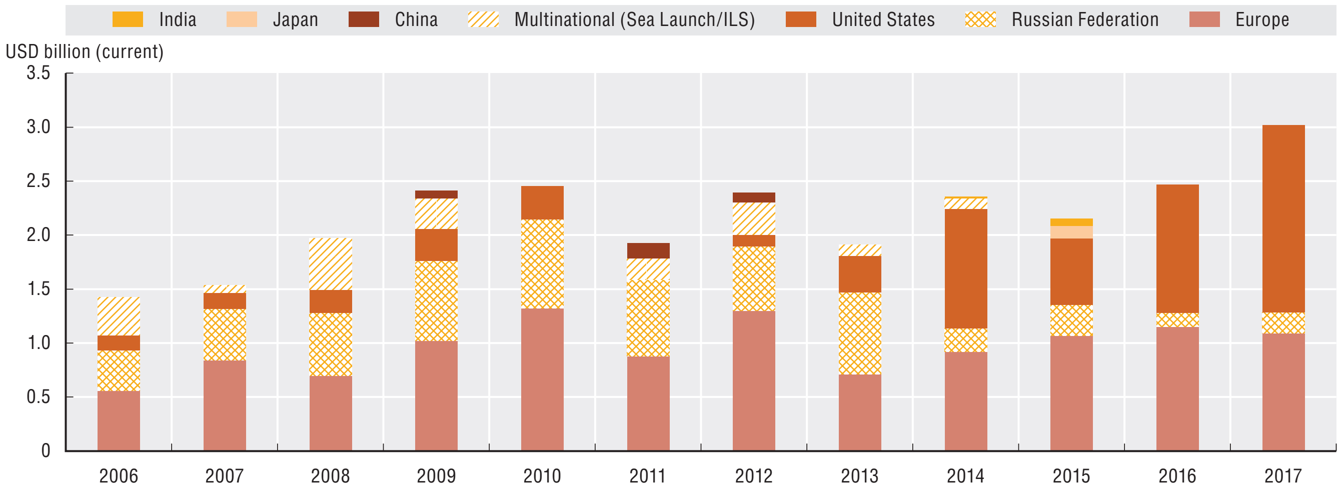
Number of successful and failed launches



Note: This figure counts both successful and failed launches and include three launch failures for China (commercial launch), Europe (commercial launch) and the Russian Federation (non-commercial launch).

Sources: Adapted from FAA (2018[30]), *The Annual Compendium of Commercial Space Transportation: 2018*, *https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2018_AST_Compendium.pdf* and equivalent reports for previous years.

Figure 4.4. Launch industry revenues estimates



Note: Estimated revenues generated from "commercial" launches, according to the US Federal Aviation Administration definition. See Box 4.1.

Source: Adapted from FAA (2018[30]), *The Annual Compendium of Commercial Space Transportation: 2018, https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2018_AST_Compendium.pdf.*

From the (re)emergence of small launchers to super-heavy launchers for interplanetary exploration

The number of launches of very small satellites, e.g. cubesats with a spacecraft mass of some 1-10 kg has grown exponentially in the last five years. Further future demand for launch services is expected from the multiple planned mega-constellations, consisting of several hundreds of small satellites in the low-earth orbit (see Box 4.1). Meanwhile, affordable launch opportunities remain limited.

Box 4.1. Ever smaller satellites

The last ten years have witnessed a revolution in the design, manufacture and deployment of satellites. Satellites vary in mass from a couple of kilogrammes or less for a small cubesat to several metric tonnes for a geostationary telecommunications satellite. A satellite with a mass of 500 kg and less is generally considered 'small'. The satellites in many of the planned satellite broadband mega-constellations are much bigger than cubesats but still much smaller than traditional telecommunications satellites, ranging from about 150 kg for the planned OneWeb constellations to 400 kg for satellites in the SpaceX Starlink constellations.

Small satellites, weighing less than 500 kg, have become very popular and cost-efficient as commercial off-the-shelf components and consumer electronics are now commonly used to build satellite platforms and instruments at the lower end of the cost range. Small satellites are making space technology more affordable and accessible to new types of users. Increasingly popular are also nano- and microsatellites (weighing between 1 kg and 50 kg), but they come with much more limited functionalities and a very short mission life (1-2 years):

- small satellite, 100-500 kg
- minisatellite, 100-180 kg
- microsatellite, 10-100 kg
- nanosatellite, 1-10 kg (e.g. cubesats)
- picosatellite, 0.01-1 kg
- femtosatellite, 0.001-0.01 kg (e.g. pocketqubes, suncubes, mainly used for educational purposes).

Cubesats are a class of nanosatellites that use a standard size and form factor, originally developed in 1999 by California Polytechnic State University at San Luis Obispo (Cal Poly) and Stanford University to provide a platform for education and space exploration. The standard cubesat size is "one unit" or "1U", measuring 10x10x10 cm, and is extendable to larger sizes stacked lengthwise; 1.5, 2, 3, 6, etc.

Source: NASA (2015[32]), *What are smallsats and cubesats?*, *https://www.nasa.gov/content/what-are-smallsats-and-cubesats.*

A comparatively low-cost option is to launch as a so-called "piggyback" payload, a secondary payload on a launch carrying a much larger satellite (FAA, 2018[30]). For instance, in 2017 the Indian Polar Satellite Launch Vehicle launched 104 satellites in one single launch: the primary payload (a government earth observation satellite, Cartosat-2), two Indian technology nanosatellites and 101 satellites (96 from the United States; and one each from Israel, Kazakhstan, the Netherlands, Switzerland and the United Arab Emirates) (ISRO, 2017[33]). For educational and non-profit cubesats, several governments also propose similar free services (e.g. NASA's Cubesat Launch Initiative, the European Space Agency's Fly Your Satellite). However, launching as a secondary payload may entail significant disadvantages both in terms of launch schedule and destination orbit, and may not be a viable option for commercial companies, which are looking for a fast access to space.

In response, both governments and private companies are investing in dedicated small launchers, i.e. those with a low-earth orbit payload capacity of less than 2 268 kg according to FAA definitions (FAA, 2018[30]). Several dozens of small launchers are being developed around the world, with many receiving venture capital funding (see Chapter 1 on private funding). As illustrated in Table 4.5, at least half a dozen small launchers have had their first orbital launch in the last five years, and more than ten launchers are in different stages of development for launch within the next three to five years (FAA, 2018[30]). Some of the most advanced launchers are Electron from the US/New Zealand company Rocket Lab, or LauncherOne from Virgin Orbit. Electron had its first orbital launch attempt in 2017 from the Mahia commercial spaceport in New Zealand, followed by a successful launch in early 2018. LauncherOne, which launches horizontally from a 747 aircraft at 10 000 metres in altitude, is expected to carry out its first orbital launch attempt in 2019. The Chinese government and private companies are also developing small launchers, both for domestic use and commercialisation, with companies such as One Space, Land Space and Linkspace (FAA, 2018[30]). After a scarcity of launch opportunities for small satellites, the next two years should see the emergence of a very competitive landscape for small launchers.

Table 4.5. Selected recent and planned small launchers for the low-earth orbit

Launcher	Year of first orbital launch	Country	Manufacturer/launch provider	Low-earth orbit capacity (kg)
Kuaizhou 1/1A	2013	China	CASIC/Expace	300
Long March 11/ LandSpace-1	2015	China	CALT/LandSpace	530
Long March 6	2015	China	SAST/CALT (CASC)/ Great Wall Industries Corp.	1 500
SS-520-5	2017	Japan	Canon/JAXA	4
Electron	2017	United States/New Zealand	Rocket Lab	225
Kaitouzhe 2	2017	China	CASIC/Expace	350
Vector R	2019 (planned)	United States	Vector	66
LauncherOne	2019 (planned)	United States	Virgin Orbit	500
Stratolaunch	2019 (planned)	United States	Scaled Composites/Dynetics	1 350
Kuaizhou 11	2019 (planned)	China	CASIC/Expace	1 500
Vector H	2019 (planned)	United States	Vector	160
OS-M1	2019 (planned)	China	One Space	205
Black Arrow 2	2019 (planned)	United Kingdom	Horizon Space Technologies	500
Alpha 1.0	2019 (planned)	United States	Firefly	1 000
Arion 2	2020 (planned)	Spain	PLD Space	150
XS-1	2020 (planned)	United States	Boeing/DARPA	1 361
NewLine-1	2020 (planned)	China	Linkspace	200

Note: First launches include launch failures.

Source: Adapted from FAA (2018[30]), *The Annual Compendium of Commercial Space Transportation: 2018, https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2018_AST_Compendium.pdf*.

Governments are also (re)turning their attention to the manned exploration of the moon and Mars, large-scale missions that require the development of launchers capable of lifting a minimum of some 50 000 kg to the low-earth orbit. In parallel, privately-funded projects of interplanetary travel and habitation are underway (see Chapter 5 on space exploration trends).

Four large launchers, from China, the Russian Federation and the United States, are currently under development, with the US Space Launch System (SLS) the most advanced, scheduled for its first launch in the early 2020s (Table 4.6). Both SLS and the planned Russian launcher are intended to play a role in the deployment of the *Gateway* in the 2020s and 2030s, a manned "outpost" orbiting the moon (NASA, 2018[34]). The Chinese launcher Long March 9 will reportedly be used for a sample return mission to Mars as well as manned and unmanned lunar missions. It could also be used to launch a space-based solar power system, which is under consideration (Jones, 2018[35]).

Table 4.6. Selected planned super-heavy launchers

Launcher	Manufacturer / launch service provider	Country	Length (m)	Diameter (m)	LEO capacity (kg)	Planned launch year	Reusable
Space Launch System (SLS)[1]	Boeing–ULA–Orbital ATK / NASA	United States	111.3	8.4	70 000-130 000	2020-21	No
Big Falcon Rocket (BFR)	SpaceX	United States	106	9	250 000	2022	Yes
Super-Heavy Space Launch Vehicle System (SH SLVS)	RSC Energia / Roscosmos	Russian Federation	n.a.	n.a.	90 000	2028	n.a.
Long March 9	CALT / People's Liberation Army	China	93	10	140 000	2030	n.a.

Note: 1. SLS is designed to evolve into more powerful configurations using the same core stage. Block 1 has a maximum launch capacity of 70 000 kg to low-earth orbit, block 1B 105 000 kg and block 2 130 000 kg.

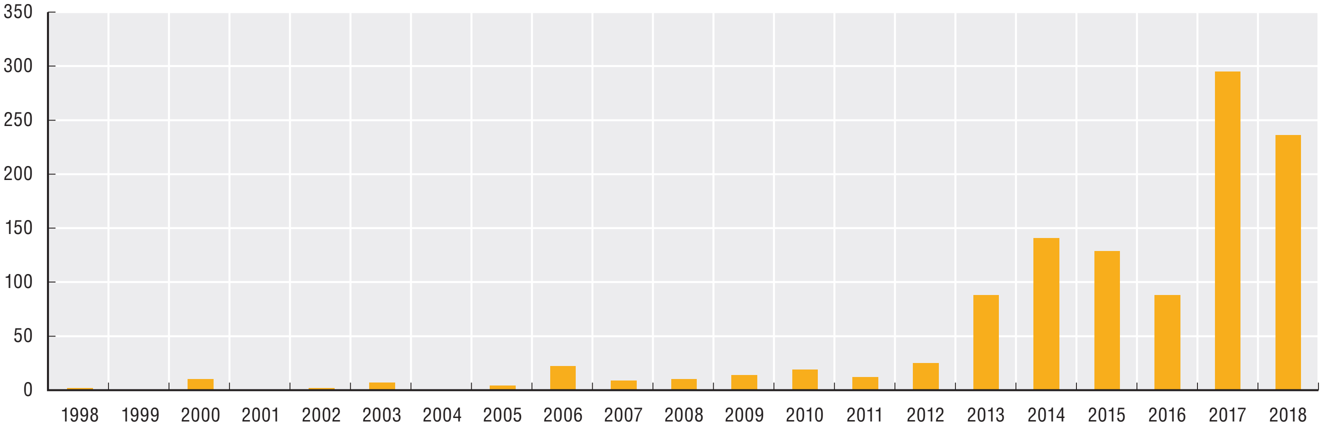
The fourth launcher, the Big Falcon Rocket (BFR), is the most powerful if measured by low-earth orbit launch capacity. While it is not a government project, BFR is being developed by SpaceX with human colonisation of Mars as the end objective (SpaceX, 2017[36]). The current design of BFR foresees a single system, one booster and one ship, that will be fully reusable and that will eventually replace the Falcon 9 and Falcon Heavy launchers and the Dragon capsule. It should be able to launch payloads to all earth orbits as well as the moon and Mars. The first launch has been set to 2022, but this could change (SpaceX, 2017[36]). The BFR, as well as the biggest configuration of SLS and the Long March 9, will all have a higher launch capacity to the low-earth orbit than Saturn V, the mythical launcher used in the US Apollo programme in 1960s, and one of the biggest space rockets ever constructed.

Cubesats as the new Swiss knife of the space sector

With growing digitalisation of all segments of space activities, cubesat constellations have shown a remarkable growth in the last five years, as illustrated in Figure 4.5. Cubesats are a class of standardised very small satellites that have low mass (mostly less than 10kg) compared with standard satellites and that are relatively low-cost to produce (OECD, 2014[23]). They consist of one or several units of 10 cm × 10 cm × 10 cm (Box 4.1). They were originally developed in 1999 by California Polytechnic State University at San Luis Obispo and Stanford University to provide a platform for education and space exploration. In the beginning they were mainly used at universities as technology demonstrators, but in the last five years they have become increasingly popular with commercial firms.

Figure 4.5. Annual launches of very small satellites

Includes successful and failed launches



Note: Includes all cubesats (0.25U to 27U), nanosatellites (1-10 kg), picosatellites (100 g-1 kg), pocketqubes, tubesats and suncubes (see Box 4.1 for more information).

Source: Nanosatellite Database (2019[37]), *Nanosatellite and cubesat database*, Version 19 January 2019, *https://www.nanosats.eu/*.

For cubesat constellation operation alone, unofficial industry statistics (e.g. the comprehensive *Nanosatellite Database*) list more than 30 start-ups either already operating or in different stages of development, headquartered in a dozen different countries on four continents (Table 4.7). There is great variation not only in the planned size of the constellation (from a couple of dozen to several hundred satellites) but also the size of the cubesat, ranging from 2U to 16U (see Box 4.1). These constellations also have an increasing variety of sensor technologies for a growing range of applications, including optical, multispectral, infrared and synthetic aperture radar for earth observations applications; GPS-radio occultation and microwave radar for weather observations; automatic identification system receivers for maritime tracking; and (mainly) narrow-band receivers for machine-to-machine communications and the Internet of Things (IoT) (Nanosatellite Database, 2019[37]).

Finally, this rush to test and develop commercial systems is bringing new challenges, as newcomers to the space industry, including start-ups, still have to follow national and international rules to launch and operate satellites in orbit. Spectrum, for instance, is a rare commodity and needs to be allocated via a well-established, although at times lengthy, regulatory process, so as to avoid dangerous interferences. Also, even very small satellites need to be tracked from the ground to avoid collision risks with other satellites in orbit. In January 2018, the first case of "rogue small satellites" was reported, as the Californian start-up Swarm Technologies, specialised in autonomous robots and the IoT, launched four nanosatellites on-board an Indian rocket, despite having had its launch license request rejected by the US Federal Communications Commission. The accumulation of space debris is another concern (see chapter 5).

Table 4.7. Selected existing and planned cubesat constellations

Company	Country	Number of launched satellites/ planned constellation size	Launch of first satellite	Cubesat size	Application/technology
ExactEarth	Canada	67/67	2008	Nanosat/hosted	AIS
Planet	United States	355/150+	2013	3U	Earth observation
Spire	United States	103/150+	2013	3U	Weather/AIS/ADS-B
Planetary Resources	United States	3/10	2014	12U	Earth observation
Astro Digital (Aquila)	United States	6/25	2014	6U/16U	Earth observation
Sky and Space Global	United Kingdom	3/200	2017	3U	Internet of Things (IoT)
GeoOptics	United States	7/?	2017	6U	Weather (GPS-RO)
Helios Wire/SIRION	Canada	2/30	2017	6U, 16U	IoT/machine-to-machine
Dauria/SatByul	Russian Federation	2/8	2017	6U	Earth observation
Swarm Technologies	United States	7/150	2018	0.25U, 1U	IoT/machine-to-machine
Kepler Communications	Canada	2/140	2018	3U	IoT
Analytical Space	United States	1/?	2018	6U	IoT
Hiber (Magnitude Space)	Netherlands	2/48	2018	6U	IoT
Astrocast (ELSE)	Switzerland/United States	1/64	2018	3U	IoT
Fleet Space	Australia	4/100	2018	12U	IoT
Reaktor Space	Finland	1/36	2018	6U	Earth observation (hyperspectral)
AISTech	Spain	1/150	2018	2U/6U	IoT/AIS/earth observation (IR)/ADS-B
Myriota	Australia	1/?	2018	n.a.	IoT/machine-to-machine
PlanetiQ	United States	0/18	2019	6U	Weather (GPS-RO)
Lacuna Space	United Kingdom	0/32	2019	6U	IoT
Blink Astro	United States	0/?	2019	3U	
NSLComm (SkyFi)	Israel	0/60	2019	6U	Internet
Aerial & Maritime (partially GomSpace)	Sweden/Denmark/Mauritius	0/?	2019	n.a.	AIS/ADS-B
Hera Systems	United States	0/48	2019	12U	Earth observation
Bluefield	United States	0/22	2019	16U	Methane emissions
Kleos Space	Luxembourg	0/20	2019	Cubesat	AIS, geolocation, orbital data
SatRevolution	Poland	0/66	2019	2U	Earth observation
Karten Space	Spain	0/14	2019	6U	Earth observation/AIS
UnSeenLabs	France	0/?	2019	6U	RF spectrum monitoring
Orbital Micro Systems	United States/ United Kingdom	0/40	2019	3U	Weather (microwave radar)

Note: Includes all cubesats (0.25U to 27U), see Box 4.1 for more information.

Source: Adapted from Nanosatellite database (2019[37]), *Nanosatellite and cubesat database*, Version 29 January 2019, *https://www.nanosats.eu*.

Looking ahead to emerging space activities

Projecting possible developments of any economic sector is a difficult exercise. Almost fifteen years ago, the OECD conducted its first two-year project in co-operation with the space community to investigate which contributions space applications could make to meet five major societal challenges up to 2030 (the environment, the use of natural resources, the increasing mobility of people and goods, growing security threats, and the move towards the information society) (OECD, 2004[38]; 2005[39]). The project included alternative future scenarios to model possible trajectories of space activities, the drawing of technology maps that proved to be quite accurate more than fourteen years later (Table 4.8), and the elaboration of key recommendations to make the sector more sustainable.

Many of these policy guidelines are still valid today. They aimed at implementing a sustainable space infrastructure; encouraging public use of that infrastructure; and encouraging private sector participation.

The project furthermore identified some of the most promising space systems and applications by 2030, which are listed in Box 4.2. The majority of the main contender applications (e.g. precision farming, traffic management, location-based services) have matured and turned into full-fletched commercial services thanks to advances in space systems, data analytics and machine learning.

Table 4.8. Possible space innovations by 2030 (anticipated in 2004)

Innovations anticipated in 2004	Situation in 2018
Increases in processing power will enhance the capacity to process masses of data collected by remote sensing satellites usefully. Combined with insights derived from biotechnology, it will be possible to develop, among other things, macro-models of environmental processes. Remote sensing, possibly combined with artificial intelligence, will be used to monitor a variety of international treaties.	Advances in computer processing power (including in-satellite orbit processing), big data analytics, development of the cloud, and the combination of drones and satellites, are leading to a strong institutional and commercial uptake of geospatial information, improved weather and climate models (which now rely for many of their variables on satellite data series). New satellite data will be increasingly used for global monitoring, as space agencies elaborate together standards to allow better uptake by policy-makers (e.g. tracking pollution on land and at sea, Co2 emissions).
Radio frequency identification (RFID) tags will use a hybrid of ground and space systems to provide "smart transport" services, keeping track not only of inventory, but possibly of people as well.	The inclusion of active and passive RFID tags in retail, healthcare, manufacturing and other sectors has become the norm, with more growth expected as electronic sensors become ever-smaller and even 3-D printed (a few million in 2003 to around 10 billion in 2016, with active RFID systems linked to GPS). Advances in processing power and electronic miniaturisation are contributing to ever more location-based services using satellite signals and data.
Manufacture of pico- or nanosatellites in low-earth orbit, as opposed to a handful of large satellites in geosynchronous orbit, to serve future telecommunications needs. Large numbers of these satellites could be put into orbit very cost-effectively because of their low mass (tens of kilograms down to hundreds of grams) and because the globe can be spanned with low- orbit devices if there are enough of them in orbit.	Cubesats have already become very common, and further fractionated mission architectures are studied in several countries. This involves research in networked systems of distributed, co-operating small-satellites, away from the current traditional, large, multifunctional satellites. Some experts see this as an evolution similar to computers, i.e. large mainframe computers of the 1970s have evolved into networks of small computers connected via Internet. This is leading to new commercial ventures (constellations of very small satellites).

Source: Adapted from OECD (2004[38]), *Exploring the Future of Space Applications*.

Box 4.2. Promising space systems and applications by 2030

On the basis of three scenarios developed in 2002-04, a list was established of possible promising space applications that could become fully operational by 2030:

Main contenders:

- Entertainment (digital radio, TV, data and multimedia broadcasting to fixed and mobile assets, high bandwidth to the home / convergence of different media);
- Meteorology and climate change (meteorological and sea condition forecasting for commercial sea shippers, pollution maps with evolution in time, monitoring of the application of treaties, standards and policies);
- Distance learning and telemedicine (broadcasting to remote areas and across national borders, medical remote surveillance);
- E-commerce (enabling changing work patterns due to mobile workforce / home working and economic consequences, HDTV teleconferencing);

Box 4.2. Promising space systems and applications by 2030 *(cont.)*

- Location-based consumer services (driver assistance and navigation aids, insurance based on real-time usage data, vehicle fleet management, asset tracking (especially high-value) and road repair management);
- Traffic management (location and positioning of aircraft and ships, optimisation of airport traffic management, optimisation of traffic management – road pricing - driver behaviour logging);
- Precision farming and natural resources management (precision agriculture for maximal efficiency in equipment and application of fertilizer, deforestation and forestry management);
- Urban planning (plans, maps and numerical terrain models, precise positioning of engineering structures and buildings, automatic control of job site vehicles, management and optimisation of job site vehicle routes);
- Disaster prevention and management (telecom capability in absence of ground infrastructure, remote assessment of damage and pollution for insurance claims).

Outsiders:

- Adventure space tourism (suborbital then orbital);
- In-orbit servicing;
- Power relay satellites.

Source: Adapted from OECD (2004[38]), *Exploring the Future of Space Applications*.

The following applications were listed as 'outsiders': adventure space tourism (suborbital then orbital), in-orbit servicing and power relay satellites. Examining today's situation, in-orbit servicing and space tourism are in the most advanced stages of development.

Adventure space tourism

Adventure space tourism operators are getting closer to opening commercial operations after years of development and testing and millions of dollars in investments. Table 4.9 shows some of the most advanced projects to date, including the only existing space tourism service, offered by Roscosmos, to travel to the International Space Station.

The planned offerings for suborbital space tourism involves 2-3 days of training and preparations for a trip that lasts about 10-20 minutes, reaching the 100 km altitude border of space and returning to Earth either horizontally or vertically.

- In December 2018, the Virgin Galactic SpaceShipTwo spacecraft reached a peak altitude of 83 kilometres, making it the first human commercial suborbital spaceflight since 2004.
- The other current suborbital space tourism contender, the New Shepard launcher programme from Blue Origin, had by the end of 2018 completed nine unmanned test flights and is expected to start manned flights in 2019-20.

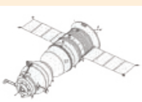
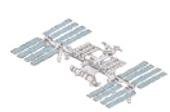
Virgin Galactic and Blue Origin, which are both backed by billionaire entrepreneurs (Richard Branson and Jeff Bezos), also intend to launch commercial and government microgravity payloads and are already part of NASA's Flight Opportunities programme providing flights for technology demonstration payloads.

Orbital space tourism services aim to typically offer a 7-11 day stay in space and costs tens of millions of dollars. Seven paying customers travelled to the International Space Station on the Russian Soyuz spacecraft between 2001 and 2009 (one customer travelled twice) and another two customers have signed up for a flight in 2021 (Space Adventures, 2019[40]). There will soon also be seats available on Boeing and SpaceX spacecraft, at undisclosed prices. The US start-up Axiom Aerospace will further be offering tourist stays on the International Space Station starting from 2020, for a price of about USD 55 million (Axiom Space, 2019[41]).

- Manned test flights have been scheduled in mid-2019 for the Boeing and SpaceX crew capsules to the International Space Station, with the first operational flights scheduled end 2019/early 2020. The Boeing CST-100 capsule has one additional seat that is intended for paying customers.
- In September 2018, a Japanese billionaire signed up for a circumlunar trip with the SpaceX Big Falcon Spaceship, to be launched on the BFR rocket. The trip has been tentatively scheduled for 2023.

Concerning stays in orbit, several companies are developing modules that would be first connected to the International Space Station and then made fully autonomous once the ISS is retired. While the primary objective would be to offer affordable solutions to governments and corporations for microgravity research, tourism would be a secondary source of income. Axiom Space plans to have their own private space stations ready for launch in 2022, while Bigelow Aerospace, which built the inflatable BEAM module that has been connected to the International Space Station since 2016, is developing two autonomous modules, B330-1 and B330-2, planned for launch in 2021 (Axiom Space, 2019[41]).

Table 4.9. Overview of existing and planned space tourism services

Distance from Earth	Destination	Company	Vehicle		First flight	Available seats for paying customers	Signed up customers (end 2018)	Price per seat
300 000 km	Deep space	SpaceX	Big Falcon Starship (BFS), launched on the BFR rocket		ca. 2023	n.a.	1	n.a.
		Blue Origin	New Glenn		ca. 2023	TBD	n.a.	TBD
400 km	Low-earth orbit	Roscosmos	Soyuz capsule		2001	1	7 (2001-09), 2 signed up for 2021 flight	USD 20-40 million
		Boeing	CST-100 Starliner crew capsule		Expected 2019-20	1	n.a.	USD 58 million (for NASA)
		SpaceX	Crew Dragon capsule		Expected 2019-20	1-3	n.a.	USD 58 million (for NASA)
		Axiom Aerospace	Tourist stay on the International Space Station. Unspecified vehicle		2020	n.a.	n.a.	USD 55 million
		Sierra Nevada	Dream Chaser, vertical launch and horizontal landing vehicle		In development	7	n.a.	n.a.
100 km	Suborbital travel	Virgin Galactic	SpaceShipTwo, airborne horizontal launch and landing vehicle		Expected 2019	6	600	USD 250 000
		Blue Origin	New Shepard, vertical launch and landing vehicle		Expected 2019	6	Ticket sale to start in 2019	TBD

Market studies base their assumptions on the global availability and preferences of high net worth individuals, with a household income of at least USD 200-250 000 or a net worth of a minimum USD 1 million. A 2002 survey found then that 19% of respondents were definitely or very likely interested in undertaking suborbital space travel, and 16% were willing to pay the maximum suggested price of USD 250 000 (the current price of a seat on Virgin Galactic's SpaceShipTwo) (Futron, 2002[42]). In a more recent market study, based on more than 1 000 interviews in 11 countries, Astrium (Airbus Defence and Space) modelled demand according to different price scenarios and projected a very rapid increase in customer demand, growing from some 600 passengers in the second year of operations to more than 40 000 in the seventeenth year (in the conservative high-price scenario) (Le Goff and Moreau, 2013[43]). Depending on the degree of optimism, annual global revenue estimates after ten years of operations range from USD 200 million to 800 million (UK Satellite Applications Catapult, 2014[44]). The most conservative of these estimates is based on a relatively limited customer base (some 1 500 customers in the tenth year of operations).

These forecasts are also driving developments for commercial spaceports, often supported by regional administrations. In the United States, the Federal Aviation Administration issued ten licences for commercial spaceports in eight federal states in 2018 (Alaska, California, Colorado, Florida, New Mexico, Oklahoma, Texas and Virginia) (FAA, 2018[45]). Commercial spaceport projects are also being considered in other countries (e.g. Italy, Sweden, the United Kingdom). The UK government has awarded funding to a vertical spaceport development in northern Scotland, while several spaceports sites for horizontal launch are under evaluation (UK Space Agency, 2018[46]). In Italy, Virgin Galactic has partnered with the Italian Space Agency and Italian companies to launch from a future spaceport in southern Italy (ASI, 2018[47]).

In-orbit servicing

Several governmental agencies and commercial companies have developed, or are in the process of acquiring, some capabilities for in-orbit servicing (Table 4.10). In-orbit servicing involves a number of complex operations in space: the servicing of space platforms (e.g. satellite, space station) to replenish consumables and degradables (e.g. propellants, batteries, solar array); replacing failed functionality (e.g. payload and bus electronics, mechanical components); and/or enhancing the mission (e.g. software and hardware upgrades). This is a major challenge as, when in orbit, space platforms can move at speeds of several kilometres a minute depending on their altitude, and it is quite challenging to have several spacecraft "flying" very close to each other.

One important step includes automated and autonomous rendezvous and docking capabilities, mastered today by organisations in Canada, China, Europe, United States, and the Russian Federation. The first International Docking System Standard is now being used on the International Space Station, to allow a diversity of spacecraft from different countries and companies to dock. Recent developments include the next generation of in-orbit habitation modules, including for example the docking of Bigelow Aerospace's first experimental inflatable module to the ISS in 2016.

Table 4.10. Selected proposed commercial in-orbit servicing services

Space vehicle	Manufacturer	Clients	Estimated launch/start of operations	Orbit	Services
MEV-1 and MEV-2	Northrop Grumman (formerly Orbital ATK)	Intelsat	2019 and 2020	Geostationary	Station keeping, incline reductions, relocations, inspections
Restore-L	MDA/SSL	NASA, to service Landsat-7	2020	Low-earth orbit	Satellite refuelling, relocations
Spacetug	Airbus Defence and Space	n.a.	In development. Several technologies tested on RemoveDEBRIS satellite in 2018.	Geostationary	Satellite servicing and refuelling, debris removal
Robotic Servicing of Geosynchronous Satellites (RSGS)	MDA/SSL	DARPA, SES	2021	Geostationary	Inspection, anomaly correction, upgrades, relocations
Space START	Thales Alenia Space	n.a.	Demonstration flight in 2022	Geostationary	Satellite servicing and refuelling, inspections, satellite deorbits and debris removal
Mission Extension Pods (MEPS)	Lockheed Martin/ Orbital ATK	n.a.	In development	Geostationary	5-year satellite life extension 'pod'

The first commercial in-orbit servicing mission is expected in 2019, by a MEV-1 spacecraft developed by Orbital ATK for an Intelsat geostationary satellite. Services will include inspections and relocations, such as station keeping and incline reductions (Shephard, 2018[48]).

In terms of in-orbit refuelling, some long-term R&D programmes are underway, increasingly supported by satellite communication operators as final customers. They have an interest in extending the commercial life of future commercial spacecraft, which would allow postponing the sizeable investment needed each time to completely replace satellites in orbit (SES Global, 2017[49]). In-orbit servicing also requires, by definition, the capacity to conduct proximity operations. This not only involves robots able to perform the required tasks technically, but also the capability of remaining close enough to the spacecraft to be effectively serviced or repaired.

Some of these planned services also include debris removal. The first successful in-orbit debris removal technology demonstrations took place in 2018. They were carried out by the RemoveDEBRIS satellite, a collaborative active debris removal project involving organisations and companies from France, Germany, the Netherlands, Switzerland and the United Kingdom and co-funded by the European Union's seventh framework programme (FP7) (Surrey Space Centre, 2019[50]). Tests have included the use of nets and harpoons to capture dummy cubesats.

Advances in this area are promising for future commercial in-orbit servicing ventures and orbital space debris cleaning initiatives. The main short-term market is seen in the life extension of geostationary satellites, with some 300 potential candidates, at least in theory (Kennedy, 2018[51]). There are still several limiting factors, including national security concerns and intellectual property and design issues. However, the key benefits of in-orbit servicing are expected in the future. Satellite design is currently heavily restricted by extreme launch conditions, but the possibility of servicing could enable a much more flexible and modular satellite design, able to take advantage of the latest advances in materials and electronics, beyond software upgrades (Jaffart, 2018[52]).

Market forecasts estimate a USD 3 billion market for in-orbit servicing over the 2017-27 period, mainly driven by life extension services (Northern Sky Research, 2018[53]).

Space mining and resources extraction

Space mining and resources extraction is missing from the 2005 promising list of commercial applications (Box 4.2). Fifteen years ago, this activity was considered far too complex and technologically challenging to be included.

In the meantime, there have been several successful scientific missions to asteroids, including two landings (on the asteroids 67P/Churyumov-Gerasimenko and Ryugu) and the sample return missions Hayabusa and Hayabusa-2 (see chapter 5 on space exploration). NASA is also supporting the development of commercial incremental technologies for space exploration, .e.g. for lunar landers in the NASA Small Commercial Lander Initiative (Tawney, 2018[54]).

There are other public and private developments in this area. The United States and Luxembourg have adapted their legal framework in preparation of commercial exploitation of space resources. Luxembourg has also launched the initiative Spaceresources.lu, in partnership with companies from Japan, the United States and the United Kingdom (Luxembourg Space Agency, 2019[55]). One of the partners, the US company Planetary Resources, which has also benefited from NASA contracts and is backed by Google co-founder Larry Page, is currently testing water detection technologies in space on cubesat platforms (Planetary Resources, 2018[56]).

A socio-economic impact assessment on space resources utilisation conducted by the Luxembourg Space Agency foresees as a possible market revenue of EUR 70-170 billion over the 2018-45 period. Resources extraction for rocket and space vehicle propellant is identified as the most economically viable short-term activity in the study, due to high confidence in demand and availability of water on the moon, Mars and other celestial bodies (Luxembourg Space Agency, 2018[57]).

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Chapter 5

SPACE EXPLORATION AND THE PURSUIT OF SCIENTIFIC KNOWLEDGE

This chapter reviews recent developments in space exploration and space sciences, the progress made in human spaceflight missions, as well as the growing challenges posed by space debris. It presents some of the main missions planned in the next decade and highlights specific trends, such as the rise of citizen science and crowdsourcing.

The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

Introduction

Space exploration is a key driver for investments in innovation and science, and it constitutes an intensive activity for space agencies, research institutes, academia and industry. Space science and planetary missions have seen an influx of new actors and new opportunities enabled by digital technologies. Human spaceflight is also developing steadily, also here with new government and private actors and with capabilities on the horizon developed by industry. A crucial challenge for the future will be the handling of space debris.

Space sciences and robotic space exploration

Space sciences and planetary missions have developed markedly over the years, with new actors joining in. Space-based science and exploration missions consist of a wide range of spacecrafts such as flyby spacecraft, orbiters, landers, rovers exploring the sun, planets and celestial bodies in the solar system, and objects and events beyond our solar system. These missions contribute to furthering human knowledge in different scientific fields (e.g. bio-chemistry, climate) and provide invaluable insights into the origins of the universe and to how planets could harbour and sustain life.

While the principal objectives of these activities are scientific to benefit communities of researchers, there may also be significant derived socio-economic impacts, such as technology development and knowledge transfers to sectors beyond the space industry. Space science and exploration activities are also characterised historically by a high degree of international co-operation, not only because of the significant costs of such missions, but also because of the need for deep space monitoring systems based on networks of giant radio antennas installed in different countries (e.g. Australia, Chile, South Africa, the United States) that communicate with the spacecraft.

Space science missions orbiting the earth

Earth-orbiting space science spacecraft, several of which are international missions, are generally dedicated to the study the universe and the sun (without the distortions from the earth's atmosphere) and fundamental physics.

Three of the largest space observatories in extended operation, capturing light and radiation in different regions of the electromagnetic spectrum are supported by the United States. They include 1) the Hubble Space Telescope (a joint mission with the European Space Agency (ESA) launched in 1990), optimised mainly for observations in the ultraviolet and visible regions of the electromagnetic spectrum (NASA, 2018[1]); 2) the Chandra X-Ray Observatory, launched in 1999 and capturing x-rays (Harvard-Smithsonian Center for Astrophysics, 2016[2]); and 3) the Spitzer Space Telescope, a cryogenically cooled infrared telescope, launched in 2003 (NASA, 2017[3]).

Europe operates three operational observatories for high-energy observations (gamma- and x-rays): Gaia, Integral and XMM-Newton (ESA, 2018[4]; ESA, 2018[5]). The Solar and Heliospheric Observatory (SOHO) is a joint US-European mission, dedicated to sun physics and space weather.

A highly anticipated forthcoming mission is the James Webb Space Telescope for infrared and near-infrared observations, currently scheduled for launch in the next couple of years (NASA, 2018[1]). NASA has the overall primary responsibility for the mission, with ESA and Canada contributing several instruments. ESA also provides the Ariane 5 launch vehicle.

The United States and the European Union also have other space science satellites in orbit, in addition to those of other countries, in particular Japan and the Russian Federation. India and the People's Republic of China (hereafter "China") each also recently launched their first dedicated astronomical satellites, ASTROSAT (India) launched in 2015, and the Hard X-Ray Modulation Telescope, HXMT (China), launched in 2017 (Chinese Academy of Sciences, 2018[6]; ISRO, 2017[7]).

In quantum physics, the Chinese experimental quantum communications satellite Micius successfully transmitted entangled photon pairs between ground stations in Beijing and Graz in Austria, over a distance of more than 1 200 km (Yin et al., 2017[8]). This is a potentially groundbreaking discovery for future long-distance secure encrypted communications.

Robotic extra-planetary missions

The last decade has seen some extraordinary firsts in extra-planetary space exploration, including the first landing on a comet (Rosetta/Philae mission); the first high-resolution close-ups of the dwarf planet Pluto; the first soft landing on the far side of the Moon and India's successful low-cost orbiter mission to Mars, to name just a few. Missions are increasingly ambitious and complex, and there are more participating countries than ever before. Table 5.1 shows the most popular extra-planetary destinations of the last 60 years.

As of early 2019, there were orbiters on three of Earth's nearest neighbours (Earth's moon, Venus and Mars). Mars has a total six orbiters from four countries/agencies (India, the Russian Federation, the United States and the ESA) two rovers and one lander (United States) (NASA, 2018[1]). NASA had another two operational orbiters exploring Jupiter (Juno) and the dwarf planet Ceres (Dawn), with the New Horizon probe continuing its journey through the Kuiper Belt after its flyby with the object 2014 MU69 (nicknamed Ultima Thule) in January 2019. In refining its course towards Ultima Thule, the New Horizons spacecraft carried out the most distant course-correction manoeuvre ever conducted (NASA, 2018[9]). The radio signals confirming the manoeuvre travelled more than 6.1 billion km and took 5 hours and 41 minutes to reach the Deep Space Network station in California (Johns Hopkins Applied Physics Laboratory, 2017[10]).

In terms of planned missions, at least 15 missions are foreseen to Earth's moon by 2025 period, from eight countries/space agencies (China, India, Israel, Japan, Korea, the Russian Federation, the United States and ESA), with a few commercial missions from American and Japanese startups planned, including flybys and moon rovers. In parallel, several long-term proposals call for setting up permanent scientific and commercial outposts on the Moon's surface (e.g. ESA's suggestion for a Moon Village by 2040).

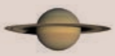
Table 5.1. Popular extra-planetary destinations, 1958-2018

As of November 2018

Planet / celestial body		Number of missions	Number of planned future missions	Orbiters	Landers/ rovers	Selected missions
	Mercury	2 (USA)	1 (carrying 2 orbiters, (ESA, JPN)	Latest: 2004-15 (USA)	..	The 2018 BepiColombo mission is to take seven years to get to Mercury (ESA, JPN).
	Venus	+40 (ESA, JPN, USA, former USSR)	1 (RUS planned for 2026) 2 flybys by BepiColombo in early 2020	1 current orbiter (JPN)	Latest: 1984 (RUS)	Venera 3 (RUS) was the first spacecraft to reach the surface of another planet in 1966. In 2015, the Akatsuki (JPN) orbiter was successfully inserted into orbit.
	Earth	+10 000 satellites launched since 1957	Hundreds	+1 000 operational satellites	..	Satellites used for communications, navigation, meteorology, climate and space science. An increasing number of commercial constellations and very small satellites.
	Earth's moon	+80	14 (IND, CHN, EUR, JPN, KOR, RUS, USA)	3 current orbiters (USA, CHN)	1 current rover and lander (CHN)	The 2019 Chinese Chang'e-4 probe, consisting of a lander and a rover, is the first mission to land on the far side of the moon.
	Mars	+40 (USA, former USSR, ESA, IND)	6 (CHN, ESA, IND, JPN, UAE, USA)	6 current orbiters (USA, ESA, RUS, IND)	2 current rovers, 1 lander (USA)	India's 2013 first Mars orbiter mission (Mangalyaan) was a technical and scientific success. The US company SpaceX is planning a cargo mission to Mars in the early 2020s.
	Phobos (Mars' moon)	..	1 (JPN/USA/CNES)	..	..	The Japanese Martian Moons Exploration (MMX) mission is planned for launch in the early 2020s. MMX will visit Phobos and Deimos, land on the surface of Phobos, and collect a surface sample.
	Jupiter	+5	1 (ESA)	1 current orbiter (USA)	..	Several flybys, making Jupiter the most visited of the Solar System's outer planets. The Juno orbiter (NASA) reached Jupiter in 2016.

Table 5.1. Popular extra-planetary destinations, 1958-2018 *(cont.)*

As of November 2018

Planet / celestial body	Number of missions	Number of planned future missions	Orbiters	Landers/ rovers	Selected missions
 Saturn	+5 (USA, EUR/ITA)	..	Latest: 2004-17 (USA)	..	Several flybys by NASA probes since 1979 (Pioneer 11, Voyager 1 and 2). The 13-year Cassini mission (USA) ended in 2017, when it deliberately plunged into Saturn's upper atmosphere.
 Titan (Saturn's moon)	1 (USA, EUR/ITA)	..	Latest: 2005 (USA, EUR/ITA)	Latest: 2005 (USA, EUR/ITA)	The Huygens probe landed on Titan, Saturn's largest moon, in 2005.
 Uranus	1 (USA)	..	..	..	Flyby of the Voyager 2 probe (1986, NASA).
 Neptune	1 (USA)	..	..	..	Flyby of the Voyager 2 probe (1989, NASA).
 Pluto (dwarf planet)	1 (USA)	..	..	..	NASA's New Horizons space probe conducted a flyby in 2015. The mission provided unprecedented high-resolution images of Pluto's surface.
 Asteroids and comets	+20 (EUR, JPN, USA)	2 (USA)	1 current orbiter (USA)	Latest: 2018 (JPN, EUR)	ESA's Philae (on the Rosetta spacecraft), the first mission designed to orbit and land on a comet, made a partially successful landing on Comet 67P Churyumov-Gerasimenko in 2014. NASA's Dawn space probe entered into the dwarf planet Ceres' orbit in 2015 and was still orbiting it in 2018.

Note: Includes only successful missions (flybys, orbiters, landers and rovers).

The early 2020s are also set to be an eventful period for Mars exploration. The most favourable alignment of the Mars and Earth orbits takes place every 18 months or so and ensures the shortest travel time between the two planets. At least six missions are planned (China, Europe, India, Japan, the United Arab Emirates and the United States) targeting the launch windows in 2020 and 2022. Japan is also preparing an ambitious mission to Mars' moons Deimos and Phobos, including a lander and sample return mission (International Space Exploration Coordination Group, 2018[11]). Going further, a Jupiter mission should be launched in 2022 with the ESA JUICE spacecraft, which will travel to this large planet and look for traces of ice and water on its moons (ESA, 2018[12]). India is considering a mission to Venus. There are also several planned asteroid missions. The Japanese Hayabusa 2 spacecraft (Peregrine falcon) became in September 2018 the first to land moving rovers on the surface of an asteroid. Before it leaves the Ryugu asteroid in 2019, the Hayabusa 2 mothership should release two more landers and touch the asteroid surface itself to collect a sample to bring back to Earth.

Considering the major achievements of recent missions such as the Indian Mangalyaan mission to Mars, the European Rosetta/Philae landing on an asteroid or the NASA New Horizons mission to Pluto, it is easy to forget the inherent challenges of space exploration. Mission success rates for Mars missions are only about 42% (47% if including partially successful missions) and for the lunar missions some 55% (NASA, 2018[13]; OECD, 2014[14]). Indeed, the Google Lunar XPRIZE for privately funded robotic spacecraft to land and travel across the lunar surface expired without a winner in 2018, after several deadline extensions (Diamandis and Shingles, 2018[15]).

The rise of citizen science and crowdsourcing

Institutional missions create enormous amounts of scientific data, and innovative methods have been put in place to make maximal use of the datasets from these and other space science spacecraft and terrestrial telescopes. One example is crowdsourcing, which has seen an increasing number of space science projects appearing in the last years.

Crowdsourcing refers to the "outsourcing" of tasks to large groups of people, often amateur volunteers, generally by means of the Internet, which allow things to be conducted at a much larger scale, and ideally process data and information better and more quickly (OECD, 2017[16]). Some of these tasks could be automated in the near future, via advances in artificial intelligence, but at this stage, the human eye is still the best detector. In 2017, for the first time a multi-planet system was discovered entirely through crowdsourcing, in a project called Exoplanet Explorers, available on the online citizen science platform Zooniverse (NASA, 2018[17]). In only 48 hours, a star with four orbiting exoplanets was detected, after some 10 000 volunteers had combed through data from NASA's Kepler space telescope. The method of detection was the so-called transit method - i.e. the brightness of a host star dips when planets pass in front of them. Volunteers had access to a field guide showing good and bad exoplanet candidates and could also discuss with the responsible researchers or fellow volunteers (Zooniverse, 2018[18]).

The Zooniverse platform, based at the University of Oxford, hosts another 16 active space science projects (as of June 2018), for instance Galaxy Zoo, Planet Four and Solar Stormwatch. The projects, shown in Table 5.2 are mostly supported and funded by space agencies, national and international research agencies and other academic organisations.

In some of these projects, the efforts of volunteers contribute directly to identifying objects or areas of interest, which can be subject to more detailed investigation by researchers. For instance, in the Planet Four project for Mars terrains, volunteers identify terrain structures using low-resolution imagery from the CTX imager on-board the NASA Mars MRO orbiter, which can then be studied in greater detail on the higher resolution images provided by the HiRISE imager, another instrument on the orbiter (Zooniverse, 2018[19]). In other cases, the most important contribution of volunteers is probably the labelling of datasets for algorithm training and improved machine detection of objects.

While crowdsourcing clearly can make important contributions to science, projects need to be carefully designed to be successful, and volunteers need to be trained. The assigned tasks need to be simple and well explained, and in projects with low participation, the quality of the results may be an issue (Mazumdar et al., 2016[20]). Participation rates vary quite significantly across projects, from hundreds to tens of thousands (in part dependant on the duration of the project, but not only).

Table 5.2. Selected citizen science projects for space science (solar system, sun and universe)

Active projects as of June 2018

Project	Volunteer tasks	Data source	Number of volunteers (rounded to nearest hundred)
Backyard Worlds: Planet 9	Scan the realm beyond Neptune and distinguish real celestial objects (brown dwarfs and low-mass stars) from image artefacts.	Wide-field Infrared Survey Explorer (WISE) mission (NASA)	47 600
Exoplanet Explorers	Detect exoplanets by looking for a dip in a star's brightness as a planet crosses (transits) in front of it.	Kepler Space Telescope (NASA)	20 000
Planet Hunters	Find planets around stars.	Kepler (K2) Space Telescope (NASA)	n.a.
Project Our Planet from Solar Storms	Classify clouds of solar matter by their complexity (by analysing and ranking pairs of imagery).	STEREO spacecraft (NASA)	600
Solar Stormwatch II	Make detailed traces of the outer edge of each solar storm. This contributes to refining and improving estimates of each storm's arrival time at Earth.	STEREO spacecraft (NASA)	3 500
Galaxy Zoo	Classify galaxies according to their shapes.	Dark Energy Camera Legacy Survey (DECaLS) and Sloan Digital Sky Survey	9 200
Gravity Spy	Classify and characterise glitches (instrumental and environmental noise) in the dataset.	Laser Interferometer Gravitational-wave Observatory (LIGO) (National Science Foundation)	12 500
Milky Way Project	Detect objects and structures in the Milky Way (e.g. bubbles, bow shocks, star clusters, galaxies).	Spitzer Space Telescope and Wide-field Infrared Survey Explorer (WISE) (NASA)	11 300
Radio Meteor Zoo	Identify meteor echoes during meteor showers. Automatic detection algorithms try to detect specific shapes associated with meteor echoes. However, none of them can perfectly mimic the human eye which remains the best detector.	Belgian RAdio Meteor Stations (BRAMS) network (Belgian Institute for Space Aeronomy)	6 500
Supernova Hunters	Filter night-time multi-galaxy data to detect supernovae.	Panoramic Survey Telescope and Rapid Response System (University of Hawaii)	7 800

Source: Adapted from Zooniverse (2018[21]), *Projects website*, *http://www.zooniverse.org/projects* (accessed on 06 June 2018).

Paving the way for new human spaceflight missions beyond Earth's orbit

More countries than ever are investing in indigenous human spaceflight capabilities, with strong policy support in the United States, China and the Russian Federation. In many parts of the world, governments and industry are developing new technical capabilities for human exploration of the cislunar space, i.e. the region between the earth and the Moon, the lunar surface, and eventually Mars. In early 2019, human spaceflight activities take place in the low-earth orbit via stays in the International Space Station (ISS) and the Chinese Tiangong-2 experimental space station. However, this is likely to dramatically change in the coming decade, if current plans hold. Table 5.3 summarises current and planned spaceflight capabilities.

The ISS has continuously supported astronauts in orbit since 2000. There are 15 countries involved in this partnership: Canada, Japan, the Russian Federation and the United States and 11 participating ESA country members (Belgium, Denmark, France, Germany, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland and the United Kingdom). The ISS has served as a catalyzer for commercial spaceflight development. Already, there are several available space vehicles for delivering cargo and crew supplies to the ISS: three government capsules from the ESA, Japan and the Russian Federation; and two US commercial capsules, provided by SpaceX and ATK Orbital. A third US commercial capsule by Sierra Nevada Corporation should fly at least six resupply missions by 2024, with its first mission in 2019. The only way for crews to reach the station is by using the Russian Soyuz capsules, but US companies Boeing and SpaceX, contracted by NASA, are developing commercial crew capsules, with the first crew test flights scheduled in 2019-20 (NASA, 2018[22]).

Planning human presence beyond Earth's orbit, the United States plans to deploy a manned outpost orbiting the moon (the *Gateway*) in the 2020s, with the first manned mission by 2023 (NASA, 2018[23]). This project will be collaborative, including possible contributions from other governments and the private sector (NASA, 2017[24]). NASA is finalising work on its new heavy-lift launcher, the Space Launch System (SLS), and the human-rated capsule (Orion), which will play a key role in the plans for the Lunar-Orbital Platform-Gateway and subsequent Mars exploration. The first launch, currently scheduled for 2019-20, will be an unmanned mission with the Orion capsule flying several thousand kilometers beyond the Moon and back to Earth (NASA, 2018[23]).

While existing Chinese space-based installations include the Tiangong-2 test bed space station, work continues on the permanent Chinese Space Station, which should be operational in 2022. Furthermore, the China Academy of Space Technology is working on successors to the current Shenzhou crew capsule. The new-generational capsule would be reusable and bigger, holding four to six taikonauts, compared to the current three, and come in two different versions: one 14-tonne version for trips to the Chinese Space Station, near-Earth asteroids and Mars; and a 20-tonne version (Jones, 2018[25]). China's longest manned space mission to date is the Shenzhou-11 mission, a 32-day visit to the Tiangong-2 space station in 2016 (Griffiths, 2016[26]).

The Russian Federation is equally working on a next-generation crew vehicle, called Federatsiya (Federation), replacing the current Soyuz capsule. The first unmanned flight is scheduled for 2022, with a manned flight scheduled the following year, in 2023 (TASS, 2017[27]). The capsule is set to fly on top a new launcher, the Soyuz-5 (TASS, 2017[27]).

In parallel to these government-led initiatives, SpaceX, a US company, is developing a fully reusable super-heavy-lift launcher (currently labelled BFG) for cargo and crew missions to Mars. The first manned mission to Mars could take place within the next decade. Other private companies, such as Virgin Galactic and Blue Orbital, continue to develop space tourism activities, aiming to offer zero-gravity/parabolic flights, sub-orbital flights and orbital space travel to private consumers (see also Chapter 4).

Many science and exploration missions are by definition highly complex, with space agencies managing multiple actors, objectives and suppliers while also having to adhere to tight cost and time schedules. A case in point is the challenging development of the James Webb Space Telescope, currently two and half years behind schedule, with delays caused by human errors, excessive contractor optimism, use of new untested technologies and the shear complexity of the project.

Space agencies aim to carry out their activities as cost-efficiently as possible while avoiding failures and malfunctions, and there have been several recent developments in specific project management and procurement procedures for science and exploration. A common thread is an increased sharing of risk between space agencies and private sector contractors.

Table 5.3. Human spaceflight capabilities in selected parts of the world

As of 2019, including planned programmes for 2020-29

	Orbital capabilities		Human-rated launcher/crew capsule capabilities	
	2010-19	2020-29	2010-19	2020-29
United States	International Space Station (ISS)	ISS, Gateway	Space Shuttle[2]	Space Launch System/Orion capsule Potential commercial contracts with: – Boeing Atlas V /CST-100 – SpaceX Falcon 9 /Dragon crew capsule
Europe	ISS	ISS	None	None
China	Tiangong-1[1] and Tiangong-2	Chinese Space Station	Long March/ Shenzhou capsule	Long March/Shenzhou second generation
Russian Federation	ISS	ISS	Soyuz launcher and capsule	Soyuz/Soyuz-5 launchers and Soyuz capsule/ PTK Federatsiya capsule

Notes: 1. Tiangong-1 was deorbited in 2018. 2. The space shuttle programme stopped in 2011.

- In Japan, JAXA has recently restructured its procurement and programme control mechanisms, after malfunctions in the 2016 ASTRO-H X-ray astronomy mission (Kinoshita, 2018[28]). The ASTRO-H mission, which took nine years to develop, lost communications with ground control only 40 days after launch. While the malfunction had multiple causes, it was found that several risks had been underestimated in the early phases of the project. This triggered a review of JAXA's overall project management and procurement mechanisms. As a result, the very early, explorative stages in the project cycle have been strengthened and extended, to eliminate potential R&D risks as early as possible. Responsibilities between the space agency and its supplying companies have also been reshuffled, with contractors taking on more independent responsibility from the preliminary design phase onwards. These changes are being applied to the management of the forthcoming Martian Moons exploration mission (MMX) and the X-ray astronomy recovery mission (XARM).
- Both ESA and NASA are considering different types of public-private partnerships for space exploration, with the private partner contributing more funding and covering more risks than what has previously been the case. For ESA, this would build on already existing partnerships in earth observation and satellite communications (Germes, 2018[29]). In the 2018-2030 NASA Exploration Campaign, the agency foresees to use commercial robotic lunar payload service contracts for surface delivery. Service contracts are also under consideration for the mid-to-large (500-1 000kg) lunar lander (Tawney, 2018[30])

The challenges and opportunities of space debris

The number of objects in space is expected to grow exponentially over the next decades, in part due to the ongoing small satellite revolution and an increase in the number of space actors. Space objects include not only spacecraft of various sizes and functions, but increasingly also space debris. Space debris refer to inactive, manmade objects and their fragments, that are orbiting Earth and eventually re-entering the atmosphere (ESA, 2017[31]). They include everything from discarded lens caps to large spent rocket stages (or even space stations), with the majority of objects smaller than 1 cm.

The uncontrolled presence of space debris in orbit can pose severe risks to functional satellites and other spacecraft. Several satellite failures have already been attributed to space debris collisions and commercial satellite operators and the International Space Station partners have had to repeatedly use space debris avoidance manoeuvres over the past years (UNOOSA, 2018[32]).

Still, the growing risks of space debris and the need to act cooperatively to protect congested orbits may contribute to opening the way for new technological solutions.

The space debris challenges

Space debris have been accumulating since the launch of the first satellite in 1957, both as a result of routine space operations and accidents and explosions. Since 1957, almost 9 000 satellites have been placed in orbit, with about 5 000 satellites still in orbit in early 2019 (1 200 of which are operational). In the last 60 years, there have been more than 500 break-ups, collisions and explosions, so-called fragmentation events.

Due to orbital decay – the process that leads to gradual decrease of the distance between two orbiting bodies – debris accumulation is uneven among different orbits. The highest concentrations of objects are found in the low–earth orbit between 800 and 1 000 kilometres of altitude and towards 1 400 kilometres. Other debris belts are close to the orbit of navigation satellite constellations, between 19 000 and 23 000 kilometres of altitude, and in the geostationary orbit at around 36 000 kilometres.

The amount of objects accumulated in Earth orbits, as reported by the European Database and Information System Characterising Objects in Space (DISCOS) database, has significantly grown over time. In particular, there has been a marked increase of objects in the low-earth orbit over the last decade. More than 13 000 objects tracked by DISCOS were located in the low-earth orbit at the end of 2017.

This accumulation of space debris constitutes a considerable and growing collision hazard for both satellites in orbit and satellites travelling through the space debris belt during orbit-raising and lowering. Given that the velocity of objects can reach up to 10 kilometres/second in low-earth orbit (LEO), eventual impacts involving larger objects may lead to the destruction of an entire spacecraft (ESA, 2017[31]). It has been argued that the increased use of electric propulsion for orbit-raising increases the length of exposure for satellites during orbit-raising.

Furthermore, people and installations on Earth can be at risk. While the majority of objects burn when entering the atmosphere, estimates suggest that, due to their size, 10 to 20% of big objects reach the earth's surface (CNES, 2017[33]). Several large spacecraft have been safely deorbited over the years, including the controlled deorbit of the 120 metric tonnes Mir space station over the South Pacific Ocean in 2001. But several large structures have also fallen back to Earth in an uncontrolled manner, most recently the Chinese spacelab Tiangong 1, which burnt up over the Pacific Ocean in 2018.

Table 5.4. Space debris in numbers

Number of launches since the start of the space age in 1957	About 5 400
Number of satellites placed into Earth's orbit	About 8 900
Number of satellites in Earth's orbit	About 5 000
Number of operational satellites	About 1 900
Number of debris objects regularly tracked by the US Space Surveillance Network and maintained in their catalogue	About 23 200
Estimated number of break-ups, explosions and collision events resulting in fragmentation	More than 500
Total mass of all space objects in Earth's orbit	About 8 400 tonnes
Number of debris objects estimated by statistical models to be in orbit	34 000 objects >10 cm 900 000 objects from 1 cm to 10 cm 128 million objects from 1 mm to 1 cm

Source: Adapted from ESA (2019[31]), *Space debris: the ESA approach*, *https://download.esa.int/esoc/downloads/BR-336_Space_Debris_WEB.pdf*.

The way forward: International cooperation and private initiatives

Mitigation efforts include the systematic surveillance and tracking of existing objects and preventive regulations and guidelines to reduce the future amount of debris. Possible technical solutions for active debris removal are being explored by space agencies and some private companies.

Several public and private actors make efforts to identify, map and track debris objects in different orbits. The US Department of Defence's Space Surveillance Network (SSN) is a global network of ground- and space-based radars, lasers and telescopes that currently track some 23 000 orbiting pieces of debris larger than 10 cm in low-earth orbit (LEO) and 30 cm in geostationary orbit (GEO). More than half of the catalogued items, some 56%, are fragments from the more than 500 recorded fragmentation events. Around 38% of the SSN`s catalogue include large space debris such as derelict spacecraft and upper stages of launch vehicles, carriers for multiple payloads and mission-related items. Functional satellites account only for 6% of catalogued items. A new surveillance and tracking system, the Space Fence, is currently under development and testing, and should be able to identify and track much smaller objects than currently possible (Lockheed Martin, 2019[34]).

Other countries and organisations also track and classify space objects, The European DISCOS database collects information on space objects, including launch information, object registration, launch vehicle descriptions, etc. The dataset comprises more than 40 000 identifiable items (ESOC, 2018[35]). The European Union supports space surveillance and tracking capabilities and services in the EUSST project, funded by Horizon 2020. Japan is planning to update and extend national capabilities and Korea is developing the OWL-Net network of robotic optical telescopes (Yoshitomi, 2018[36]; Choi et al., 2018[37])

Existing catalogues cover only a fraction of actual collision-prone objects. Estimates from debris environment modelling exercises indicate that around 166.8 million debris objects bigger than 1 millimetre may currently be circling the earth (ESA, 2017[31]). Of these objects, 166 million would be smaller than 1 cm.

This is opening the market for commercial products and services collecting, processing and analysing data. One example is the US start-up LeoLabs, which proposes space debris mapping services via radars located in different parts of the world to public and private satellite operators. The main innovation lies in the data platform made available to operators and developers, which addresses the fundamental shortage of space situational awareness data in the sector and provides datasets that can be used to train and perfect object-detecting algorithms and develop applications. The company plans to have six low-cost radars up and running by the end of 2019.

An important avenue of action is the sharing of data. The US Strategic Command has data-sharing agreements with some 20 countries (Australia, Belgium, Brazil, Canada, Denmark, France, Germany, Italy, Israel, Japan, Korea, the Netherlands, New Zealand, Norway, Poland, Romania, Spain, Thailand, the United Arab Emirates and United Kingdom), the European Space Agency, EUMETSAT and almost 80 commercial satellite owners, operators and launch providers (US Strategic Command, 2018[38]). In 2017, the US Strategic Command issued hundreds of warnings to their partners, with more than 80 confirmed collision manoeuvres from satellite operators (Weeden, 2018[39]).

The problem of space debris and the challenges it poses require coordinated efforts from both public and private actors at the global level. Discussion are currently taking place at the Inter-Agency Space Debris Co-ordination Committee (IADC) and the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS). Private actors also have an important role to play as satellite operators and developers of technological solutions.

- The Inter-Agency Space Debris Co-ordination Committee includes 13 major space agencies which exchange information on space debris research activities. The main goal is to foster cooperation in space debris research, review the progress of ongoing cooperative activities, and identify potential debris mitigation options (IADC, 2018[40]). The IADC have produced several guidelines and draft plans over the last decade, including the 2007 "Space Debris Mitigation Guidelines", which were later endorsed by a United Nations' General Assembly resolution (see Table 5.5). Later, in 2015, during its 33rd meeting, the IADC underlined the necessity of a concrete plan to mitigate the effects of the fast-appearing large constellations of small satellites in LEO (IADC, 2017[41]).
- The IADC also participates in and contributes to the United Nations space debris activities via the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space (UN COPUOS). The Committee offers governments and organisations a platform to facilitate the exchange of information in the area of space debris research. Recently, the outcomes of these interactions led to the publication of a compendium of space debris mitigation standards (UN COPUOS, 2018[42]).

In addition to the work of the IADC and of the UN COPUOS, several other international cooperation mechanisms exist. First, the European Code of Conduct for Space Debris Mitigation was developed and formally adopted in 2004 by the Italian Space Agency (ASI), the British National Space Centre (the current UK Space Agency), the French Space Agency (CNES), the German Aerospace Agency (DLR) and the European Space Agency (ESA). The Code defines measures to reduce on-orbit break-ups and collisions of spacecraft, facilitate debris removal and limit the number of objects released during normal spacecraft operations. Second, ESA's Space Debris Mitigation Policy for Agency Projects, launched in 2014, sets the technical requirements on space debris mitigation for projects run by agencies and defines the associated internal responsibilities. Finally, the International Telecommunications Union

(ITU) Recommendation ITU-R S.1003.2 of 2010 establishes guidelines about disposal orbits for satellites in the geostationary satellite orbit to decrease debris accumulation locally.

Table 5.5. Selected international cooperation mechanisms in the area of space debris

Year	Organisation	Mechanism
2017	Inter-Agency Space Debris Coordination Committee (IADC)	IADC Statement on Large Constellations of Satellites in low-earth Orbit
2016	United Nations Committee on the Peaceful Uses of Outer Space (COPUOS)	Compendium of space debris mitigation standards adopted by states
2014	ESA	Space Debris Mitigation Policy for Agency Projects
2010	UN COPUOS	Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space
2010	International Telecommunications Union (ITU)	Recommendation ITU-R S.1003.2, “Environmental protection of the geostationary-satellite orbit”
2007	IADC	Space Debris Mitigation Guidelines
2004	ASI, British National Space Centre, CNES, DLR, ESA	European Code of Conduct for Space Debris Mitigation

ESA is currently developing new models to analyse space debris and their dynamics over time and evaluate the effectiveness of mitigation practices, such as the Debris Environment Long-Term Analysis (DELTA) tool (ESOC, 2016[43]). The model forecasts future trends on the basis of different possible individual mitigation actions implemented in the present. Scenarios can be built for the low, medium and geosynchronous Earth orbits, over a number of years and for all objects larger than a user-defined size. Several conditions can be selected to characterise the predictions, including, among the others, future traffic profiles and the enforcement of debris mitigation and active debris removal measures. However, even in case of full compliance with existing rules, long term debris proliferation will continue (ESA, 2017[44]). International cooperation guidelines trying to mitigate the creation of space debris may slow down the accumulation of space objects, but will not resolve the problem and eliminate the risks. For this, active debris removal would be necessary.

For this reason, several public and private actors are working to identify potential space debris removal solutions. ESA’s Clean Space initiative is looking at the required technology developments, including advanced image processing, complex guidance, navigation and control and innovative robotics to capture debris. In 2018-19, the European RemoveDebris mission is testing several active debris removal technologies on-orbit.

Meanwhile, private sector actors are developing products and services to meet the demand for space debris removals. The goal is to develop commercially affordable debris removal solutions adopting innovative technics to capture and then destroy large debris objects, while monitoring smaller objects. As an example, Astroscale is developing deorbit services using small satellites, capable of docking with big debris objects and bringing them to the atmosphere to be burnt. Both Airbus and Thales Alenia Space are developing on-orbit servicing vehicles with debris removal functionalities (Lamigeon, 2018[45]).

International cooperation is necessary to mitigate the problem of debris accumulation in Earth’s orbits. Timely and coherent international coordination and shared agreements on the “rules of the game” will be crucial. Regulations and guidelines need to adapt to the evolving nature of space activities, and innovation. Public authorities and governments in general must make sure that directives are well received and then respected by space users in every country. This approach does not have to come at the cost of limitations in private actors’ initiative in the space sector. One of the most important roles of governments is still to support commercial activities in space. Creating the right institutional framework and incentives for private business is essential to promote the role of space as a provider of socio-economic benefits. Governments should advocate the importance of respecting debris mitigation rules in order to reduce the risks associated to investments in space.

Promoting and sustaining space surveillance activities is another key area for policy intervention. This entails supporting existing space surveillance and tracking (SST) systems which make it possible to detect and catalogue space debris and predict their orbits (ESA, 2017[44]). It is also important to develop improved analytical tools to derive applications and services, as it is the case for collision warning systems. Both public and private actors can turn these space debris uncertainties into opportunities for collaboration and new technological developments.

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Chapter 6

A NEW SATELLITE COMMUNICATIONS ENVIRONMENT

The chapter briefly reviews the state of play in satellite communications, which is undergoing significant transformation. For decades, satellite communications have been the fastest growing commercial space market, driving innovation and growth along the space sector's value chains. New technologies, business models and consumer behaviours are disrupting markets (e.g. television, broadband and the Internet of Things), with impacts throughout the space sector's value chains.

The state of play in satellite communications

Telecommunication services rely on the complementary capabilities of different types of networks, whether they be fixed and terrestrial mobile networks, or satellite networks (OECD, 2016[1]). In this complex infrastructure, satellite networks occupy a special niche based on their technical capabilities, as they can broadcast signals over large geographic areas. They have the capacity to deliver data, voice and video services to remote and rural locations, as well as to provide telecommunication services to users on the move (e.g. ships at sea, aircrafts). In this context, satellite communications have been the fastest growing market for the space industry, representing at times almost half of commercial satellite manufacturing revenues, driving innovation and growth along the space sector's value chain (OECD, 2014[2]). But the state of play in satellite communications have recently been changing.

As key actors in the broader telecommunications environment, satellite network operators lease or sell bandwidth capacity from their satellites in-orbit. Many of them have in parallel developed full turn-key solutions and equipment to bring value-added services and expand their customers' base. These network operators have traditionally branched out between providers of fixed satellite services (i.e. leasing capacity for video, voice and data traffic – more than 50 operators around the world) and providers of mobile satellite services (i.e. addressing specifically users in maritime and aeronautical markets in particular – around a dozen operators). But this line, based on different technological solutions and international spectrum sharing allocations, is blurring ever more, as all satellite network operators diversify their activities, invest in different types of satellites to complement their fleet, and increasingly compete in existing markets (OECD, 2016[3]).

Satellite networks operators link up with suppliers of electronics equipment, and value-adding services providers supporting the consumer markets. These include direct-to-home (DTH) providers and very small aperture terminal (VSAT) suppliers, many of which deliver full network solutions to users. Lines are also increasingly blurring between network operators and multimedia providers, as vertical integration and concentration of telecommunications and content companies are accelerating in many parts of the world (OECD, forthcoming[5]). Estimates for satellite communications markets vary, but fixed satellite services could amount to USD 17.9 billion in 2018 (i.e. backhaul, broadcasting); mobile satellite services around USD 4 billion (i.e. networks of communications satellites intended for use with mobile terminals); satellite radio some USD 5.8 billion and satellite broadband representing some USD 2.4 billion in revenues (Bryce Space and Technology, 2019[4]).

As seen in previous chapters, the space industry is currently being transformed by new manufacturing processes and technological innovations. Focussing briefly on satellite communications in this chapter, the state of play is particularly affected by:

- General developments in communication networks and services' markets around the world, with expanding terrestrial networks (see the OECD extensive analysis of telecommunication markets and their policy environment on the *OECD Broadband Portal* (OECD, 2019[6]);
- The roll-out of innovative space technologies in telecommunications (such as the new generation of High-Throughput Satellites (HTS); reprogrammable satellites that can adapt to changes in bandwidth demand from different regions and customers; new ground segment equipment) with significant increases in total amounts of capacity in orbit, leading to satellites services' declining prices;
- Evolving customer needs and requirements, particularly when accessing television services and connectivity on the move (see section 6.2);
- New entrants' business models and the possible impacts of large satellite constellations, particularly for future satellite broadband services (see section 6.3 and OECD (2017[7])).

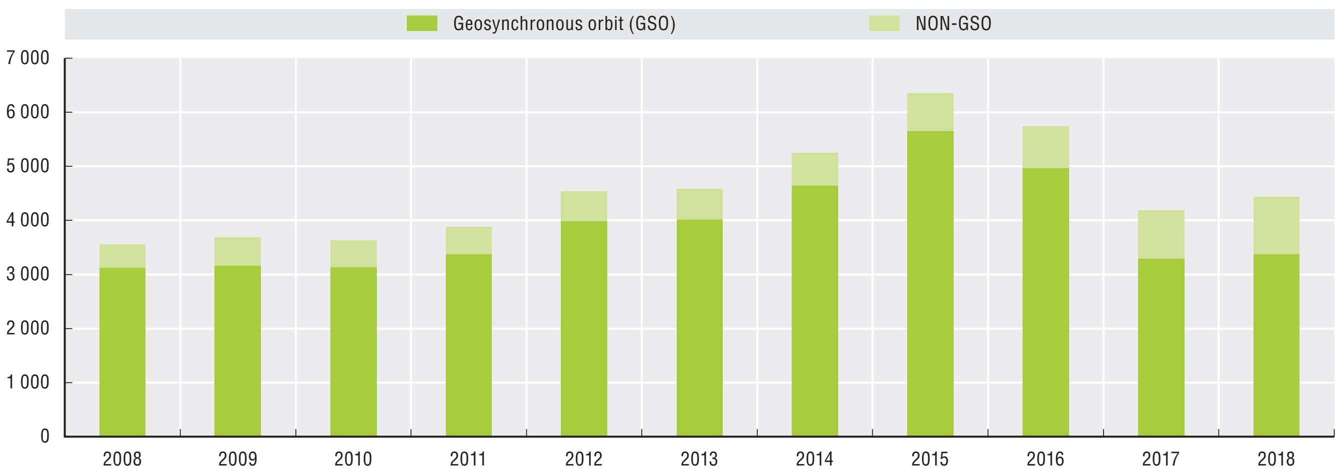
These elements are impacting commercial satellite network operators' strategies, as many have been postponing their procurement orders for new geostationary communications satellites (that usually last for fifteen year or more), with possible lasting effects in the commercial space sector.

The number of geosynchronous (GSO) satellite filings (i.e. an indicator of potential future GSO demand, as operators need to secure orbital slots and spectrum allocations, before they procure and launch satellites) has significantly risen over the last decade almost doubling from 2008 to 2015, before slowing down the following years (Figure 6.1). This is an imperfect indicator as many companies go through the filing process (first domestically then national administrations register the satellite networks at the ITU on behalf of the operators) to reserve orbital slots and frequencies, and do not always pursue development. Still, even with slowing-down trends, the current downturn in the sales of geosynchronous telecommunications satellites has been rather brutal, with only five commercial satellite orders in 2017, down from 17 in 2016 and 24 in 2015. As a consequence, out of the 15 different space manufacturers around the world able to design and produce geostationary satellites (a record number of companies for an ever smaller market), several are now starting to exit the commercial GSO market, to compete on institutional and defence-related space markets (see Chapter 1).

In parallel, international filings for non-geosynchronous satellites, i.e. satellites in lower orbits, have continuously grown over the period 2008-18, from 438 filings in 2008 to a record 1 066 in 2018, with more recent domestic filings to be included (International Telecommunication Union (ITU), 2019[8]). The list of satellite network operators and projects are growing, as many actors are investing in large satellite constellations.

Figure 6.1. Satellite filings by orbit type

Total number of filings



Source: ITU (2019), “ITU Radiocommunication Bureau (BR) 2018 Annual Space Report to the STSC 2019 Session on the use of the geostationary-satellite orbit (GSO) and other orbits”.

The next two sections provide a brief overview of satellite television markets, and of broadband services and the Internet of Things.

Satellite television at a crossroad

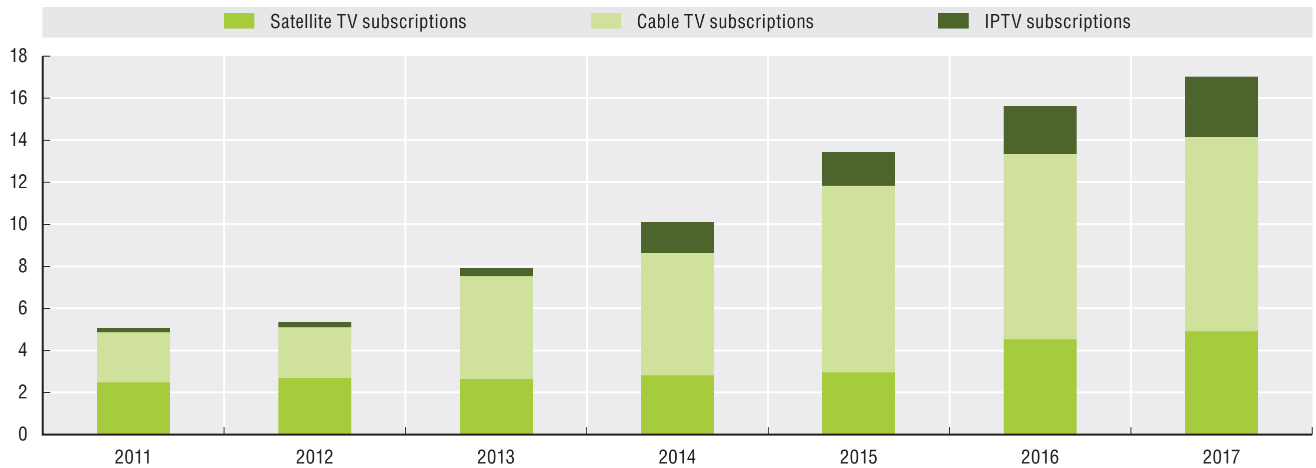
For many years, satellite networks have been the only way for millions of people to receive television programming in remote and rural areas, offering also for populations in urban areas different choices of channels. Satellite television or direct-to-home television broadcast (DTH) is today widely available in OECD countries via one or more suppliers, with signals received by satellite dishes and set-top boxes, often complementing other subscription based television services (pay-TV) provided by cable operators.

But the market structure for television programming and broadcasting activities has changed significantly, as all countries have introduced digital television and many have switched off analogue television in the past decade. Telecommunications operators now routinely offer television services bundled with other services, via Internet Protocol Television (IPTV) as part of triple play or quadruple play packages (i.e., television and telephone; broadband, adding mobile for quadruple play) (OECD, 2018[9]). Video on demand has also become an important channel to distribute audio-visual content, with an increasing number of suppliers offering streaming or downloads on the Internet. For example, increased competition now comes from streaming platforms and Subscription Video on Demand providers such as Netflix and Amazon Prime, which were relatively negligible five years ago. Many of the large media companies that are traditional customers of satellite capacity to deliver television programmes via direct-to-home platforms (e.g. Sky, Dish, DirecTV, Tata Sky Ltd) are also launching their own streaming platforms. As business models, products and services are changing rapidly, the role of telecommunication operators are evolving, with important policy implications (OECD, forthcoming[5]).

In this context, when comparing satellite TV, cable TV and IPTV subscriptions, cable-TV leads, but the number of satellite TV subscriptions has more than doubled since 2011, reaching 4.92 subscriptions per 100 inhabitants in 2017 (Figure 6.2). Internet Protocol Television (IPTV) subscriptions have also been rising steadily since 2014, supported by smartphones' developments.

Figure 6.2. Subscribers of TV broadcasting by technology

Number of subscriptions per 100 inhabitants

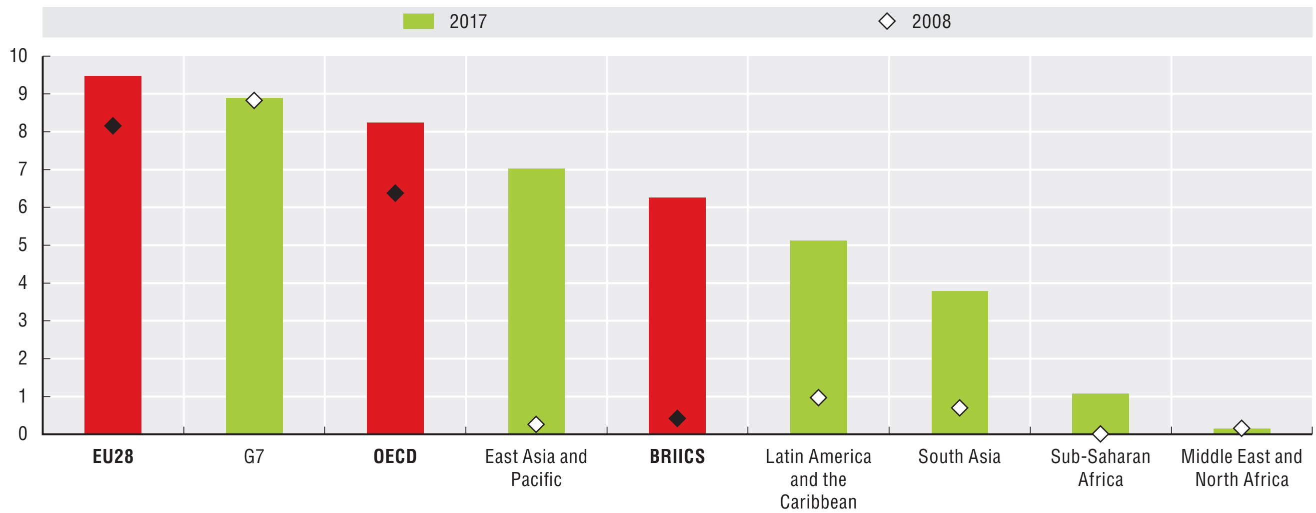


Source: Calculations based on ITU World Telecommunication/ICT Indicators 2019 database.

In terms of geographic coverage, Europe has the highest penetration of satellite TV subscriptions (Figure 6.3), and the recent downturn in satellite television has so far been limited to some regions (mainly concentrated in North America). When examining the rates of subscriptions Sub-Saharan Africa and East Asia are the fastest growing regions (Figure 6.4). However, they both had a very low penetration of satellite TV at the beginning of the period. East Asia registered an annual growth in subscriptions as high as 44.2%, followed by BRIICS (35.1%), and other developing regions including South Asia (20.6%) and Latin America and the Caribbean (20.3%).

Figure 6.3. Subscribers of satellite TV by region

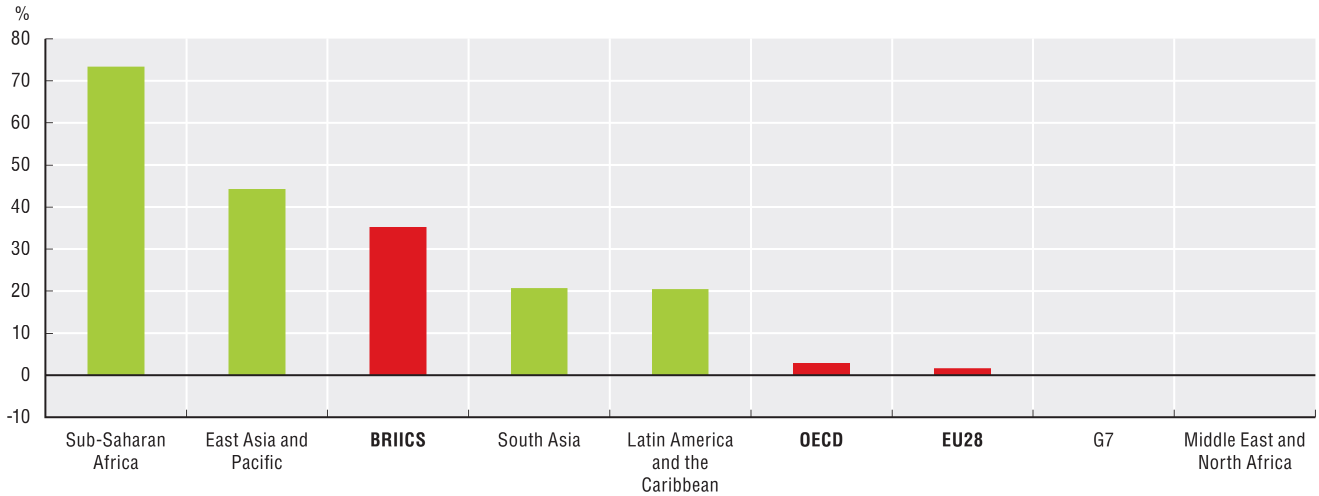
Number of subscriptions per 100 inhabitants



Source: Calculations based on ITU World Telecommunication/ICT Indicators Database, January 2019.

Figure 6.4. Growth of satellite TV subscriptions by region, 2008-17

Average annual growth rate



Source: Calculations based on ITU World Telecommunication/ICT Indicators Database, January 2019.

Looking ahead, direct-to-home television markets could continue to grow in some parts of the world, where advanced terrestrial solutions for television and video streaming platforms are often not yet deployed. But satellite networks operators are looking at emerging applications for their satellite fleets, such as consumer broadband and the Internet of Things (IoT).

Consumer broadband and Internet of Things on the rise

Broadband connectivity is becoming a crucial driver for economic activity around the world (OECD, 2019[10]). In addition, the Internet of Things may rapidly transform business processes and even our societies at an unprecedented scale with possibly 25 billion devices connected by 2020 (OECD, 2016[11]).

Broadband services to regions unserved or underserved by terrestrial technologies represent therefore a growth market virtually every satellite network operator is now addressing. In this context and as recent OECD analysis reveals (OECD, 2017[7]), satellite systems could increasingly:

i) fill the coverage gap to deliver broadband service to residential and business users in remote and isolated geographic areas by offering ubiquitous and easy to deploy solutions ("last mile" solution);

ii) provide backhaul or backbone network interconnection to the global Internet for terrestrial fixed or mobile telecommunication network service providers (the "middle mile" solution);

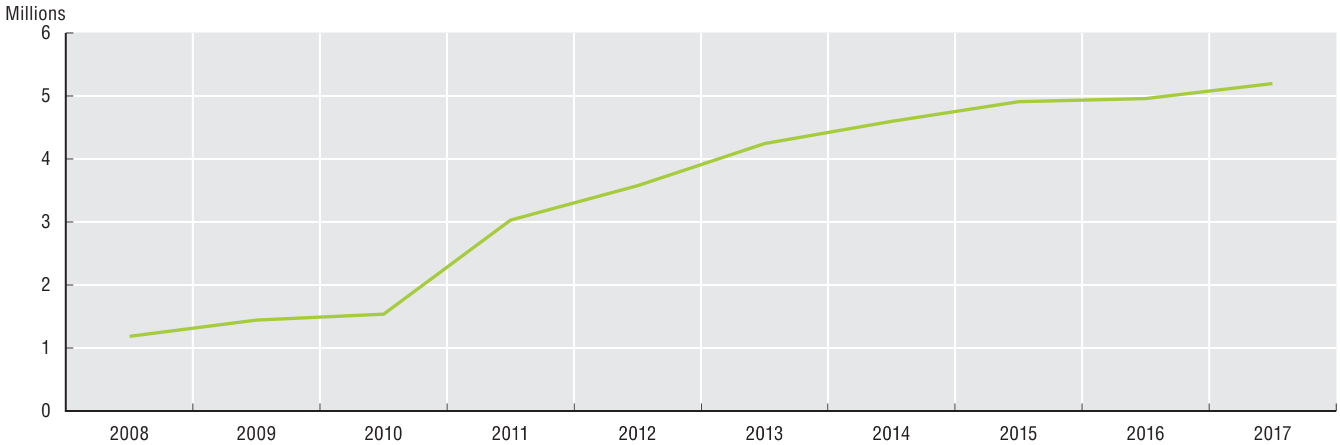
iii) and potentially expand the market for satellite broadband through the use of satellites in low-earth orbit to deliver broadband to lower density areas closely adjoining urban areas (OECD, 2017[7]).

Compared to other technologies, satellite broadband still accounts for a very small share of total fixed broadband subscriptions (less than 1% in most countries). Digital subscriber line (DSL) is still the dominant technology, making up 38% of fixed broadband subscriptions in the OECD area, but it is gradually replaced by fibre (OECD, 2019[10]). Satellite subscriptions have grown steadily over the last decade, thanks to the rolling out of new technologies. The number of subscriptions in absolute terms rose from around 1.2 million in 2008 to more than 5.2 million in 2017 (Figure 6.5). The number of satellite broadband subscriptions per every 100 inhabitants almost quadrupled from 2008 to 2017, increasing from 0.018 to 0.07.

G7 and OECD countries display the highest satellite broadband penetration, with 0.23 and 0.14 subscriptions respectively per every 100 inhabitants in 2017, with a doubling in the number of subscriptions since 2008. The United States and Australia have the largest number of subscriptions per 100 inhabitants (around 0.5), in view of their geography and availability of services (Figure 6.6).

Figure 6.5. World-wide satellite broadband subscriptions

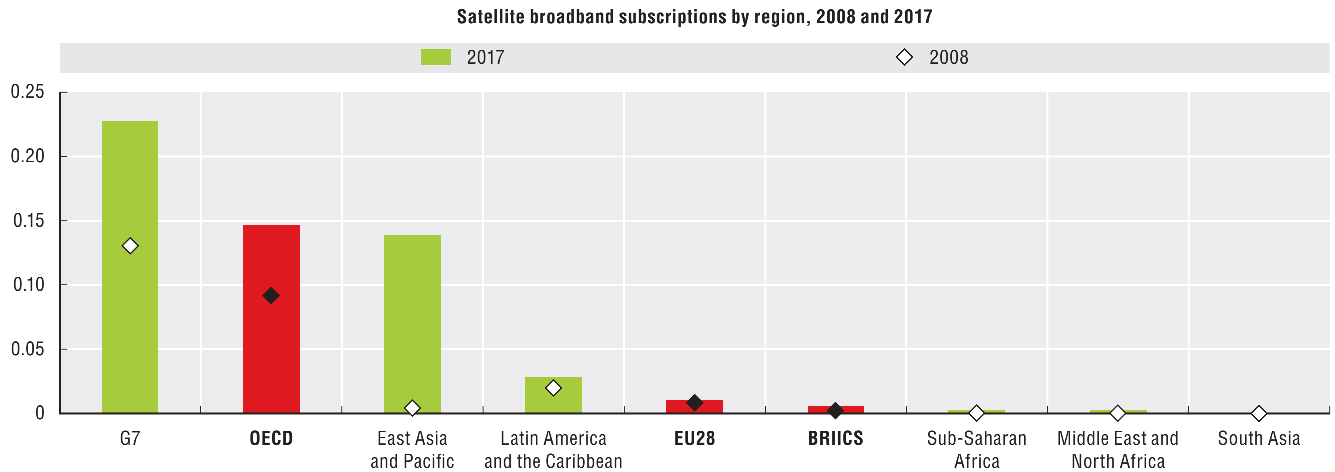
Total number of subscriptions

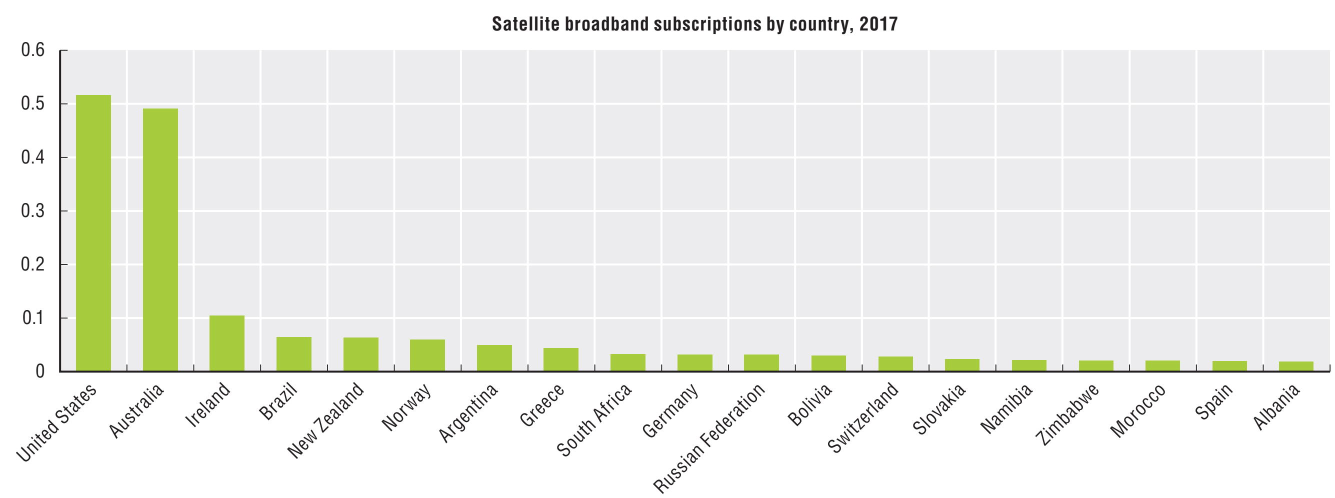


Source: OECD, Broadband Portal, *http://www.oecd.org/sti/broadband/broadband-statistics*; ITU World Telecommunication/ICT Indicators Database, January 2019.

Figure 6.6. Satellite broadband subscriptions by region and by country

Number of subscriptions per 100 inhabitants



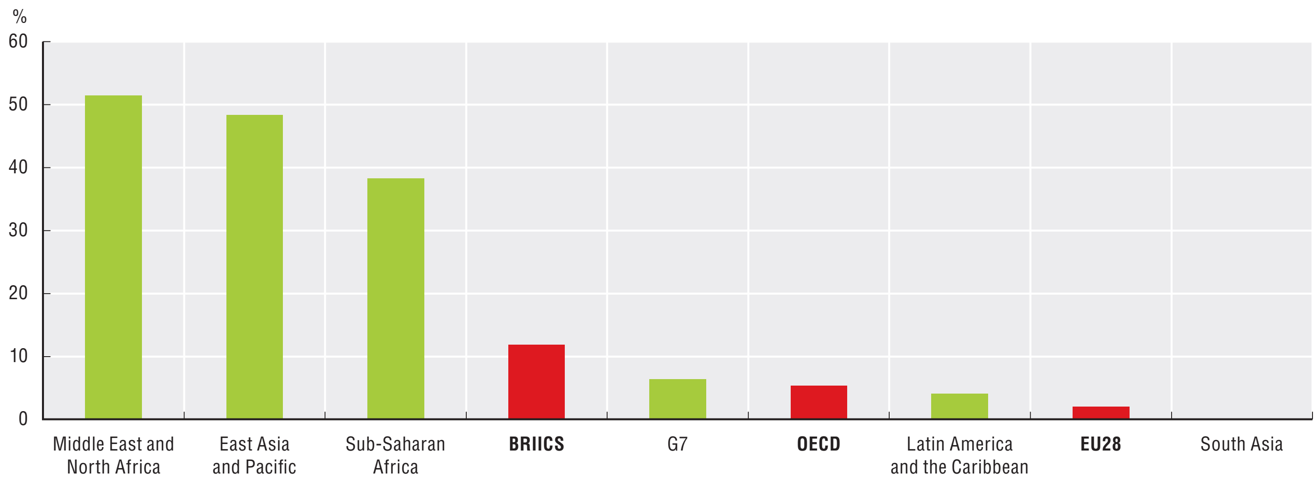


Source: OECD, Broadband Portal, *http://www.oecd.org/sti/broadband/broadband-statistics*; ITU World Telecommunication/ICT Indicators Database, January 2019.

The Middle East and North Africa have the highest average annual growth rate of satellite broadband subscriptions over the 2008-17 period (51.45%), but this is mainly due to the initial very low diffusion of the technology at the beginning of the period (Figure 6.7). Subscriptions in East Asia and the Pacific grew on average at a rate of 48.4% per year, while OECD countries registered growth rates of 5.4%.

Figure 6.7. Growth of satellite broadband subscriptions by region, 2008-17

Average annual growth rate



Source: OECD, Broadband Portal, *http://www.oecd.org/sti/broadband/broadband-statistics*; ITU World Telecommunication/ICT Indicators Database, January 2019.

Satellite's marginal role in broadband delivery has been mainly due to costs and latency (i.e. time-lag when communicating, viewing videos or downloading documents). Relaying a signal through a satellite stationed above the earth at 36 000 km may add up to half a second of latency round-trip due to the distances involved. As mentioned previously, some of these issues are alleviated by maturing technologies and the launch of new geostationary high-throughput satellite (HTS) systems, which significantly increase the quality of signals (see also chapter 4 on digitalisation trends).

In addition, the ongoing developments of satellite constellations in low-earth orbit could further reduce latency effects, depending on how close to the earth the satellites are placed. The 25 to 50 millisecond latency that some operators anticipate is still much higher than the expected next generation of wireless networks (5G) single-digit latency.

Almost twenty companies have announced plans to launch new fleets of satellites in the next five years to deliver broadband services (Table 6.1). However, most satellite broadband solutions at present are mainly complementary to existing networks in order to reach rural and remote areas. Some of these companies are backed either by existing satellite operators (e.g. O3b with SES; LeoSat with Hispasat and Sky Perfect JSAT) or manufacturers (e.g. OneWeb with Airbus; Starlink with SpaceX), but all have filed or will file for spectrum and orbital resources allocation. The investments required could range from USD 3.5 to 12 billion for a first-generation constellation, depending on the number of satellites, and the space and ground-based infrastructure chosen.

Beyond satellite constellation development, one challenge will be the actual terminal devices to reach consumers, with needed mass production of low-cost broadband receivers, using flat-panel and automatically steerable antennas.

Already for many satellite networks operators, much of their revenues are driven by products, antenna systems and ad-hoc receivers (e.g. inflight connectivity terminals) beyond satellite capacity provision. The links with suppliers of consumer electronics, software and enterprise equipment will therefore play a key role for the market success of constellations, as they will provide essential layers of services on top of the satellite broadband connection (i.e. a bit like multimedia equipment and air conditioning contribute to the purchase of a car). Strategies differ, as some satellite operators are developing partnerships with key electronics equipment players or are anticipating further vertical integration to design their own consumer equipment solutions. The importance of developing and rolling out ready-to-use consumer electronics will be one of the markers for the future of satellite broadband and, like other downstream space activities, may become the main source of profit, far beyond the initial investments in the satellite infrastructure.

Table 6.1. Selected planned satellite constellations in low- and medium-earth orbits

Name of the constellation	Expected number of satellites (altitude)	Operator / Manufacturer	Comments
Astrome Technologies (India)	600 (1 400km)	Astrome / TBD	Planned launch of 150 satellites weighing 175 kg each by 2020-21. The startup is currently fundraising.
Boeing V-Band (USA)	2956 (1 030-1 080km)	Boeing	Boeing has secured radio spectrum rights for 1 400 satellites.
Commsat (China)	72 (600 km)	Commsat	Seven small satellites were launched in 2018 to test Internet of Things services, with full constellation planned to be launched by 2022.
Hongyan (China)	300 (1 100km)	China Aerospace Science and Technology Corporation	First demonstrator launched in 2018, 9 satellites orbited by 2020 with the 300+ satellite system to be completed by 2025. A facility with the capacity to manufacture 130 satellites per year is being built in Tianjin.
Kuiper Project (USA)	3200 (590-630km)	Amazon, Kuiper Systems / TBD	Project announced by Jeff Bezos (Amazon) in early 2019
LeoSat (USA)	108 (1 432km)	LeoSat / Thales Alenia Space	Plans to launch satellites in 2021-2022.
O3b Networks (The Netherlands)	27 (8000km)	SES Networks / Thales Alenia Space	One of the precursors in satellite broadband, which started deploying its 1st generation of satellites in 2013 (20), with a new generation of 7 satellites by 2021 (customers in 50 countries)
OneWeb Satellites (USA / UK)	900 (1 200km)	OneWeb Satellites (Airbus Defence and Space et OneWeb) / Airbus Defence and Space	The first six satellites were launched in early 2019, and enough private capital raised to cover the production of 650 satellites (15 satellites per week), with services expected by 2021
Starlink (USA)	4425 (1 100-1 325km)	SpaceX	First demonstration satellites flew in 2018, a second generation may consist of 7500 satellites.
Telesat LEO (Canada)	117 (1 000km)	Telesat / TBD (Blue Origin for first launches)	Selection of satellite and ground station manufacturers by mid-2019. Global coverage planned by 2022.
Samsung (Japan)	4600 (1 500-2 000km)	TBD	
ViaSat-3 (USA)	20 (8 200km)	Viasat / Boeing	Three ultra-high capacity satellites planned for launch in 2021 and 2022 to complement existing services.
Xinwei (China)	32 (TBD)	TBD	
Yaliny (Russia)	135 (600km)	TBD	

In addition to broadband consumer markets, the Internet of Things (IoT) is also expected to grow significantly. The IoT connects everything and everyone to the internet through sensors and devices, leading to the need to develop relevant metrics to assess the effects of the IoT in different policy areas (Box 6.1) (OECD, 2018[12]). As the network of objects grows and seeks to collect and exchange data, satellites could play a role in enabling communications in the wireless infrastructure. It is important to highlight that satellite connectivity is complementary to existing IoT network solutions. IoT solutions are supported by several connectivity providers, all playing an important and complementary role, such as Low Power Wide Area Network providers (e.g. LoRa, SigFox), mobile network operators, fixed broadband and satellite providers (OECD, 2018[12]).

Many actors in the space sector have decades of experience in tracking objects, with for example the Iridium and ORBCOMM constellations which already addressed the burgeoning machine-to-machine (M2M) business some twenty years ago. Inmarsat and other mobile operators have also connected “objects” that move, such as planes, trains, automobiles, ships, and cruise lines, since the 1980s. Others monitor endangered wildlife with tags. According to the World Meteorological Organization’s *Satcom*

Handbook, which provides guidelines to scientists considering the use of satellite communications for collecting data from remote instrumentation on land or at sea, at least ten satellite systems are currently operating and taking on new users (e.g. Argos, DCS, Globalstar, Gonets, Inmarsat, Iridium, O3B, Orbcomm, Thuraya) (WMO/IOC, 2018[13]).

Box 6.1. Defining the Internet of Things (IoT)

There are many definitions of the Internet of Things (IoT) currently co-existing. Based on the Cancun Ministerial mandate on the Digital Economy (2016), which highlighted the importance of developing metrics to assess the effects of the IoT in different policy areas, the OECD has developed the following working definition:

> *"The Internet of Things includes all devices and objects whose state can be altered via the Internet, with or without the active involvement of individuals. While connected objects may require the involvement of devices considered part of the "traditional Internet", this definition excludes laptops tablets and smartphones already accounted for in current OECD broadband metrics."*

To support measurement, a taxonomy has been developed to provide a breakdown of IoT into categories given that many connected devices will have different network requirements. For example, critical IoT applications such as remote surgery and automated vehicles will require high reliability and low latency connectivity, whereas Massive and disperse Machine-to-Machine (M2M) sensors used for agricultural applications may not be that sensitive to latency or network speeds. Within the IoT proposed measurement framework, the two main categories of IoT proposed are: Wide Area IoT, and Short Range IoT. The Wide Area IoT category includes devices connected through cellular technology as well as those connected through Low Power Wide Area Networks, whereas the Short Range IoT category includes devices using unlicensed spectrum with a typical range up to 100 metres. Within the category of Wide Area IoT, two subcategories are further suggested: 1) Massive M2M devices (e.g. sensors for agriculture or smart cities), and 2) Critical IoT applications (e.g. remote surgery applications, fully automated vehicles and other industrial robotics applications).

Source: OECD (2018), IoT measurement and applications, *OECD Digital Economy Papers*.

Satellite-related IoT activities are multiplying, demonstrating the increased linkages with terrestrial based networks but also strategic reorientations of many satellite network operators. For example, on top of satellite television broadcasting and communication services, Eutelsat is also exploring the possibility to develop a constellation in low-earth orbit to provide new Internet of Things services for many sectors like agriculture, energy, or logistical supply chains (e.g. track objects and provide basic information, like temperature). The operator ordered a nanosat dubbed ELO (Eutelsat LEO for Objects) to be launched in 2019, and cooperates with the French firm Sigfox, which already operates a ground network in more than fifty countries dedicated to the Internet of Things, covering some 658 million people.

As a final note, the roll-out of the fifth generation (5G) mobile systems, and the seamlessl integration of satellite into a larger IoT framework will provide opportunities for terrestrial and satellite network operators alike. 5G is anticipated to be the first generation of wireless networks conceived to connect tens of billions of devices and sensors via the Internet (OECD, 2019[14]). It should provide higher speeds (i.e. 200 times faster than 4G), faster data transfer (i.e. 10 times less than 4G), and networks that better support a wide diversity of applications. International standards and a globally harmonised spectrum framework (see Box 6.2 on selected satellite-related issues) will be needed to enable economies of scale and facilitate cross border coordination to allow seamless connections between different networks (OECD, forthcoming[15]).

The new environment for satellite telecommunications will certainly be shaped by different elements, including further technological changes, competition between incumbents and new actors, possible consolidation, international industry-led standardisation and regulations.

Box 6.2. Selected spectrum issues for satellite networks

The next World Radiocommunication Conference (WRC-19) will take place in late 2019 to discuss updates to the Radio Regulations, which set out the basic international rules of spectrum use between the 193 member countries of the ITU. Many issues will be examined, including spectrum allocations for the fifth generation (5G) mobile systems, the introduction and use of the Global Aeronautical Distress and Safety System, and a much expected review of the regulatory framework for satellite networks. A variety of spectrum sharing issues will be addressed, and decisions will have impacts in equipment development and production, as well as interoperability issues. They particularly include for satellites:

- Possible changes in the frequency assignments procedures for satellite networks.
- The coexistence and possible new sharing of frequency bands between geostationary and non-geostationary satellites, which have been historically allocated to the fixed satellite services.
- The allocation of portions of this band for new terrestrial services, mainly the fifth generation (5G) mobile systems / International Mobile Communications (IMT) services.
- The protection of passive services (i.e. earth observations satellite, radio astronomy, and space research services) in adjacent frequency bands. For example, there are risks that new services interfere in the spectrum band allocated so far to radar location services, used already by a number of satellite earth observation programmes such as the European Copernicus (Sentinels-1, -3 and -6), NASA and CNES' Jason programme, and Canada's RADARSAT-2 and -3.
- New spectrum allocations to maritime mobile-satellite services, to deal with the growing number of autonomous maritime radio equipment which uses spectrum designated originally to the Automatic Identification System (AIS) for maritime safety (see also chapter 7).
- And a review of the spectrum needs for non-GSO satellites with short duration missions (typically very small satellites), to assess the suitability of existing allocations to the space operation service and, if necessary, to consider new ones.

All these issues to be discussed internationally before the end of 2019 will have impacts for the space sector's near-term future.

Overall, satellite networks should be able to play on their strengths and specific capabilities, to become further integrated and optimised in the broader telecommunications infrastructure. As useful complements to terrestrial networks, particularly in underserved geographic areas, they will contribute to maximise the development of an inclusive digital economy.

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Chapter 7

BRINGING SPACE TO EARTH WITH DATA-DRIVEN ACTIVITIES

This chapter examines the growing volume and variety of satellite data and signals, and how they affect downstream applications such as weather and climate monitoring, earth observation and satellite positioning, navigation and timing. Trends in big data and digitalisation are also creating new opportunities. Building on advances in analytics and machine learning, innovative ecosystems of start-ups are using satellite data and signals in original ways and developing brand new products and services.

The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

Introduction

Satellites produce increasing amounts of data and signals that can be commercially exploited. A significant share of these data comes from institutional programmes for earth observation, weather and climate monitoring and satellite navigation, many of which are free and open for everyone to use.

Furthermore, with the decreasing costs of producing and launching single satellites and commercial constellations, more and more organisations produce their own sets of data. The volume and variety of satellite data will significantly increase in the near future. Next-generation satellites and small satellite constellations will provide higher spatial resolution and increased spectral coverage combined with higher revisit times. All of these trends are opening ever more opportunities for start-ups developing new products and services based on data analytics and artificial intelligence.

This chapter examines some of these developments in greater detail, focusing on the growth in satellite data and signals and how this affects specific applications, notably weather and climate monitoring, earth observation and satellite navigation. A final section is devoted to the growth in activities building on data analytics and artificial intelligence.

Exponential growth in the availability of satellite data and signals

Satellites cover the entire earth's surface, including highly isolated, hard-to-reach areas. Also, depending on the type of the orbit from which the satellite is rotating the earth, a satellite may return to the same spot of observation at roughly the same time every day, facilitating the systematic collection of data over time. Every day, earth observation satellites gather enormous amounts of information about the earth's physical, chemical and biological systems for civil, military and commercial purposes.

There are some 135 civil institutional earth observation missions in orbit carrying instruments from almost 30 economies/agencies, as recorded by the Committee on Earth Observation Satellites (CEOS), the co-ordinating body for earth observation missions (CEOS, 2018[1]) (Figure 7.1). This does not include the more than 30 weather satellites constituting the core space infrastructure of the World Meteorological Organization's Integrated Observing System (WIGOS) (WMO, 2019[2]). Agencies in the United States, the People's Republic of China (hereafter "China"), Europe and France participate in the highest number of missions. Several national missions are joint operations with the military or public-private partnerships (CEOS, 2018[1]).

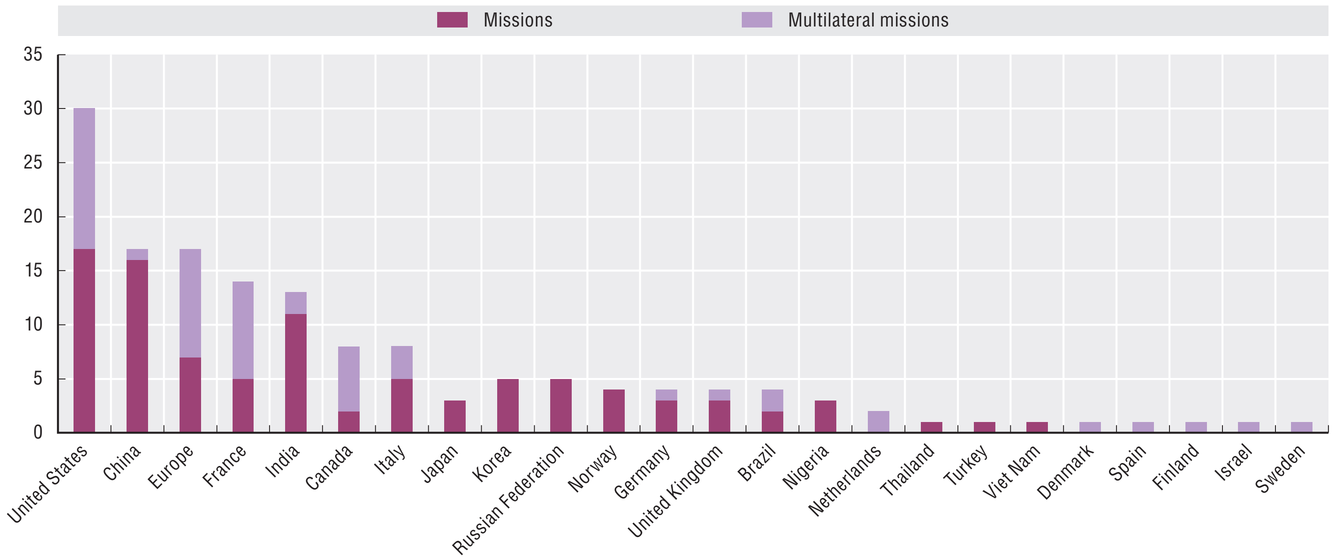
More than 30 missions are multilateral, with two or more economies contributing mission instruments. The United States, Europe and France participate in the highest number of multilateral missions (some 18, 10 and 9 multilateral missions, respectively).

Each mission flies one or several instruments, typically collecting multi-purpose land imagery (optical, multispectral, radar) or environmental observations (CEOS, 2018[1]). Several space agencies may each be responsible for the management of data generated by each instrument. For example, the Netherlands currently has two instruments in orbit, OMI (Ozone Monitoring Instrument) on the US satellite AURA, and TROPOMI (TROPOspheric Monitoring Instrument) on the European Sentinel-5P satellite. The Royal Netherlands Meteorological Institute processes and analyses the scientific data from these two instruments.

More than 100 earth observation missions are currently being prepared or considered for 2019-30, as shown in Figure 7.2, with some 26 foreseen launches in 2019 (CEOS, 2018[1]). It is important to note that the number of planned launches decrease over the time period, because of uncertainty in long-term mission planning, not because of less planned missions.

Figure 7.1. Number of national and multilateral operational earth observation missions

As of October 2018

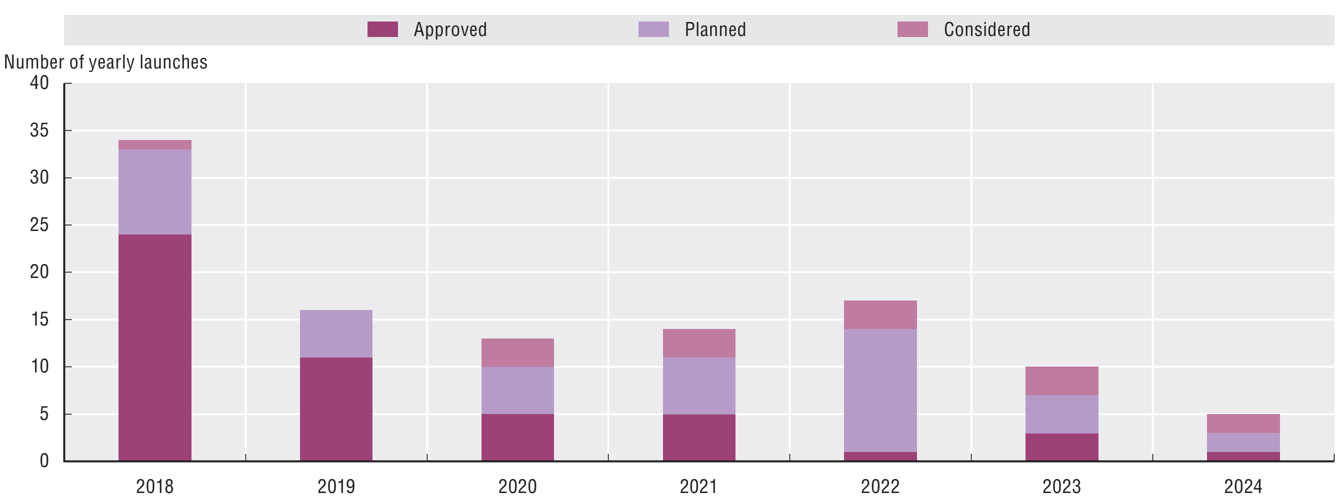


Note: Only includes missions recorded in the CEOS database and excludes weather satellites part of the World Meteorological Organization's Integrated Global Observing System (WIGOS). Multilateral missions refer to missions including two or more countries/institutions and have multiple counts.

Source: Adapted from CEOS (2018[1]), "CEOS Database: Catalogue of satellite missions", in *CEOS Earth Observation Handbook*, *http://database.eohandbook.com/database/missiontable.aspx*.

Figure 7.2. Forthcoming and considered earth observation missions

As of October 2018



Note: Only includes missions recorded in the CEOS database and excludes weather satellites part of the World Meteorological Organization's Integrated Global Observing System (WIGOS).

Source: Adapted from CEOS (2018[1]),"CEOS Database: Catalogue of satellite missions", in *CEOS Earth Observation Handbook*, *http://database.eohandbook.com/database/missiontable.aspx*.

The growing number of satellites as well as the increasing performance, complexity and resolution of instruments are leading to an explosion in the volume of data generated by earth observation satellites. For example, a single Sentinel-1 satellite in the European Copernicus constellation is able to map the world once every 12 days (ESA, 2017[3]) and produces an estimated 1.5 petabytes (10^{15}) of raw data per year (OECD, 2016[4]). Similarly, the future joint Indian/US mission NISAR scheduled for launch 2021 for dual frequency synthetic aperture radar observations, is expected to produce some 7.2 petabytes of data per year, or 19.9 terabytes every day (Murphy, 2017[5]). From 2012 to 2018, the data volume from some fifteen European and US satellite missions has grown from an annual 2 petabytes to now more than 12.5 petabytes (Schreier, 2015[6]). This is an important challenge for long-term data storage and handling, as more missions develop.

In terms of data policies for all these missions, governments have created a multitude of programmes and initiatives to encourage the commercial use of satellite data and signals, many of which are starting to bear fruit. This includes open data policies and the development of specific services and applications to make data more accessible to the public. This is not specific to the space sector. All across the OECD, governments work to enhance access to publicly funded data (Box 7.1).

Box 7.1. Enhanced access to publicly funded data: remedying the challenges

Data access and sharing represents a growing priority for policymakers in the science, technology and innovation (STI) domain and beyond in our knowledge-based society. Enhanced access to publicly funded data for STI brings indeed a number of benefits, such as economic growth, improved transparency and accountability, while contributing to public trust in research.

A number of initiatives have been introduced at both international and national levels to promote enhanced access to and sharing of data. International initiatives are typically recommendations and guidelines on data access, data preservation, and interoperability (e.g. *OECD Recommendation on Access to Research Data from Public Funding; the Findable, Accessible, Interoperable and Reusable (FAIR) Principles*). There is also the European Commission *Open Data and Public Sector Information Directive*, which aims to facilitate the availability and re-use of public sector data.

As demonstrated by ongoing OECD work in the framework of the Committee for Scientific and Technological Policy (CSTP), many challenges need to be addressed when drafting data access policies for publicly funded data:

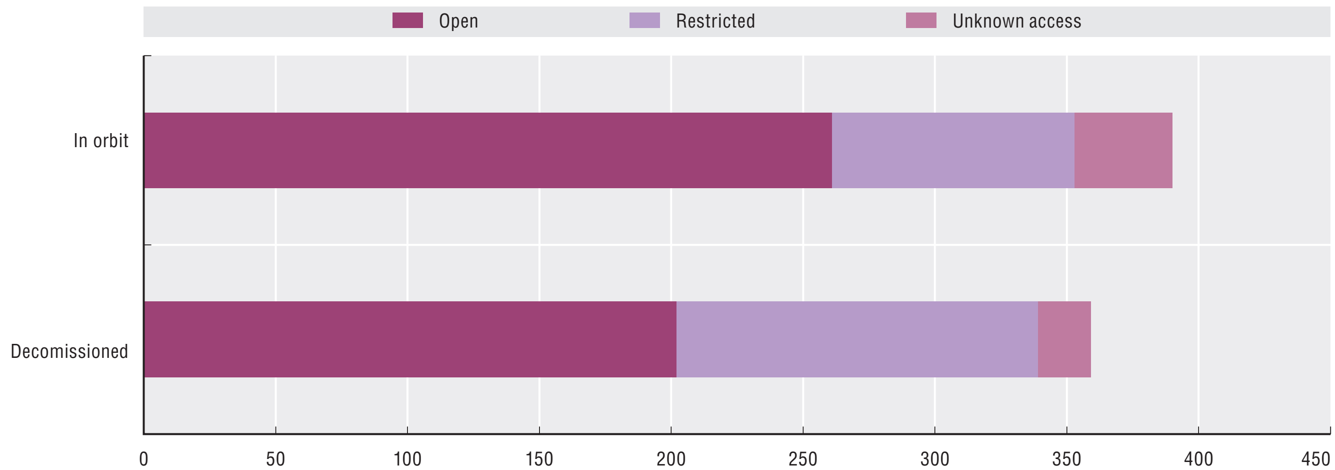
- *Balancing the benefits and risks of data sharing*: The benefits of enhanced access to data need to be balanced against the issue of costs, privacy, security, IPR and preventing malevolent uses.
- *Ensuring that technical standards and practices keep up with the pace of technological progress*: Technology development far outpaces standard-setting, creating regulatory gaps. Implementing the FAIR principles is an important initiative to close this policy gap.
- *Defining responsibility and ownership*: New technologies (e.g. text and data mining) and public-private partnerships create new challenges in terms of IPR protection and "data privatisation".
- *Formulating appropriate incentives and rewards that value data-sharing*: More remains to be done to raise researchers' awareness of open-government data and enhance the appeal of sharing access to data.
- *Creating business models and funding for enhanced data sharing*: Costs are most often borne by data providers, while benefits accrue to users. Although shared access to data does not necessarily mean free data, in many research fields, data are expected to be provided free of charge at the point of use.
- *Building human capital and institutional capabilities* to manage, create, curate and reuse data.
- *Developing legal frameworks for the exchange of sensitive data across borders*: Sensitive datasets can be shared on a more restricted basis with trusted and certified users. International legal frameworks that ensure similar levels of legal protection for cross-border exchanges are missing.

Source: OECD (forthcoming), *Enhanced Access to Publicly Funded Data for Science, Technology and Innovation*, OECD Publishing, Paris.

Governments are taking steps to make earth observation data as accessible as possible to external users. This is not only a question of granting formal access, but also, increasingly, of finding technological solutions for storing, processing and sharing ever growing amounts of data. Data from several institutional missions are free and open to use for both research and commercial purposes (NASA, 2018[7]; ESA, 2018[8]). Indeed, when looking at instrument/mission combinations currently in orbit (including weather satellites), there is open access to data from 261 of 390 instruments, or almost 70% (as shown in Figure 7.3). Open access may in some cases require user registration or formal requests for data (advanced protocol), and there may also be some restrictions on the timeliness, size and formats of data downloads (CEOS, 2018[9]). Ninety-two instruments, or 24%, have restricted data access (CEOS, 2018[9]), providing exclusive national or regional access (e.g. the Russian Federation) or for commercial reasons (e.g. the Italian Cosmo-SkyMED constellation, the French SPOT and Pleiades satellites, German TerraSAR-X and TanDEM-X) (CEOS, 2018[9]). Restricted data repositories may still grant affordable conditional access to specific users (CEOS, 2018[9]). This is an improvement compared with data access of decommissioned instruments, where about 40% of instruments had restricted data access (CEOS, 2018[9]).

Figure 7.3. Evolution of satellite earth observation data access by instrument

Number of mission/instrument combinations on completed and operational missions as of November 2017



Source: Adapted from CEOS (2018[9]), *CEOS virtualization environment (COVE) portal*, *http://www.ceos-cove.org/en/*.

Earth observation data are processed and distributed via distribution centres at both the national and international level, such as the World Data Centre for Remote Sensing of the Atmosphere, hosted by the German Aerospace Center (DLR), ESA's GEOSS Portal, or the NASA EOSDIS image archives (Schreier, 2015[6]; ESA, 2018[10]; Davies, 2015[11]).

Box 7.2. Selected takeaways from NOAA's Big Data Partnership project: NEXRAD data

The US National Oceanic and Atmospheric Administration (NOAA) is the owner and steward of enormous amounts of climate and earth observation data. Although most of NOAA's data are open, only a small share have been easily accessible. This was the underlying rationale for launching the Big Data Partnership research project in 2015, where academic and commercial actors (Amazon Web Services (AWS), IBM, Google and University of Chicago's Open Commons Consortium) partnered with NOAA to host and process selected datasets. The objective of the project was to evaluate ways to provide NOAA's vast amounts of data to the public while at the same time enabling new economic opportunities (Wooldridge, 2016[12]).

One of NOAA datasets, NEXRAD Level II, compiles data from a ground-based network of weather radars that contributes to the "analysis and early detection of tornadoes, rain, ice, snow, flash floods, hail, and destructive wind". Starting in 2015, the NEXRAD Level II 1991-2015 data archive, including more than 270 (compressed) terabytes and 180 million files, was transferred to AWS, Microsoft, and Google, with AWS the first provider to make the dataset available on the cloud. AWS also arranged a feed from real-time NEXRAD data, provided by the University Corporation for Atmospheric Research (UCAR). In this way, archived and real-time data could be accessed simultaneously, via the same mechanism.

Results were very positive. The project resulted in a doubling in the volume of accessed NEXRAD data between 2013 and 2016, while there was a 50% reduction in the volume of data delivered from NOAA servers. 80% of NEXRAD archive orders are now fulfilled by AWS. Among users, the

Box 7.2. Selected takeaways from NOAA's Big Data Partnership project: NEXRAD data *(cont.)*

Climate Corporation, one of the partnering organisations, found that the combined access to both real-time and archived data shortened research projects by several months and made it possible to carry out evaluations on larger datasets. Furthermore, new research opportunities were identified (e.g. bird migration, mayfly studies).

Source: Ansari et al. (2018[13]), "Unlocking the potential of NEXRAD data through NOAA's big data partnership", *Bulletin of the American Meteorological Society*, *http://dx.doi.org/10.1175/BAMS-D-16-0021.1*.

Several countries have also taken extra steps to make data available for societal and commercial applications, by creating national data portals, for example the Geoscience Data Cube in Australia, satellittdata.no in Norway, Satellite Data Portal in the Netherlands, a digital data platform in New Zealand (Australian National Computational Infrastructure, 2018[14]; Norwegian Space Centre, 2018[15]; Netherlands Space Office, 2018[16]; Centre for Space Science Technology, 2017[17]). The Committee on Earth Observation Satellites and other partners supported the 2018 launch of the Africa Regional Data Cube. In Europe, five industrial consortia have been assigned by the European Union to provide scalable computing and storage platforms, so-called Data and Information Access Services, in order to facilitate the third-party access and use of Copernicus data (ESA, 2017[18]).

Zooming in on weather and climate monitoring

Satellite observations play an essential role in weather and climate monitoring. Geostationary satellites provide imagery to identify real-time weather patterns and perform short-term forecasts. Data from polar-orbiting satellites are increasingly used in numerical weather projection models. This increased use and reliance on satellite systems in weather and climate monitoring has a positive impact on weather forecast performance, and on the economy and society as a whole.

Weather

Satellite observations have been used in weather forecasting for more than 50 years. Today, satellite sensors (e.g. infrared and microwave sounders, imagers, GPS receivers for radio occultation) provide data on the state of the atmosphere and ocean surface and play an essential role in preparing weather analyses, forecasts, advisories and warnings, as well as monitoring the climate. For example, the European Centre for Medium-Range Weather Forecasts, an intergovernmental meteorological research organisation, reports that the number of satellite instruments that it actively uses in numerical weather prediction models has significantly increased in the last 10 years, from 12 to 50 between 2000 and 2013 (English et al., 2013[19]). In France, satellites provide 93% of data used in Météo-France's Arpège model (OECD, 2014[20]).

Three main types of satellites provide data for weather and climate monitoring: geostationary and polar-orbiting weather satellites and selected environmental satellites. These weather satellites are operated by national agencies in China, France, India, Japan, Korea, the Russian Federation, the United States and EUMETSAT for Europe, and are co-ordinated by the World Meteorological Organization (WMO).

As of early 2019, there are 20 geostationary weather satellites orbiting the earth at an altitude of about 36 000 km (Table 7.1). The geostationary orbit follows the earth's rotation, so that the satellite remains continuously fixed above the same position. The satellites' positioning at different longitudes along the equator allows global coverage. Another 17 polar-orbiting weather satellites (at a much lower altitude, some 850 km) circle the earth in sun-synchronous orbit. Sun-synchronous satellites revisit a given spot on Earth every day at the same hour (e.g. "morning" or "afternoon" satellites), making some 14-15 orbits per day, depending on the satellite's distance from Earth (Table 7.2). Beyond the technical aspects, the set-up of these geostationary weather satellites is a great example of a very practical international cooperation and coordination scheme that benefits billions of individuals, with information feeding into daily weather forecasts.

Table 7.1. Current geostationary weather satellites

As of January 2019

Satellites' orbital position	East Pacific	West Atlantic	East Atlantic	Indian Ocean	West Pacific
United States (National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration)	1 satellite (GOES-15)	3 satellites (GOES-14,[1] -16 and -17[1])			
Europe (EUMETSAT)			3 satellites (Meteosat-9[1], -10 and -11)	1 satellite (Meteosat-8)	
India (Indian Space Research Organisation)				2 satellites (INSAT-3DR, INSAT-3D)	
Russian Federation (RosHydroMet)				1 satellite (Electro-L N2)	
China (China Meteorological Admin.)				4 satellites (Feng-Yun-FY-2E, FY-4A, FY-2G, FY-2H)	1 satellite (FY-2F[1])
Korea (Korea Meteorological Administration)					2 satellites (COMS-1, GEO-KOMPSAT-2A[2])
Japan (Japan Meteorological Agency)					2 satellites (Himawari-8 and -9[1])

Notes: 1. Stand-by. 2. The satellite is about to become operational (in "commissioning" mode).

Source: WMO (2019[2]), *Satellite status*, *http://www.wmo.int/pages/prog/sat/satellitestatus.php*.

Table 7.2. Current polar-orbiting weather satellites (in sun-synchronous orbit)

As of January 2019

	Early morning orbit	Morning orbit	Afternoon orbit
United States	2 satellites (US Defense Meteo. Satellite Program DMSP-F17, DoD, NOAA-15, NOAA)	2 satellites (DMSP-F18, DoD, NOAA-18, NOAA)	6 satellites (Suomi-NPP, NOAA/NASA; DMSP-F14, DMSP-F15 and DMSP-F16, DoD; NOAA-19, NOAA and NOAA-20, NOAA/NASA)
Europe		3 satellites (Metop-A, Metop-B and Metop-C[1], (EUMETSAT)	
Russian Federation		1 satellite (Meteor-M N2, RosHydroMet)	
China		1 satellite (FY-3C, CMA)	2 satellites (FY-3B and FY-3D, CMA)

Notes: For the US Defense Meteorological Satellite Program (DMSP) satellites, the US Department of Defense (DoD) is responsible for development and operations, while the National Oceanic and Atmospheric Administration (NOAA) provides linkage with the civilian meteorological community.

1. The satellite is about to become operational (in "commissioning" mode).

Source: WMO (2019[2]), *Satellite status*, *http://www.wmo.int/pages/prog/sat/satellitestatus.php*.

In addition, the WMO counts another 84 low-earth orbit satellites contributing to the WMO Integrated Global Observing System (WIGOS), measuring selected climate parameters (WMO, 2019[2]). 25% of these are bilateral or multilateral missions, with different countries contributing instruments. For instance, the National Aeronautics and Space Administration (NASA) in the United States is co-operating with the Japan Aerospace Exploration Agency (JAXA) on the GMP Core Observatory, while the French space agency, the Centre national d'études spatiales (CNES), is co-operating with India on two different missions (Megha-Tropiques and SARAL) (WMO, 2019[2]).

The value of satellite weather and climate observations has been subject to several cost-benefit analyses (for example Gray (2015[24]; EUMETSAT, 2014[25])). An effective weather service (including both space and terrestrial observations) has been found to bring numerous socio-economic benefits through lives saved, cost avoidances (flood and storm damage avoidance for property and infrastructure, etc.), efficiency gains (e.g. route planning optimisation for marine and air transport; improved capacity planning and anticipation of demand for the energy sector; improved planning and fertiliser use in agriculture, etc.) (Gray, 2015[24]; EUMETSAT, 2014[25]). A recent cost benefit analysis of the Chinese Public Weather Service, using willingness-to-pay methodology, found a very high national cost-benefit ratio of 1:26 (Yuan, Sun and Wang, 2016[26]) (see also chapter 2).

The main contribution of weather satellites to weather forecasting is significantly improved forecast accuracy. For instance, according to the UK Met Office statistics on forecast sensitivity to observations, weather satellites (geostationary and polar-orbiting) contribute 64% to error reductions in one-day forecasts (EUMETSAT, 2014[25]). Polar-orbiting satellites play a particularly important role, contributing 58% to error reductions, in particular the Metop satellites (EUMETSAT) (24.5%), and the National Oceanic and Atmospheric Administration/Department of Defense (NOAA/DoD) satellites (20.5%) (EUMETSAT, 2014[25]).

Box 7.3. Space weather observations

Space weather observations allow the monitoring of the sun, and of planetary and interplanetary environments that may affect Earth, such as solar storm and coronal mass ejections (WMO, 2017[21]). These events can produce and project cosmic rays and energetic particles or cause geomagnetic storms, all of which can seriously affect space-based and/or ground-based human activities and infrastructure, causing electrical failure, blocking radio communications, modifying Global Navigation Satellite System (GNSS) signals, etc. Space weather forecasts make it possible to reduce or avoid damage, by diverting or cancelling flights and switching off or putting vulnerable infrastructure in safe mode.

One of the largest geomagnetic storms on record occurred in 1859, disabling telegraph systems in North America and Europe and producing auroras visible as far away from the poles as Hawaii and Queensland, Australia. A coronal mass ejection of similar magnitude, with potential catastrophic consequences, missed the earth by a week in 2012 (NASA, 2014[22]). Knowledge about the potential impact of future events is growing, as more and more countries (Canada, Netherlands, United Kingdom, United States) conduct studies in this domain.

The most recent severe space weather incident took place in Quebec in 1989, when Hydro Québec's electrical grid was disabled, leaving six million people without electricity for nine hours (Canadian Space Agency, 2017[23]). Several minor events have damaged satellites and disrupted terrestrial electrical and communication networks. In 2005, a solar storm caused a 10-minute disruption to GPS navigation signals.

The World Meteorological Organisation currently lists six satellite missions for space weather observations. Five are US missions and one, the Solar and Heliospheric Observatory (SOHO), is a joint mission between NASA and the European Space Agency (WMO, 2019[2]). Most missions are located at the first Lagrange Point (L 1), some 1.5 million km from Earth in the direction of the sun, and a stable location from which to monitor solar activity. Another joint European-US mission, the Solar Orbiter, is planned for launch in 2020.

Table 7.3. Current civilian satellites dedicated to space weather monitoring

As of January 2019

	Lagrange 1 (L1) orbit	Ecliptic orbit
United States	3 satellites (ACE, NASA/NOAA; WIND, NASA; DSCOVR, NOAA/NASA)	2 satellites (STEREO, NASA)
Europe	1 satellite (SOHO, ESA/NASA[1])	

Note: 1. In co-operation with NASA.

Source: WMO (2019[2]), *Satellite status*, *http://www.wmo.int/pages/prog/sat/satellitestatus.php*.

Both the European Centre for Medium-Range Weather Forecasts and the German meteorological service have carried out data denial simulations to estimate the impact of the loss of polar-orbiting satellites on short-range forecast accuracy. The European Centre for Medium-Range Weather Forecasts found that a simultaneous loss of both European and US satellites would cause a 15-20% reduction in accuracy (EUMETSAT, 2014[25]). The German meteorological service looked specifically at the impact on the accuracy of short-range forecasts of major (winter) storms. The simulations showed that the absence of satellite observations led to significant errors in determining the severity, location and evolution of the storm (EUMETSAT, 2014[25]).

Climate change monitoring

The need to study and monitor climate change has never been so important, as higher temperatures, rising sea levels, acidification of the ocean – with effects on marine ecosystems – and changing patterns of precipitation, and more extreme weather events are multiplying. The evidence feeds into policy making, as countries aim to achieve strong and inclusive economic growth while reorienting their economies towards development pathways with low greenhouse gas emissions and high resilience to the effects of climate change (OECD, 2017[27]).

International co-operation and co-ordination in monitoring climate variables is mainly carried out by three complementary bodies: the Committee on Earth Observation Satellites (CEOS), responsible for the co-ordination of the earth observation programmes worldwide; the Coordination Group for Meteorological Satellites (CGMS); and the Global Climate Observing System (GCOS), which co-ordinates and leads international climate data collection. A joint CEOS-CGMS Working Group on Climate was established in 2010 and is responsible for implementing the global architecture for climate monitoring from space (Joint CEOS/CGMS Working Group on Climate, 2017[28]; Joint CEOS/CGMS Working Group on Climate, 2018[29]).

To better monitor climate change, the Steering Committee of the GCOS has introduced a number of essential climate variables (ECV), which refer to the "physical, chemical or biological variables that critically contribute to the characterisation of Earth's climate" (WMO, 2018[30]). Satellite data observations provide significant, and in some cases unique, contributions to more than half of the 50 ECVs that are currently in use (Table 7.4).

Table 7.4. Satellites' contribution to measurements of essential climate variables

Spheres	Essential climate variables
Atmospheric (over land, sea and ice)	Surface: air temperature, wind speed and direction, water vapour, pressure, ***precipitation, surface radiation budget***
	Upper-air: ***temperature, wind speed and direction, water vapour, cloud properties, Earth radiation budget (including solar irradiance)***
	Composition: ***carbon dioxide, methane and other long-lived greenhouse gases, ozone and aerosol***
Oceanic	Surface: ***sea-surface temperature***, sea-surface salinity, ***sea level, sea state, sea ice, surface current, ocean colour***, carbon dioxide partial pressure, ***ocean acidity, phytoplankton***
	Sub-surface: temperature, ***salinity***, current, nutrients, carbon dioxide partial pressure, ocean acidity, oxygen, tracers
Terrestrial	River discharge, water use, groundwater, lakes, ***snow cover, glaciers and ice caps, ice sheets***, permafrost, ***albedo, land cover (including vegetation type)***, fraction of absorbed photosynthetically active radiation, leaf area index, ***above-ground biomass, soil carbon, fire disturbance, soil moisture***

Note: Essential climate variables to which satellites make a significant contribution are in bold italic.

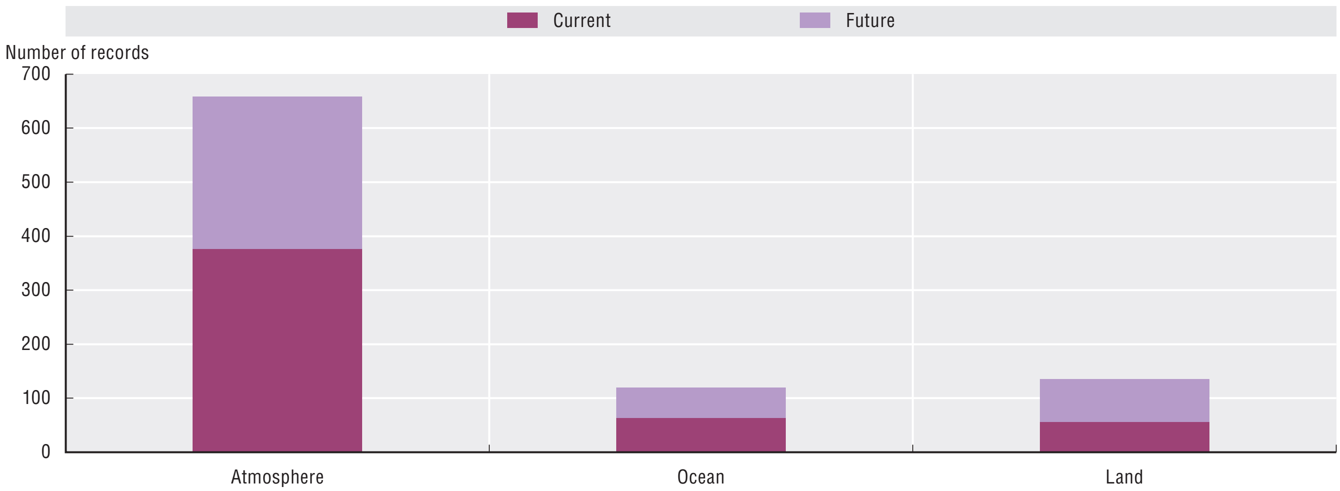
Source: OECD (2016[4]), *Space and Innovation*, *http://dx.doi.org/10.1787/9789264264014-en*.

Many ECVs are further subdivided into so-called ECV "products", which are associated with multiple climate data records based on satellite observations and measurements, generally provided by space agencies (e.g. CNES, NASA, JAXA), meteorological agencies (e.g. NOAA, Norwegian Meteorological Institute) or research organisations (e.g. Centre for Polar Observation and Modelling). For instance, the ECV for atmospheric water vapour has three ECV products: total column water vapour, tropospheric and lower-stratospheric water vapour, and upper tropospheric humidity, for which there are currently 59 climate data records. Climate data records can be based on the observations of multiple instruments and satellites, and potentially changing measurement approaches (Joint CEOS/CGMS Working Group on Climate, 2017[28]) .

The Joint CEOS/CGMS Working Group on Climate has prepared an inventory of existing and planned climate data records to get an overview of existing resources and to identify gaps, based on inputs from ten CEOS and CGMS members. The inventory has identified a total of 495 existing records, with another 417 firmly planned and approved future records. Future climate data records can be planned for past, current and future satellite missions (Joint CEOS/CGMS Working Group on Climate, 2018[31]).

Most climate data records can be found for the atmospheric sphere (76% of existing products), followed by the oceanic sphere (13%) and the terrestrial sphere (11%), as is illustrated in Figure 7.4. The relatively low number of data records in the land category is due to several factors, including the low temporal resolution of satellite data and a relatively high risk of errors if satellite optical data are used in isolation (cloud cover, poor illumination at high latitudes). Furthermore, the limited availability of *in situ* data makes it difficult to properly estimate and assess uncertainty (Joint CEOS/CGMS Working Group on Climate, 2017[28]).

Figure 7.4. Current and future essential climate variable data records by domain

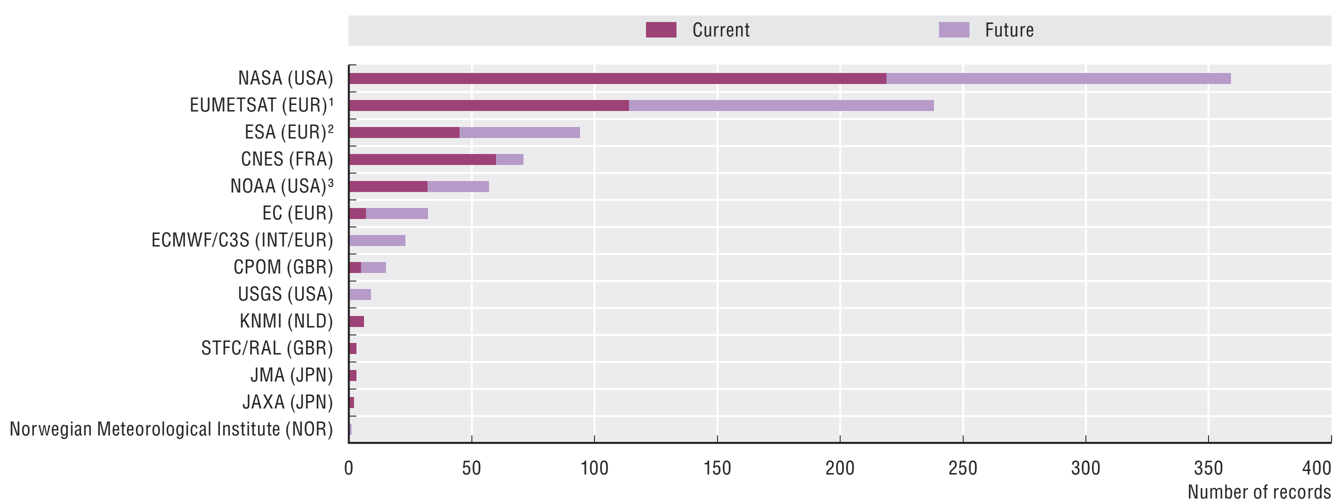


Note: Future climate data records can be planned for past, current and future satellite missions.

Source: Joint CEOS/CGMS Working Group on Climate (2018[31]), *ECV Inventory Access*, *http://climatemonitoring.info/ecvinventory?sorts[Domain]=1*.

Figure 7.5 shows the distribution of current and future data records by responsible organisation (i.e. data steward). NASA maintains the highest amount of current data records, followed by EUMETSAT, ESA and CNES.

Figure 7.5. Current and future essential climate variable data records by organisation



Note: Future climate data records can be planned for past, current and future satellite missions.

1. This includes data records from EUMETSAT, EUMETSAT/CM-SAF, and EUMETSAT/OSI-SAF/Météo-France.

2. This includes data records from the ESA, ESA/DWD and ESA/SatOC.

3. This includes data records from the NOAA/NCEI and NOAA/NCEI/NESDIS.

Source: Joint CEOS/CGMS Working Group on Climate (2018[31]), *ECV Inventory Access*, *http://climatemonitoring.info/ecvinventory?sorts[Domain]=1*.

Ensuring continuity of observations

There is a record number of weather and environmental satellites in orbit, but it remains a key priority and challenge to ensure continuity of existing observations, increase coverage and extend the observation systems to include additional parameters identified by international conventions and the scientific community.

The timeliness and accuracy of numerical weather projection models depend on the availability of uninterrupted data series. Although the benefits of weather satellite observations are well documented, funding is limited in several OECD countries and the sustainability of essential long-term data series remains vulnerable. To further improve weather forecasts, more observations are also needed.

In the climate domain, there are also demands for more data. The COP 21 Paris Agreement has for instance identified the need to monitor anthropogenic (human-made) greenhouse-gas fluxes. The GCOS *2016 Implementation Plan* also foresees space-borne prototypes for measuring point source fluxes from different emission sources (such as fossil fuel plants) (WMO, 2016[32]).

As it becomes difficult to fund follow-up or new missions, international and inter-agency co-operation and data-sharing arrangements become ever more important to coordinate future activities, address potential data gaps and share costs. Chinese weather satellites will complement polar-orbiting observations in the coming years, and agreements have been made for data exchanges (WMO, 2015[33]). The United States has a bilateral agreement with the Japan Aerospace Exploration Agency (JAXA) for use of specific instrument data, and it is partnering with Europe for a follow-on mission to the Ocean surface topography mission (Jason-2) (WMO, 2015[33]).

The private sector, already heavily represented in weather data processing, analysis and distribution, is increasingly interested in the first-hand collection of satellite observational data. Companies are mainly using nanosatellites equipped with GNSS radio-occultation sensors, a relatively recent technology for atmospheric measurements. Increasingly efficient, current weather nanosatellites could already be capable of observing about half of the essential climate variables, according to private sector reports (Condor, 2018[34]). The United States has started to test the quality and use of commercial weather data, with two pilot projects performed/planned by NOAA since 2016. So far, the first project only covered contracts and data quality assessments, but the second pilot project will be more comprehensive and also look into issues such as the impact on numerical weather prediction models and data rights (St. Jean, 2018[35]). NOAA has identified several challenges in using commercial weather data that will need to be resolved, including the operational stability of data and the potential impact on domestic and international partnerships and data-sharing arrangements (St. Jean, 2018[35]).

Data for navigation, positioning and timing

Modern societies also depend on global navigation satellite systems (GNSS) for precise positioning, navigation and timing. GNSS signals distribute the precise timing information needed by critical infrastructures such as power grids, communications systems and banking operations. They are also invaluable for several government activities and services, such as military operations or emergency response, providing precise information on the positioning of landmarks or personnel. Furthermore, GNSS and related systems play a key role in transportation, for instance enhancing airport safety and capacity, and are one of the key incremental technologies for driverless cars.

Governments are making important infrastructure investments in GNSS and satellite-based augmenting systems (SBAS), and the availability and precision of GNSS signals will significantly increase in the coming 5-10 years.

GNSS systems refer to constellations of satellites that transmit positioning and timing signals to ground receivers (European GNSS Agency, 2018[36]). The constellations, consisting of a minimum of 24 satellites to ensure global coverage, orbit the earth in 6 different planes in the medium-earth orbit, at an altitude of some 20 000 km (US Air Force, 2018[37]). To get an idea of the precision of the broadcasted signals, on a specific day in 2016, the GPS signals in space had an average user range error of some 0.7 metres, 95% of the time (US Air Force, 2018[37]). However, the actual accuracy of signals for terrestrial users will generally be lower and depends on several factors, such as satellite geometry (number of satellites in line of site), atmospheric conditions, local topography and type/level of surrounding built area, indoor/outdoor, receiver design/quality, etc.). Space agencies operate with different estimates for signal accuracy, ranging from 5 metres to more than 30 metres.

There are currently two operational GNSS systems with global coverage: the US Global Positioning System (GPS) and the Russian GLONASS. Two other systems are expected to reach global coverage by 2020: the European system Galileo and the Chinese Beidou constellation, which currently covers China and other countries in the Asia-Pacific region (US Air Force, 2017[38]). Furthermore, there are two regional global navigation satellite systems, the Quasi-Zenith Satellite System (QZSS) in Japan and Navigation with Indian Constellation (NAVIC) in India. The Japanese QZSS constellation, which currently comprises four satellites, became operational in 2018 and is fully compatible with US GPS satellites. In this way, coverage over Japan is increased, which for instance contributes to high-precision positioning in urban areas (e.g. it avoids multipath errors caused by reflections off buildings) (Japanese Cabinet Office, 2018[39]). The Indian seven-satellite NAVIC constellation is similarly interoperable with the US GPS constellation, while ensuring autonomous operations over Indian territory. In early 2018, the Korean government published plans to develop a regional GNSS system, to be operational in the early 2030s (Government of Korea, 2018[40]).

As it is shown in Table 7.5, the constellations provide different types of services, typically a free public service for civilian use, a restricted higher precision service for government applications and sometimes also different types of messaging services, typically for disaster mitigation (e.g. India, Japan).

Table 7.5. Global navigation satellite systems for precision, navigation and timing services

As of January 2019

System	Country	Coverage	Operational status	Services provided
Global Positioning System (GPS)	United States	Global	Operational with full global coverage since 1995	Standard positioning service (civilian use) Precise positioning service
GLONASS	Russian Federation	Global	Operational with full global coverage since 2011	Channel of standard accuracy (civilian use) Channel of high accuracy
Galileo	Europe	Global	Under development, full global coverage by 2020	Open service (free of charge, for positioning and timing) Commercial service (additional navigational signal and possibility to encrypt signal) Public regulated service (government-authorised users) Search and rescue service (Europe's contribution to COSPAS-SARSAT)
Beidou	China	Global	Currently covering the Asia-Pacific region, full global coverage by 2020	Open service (civilian use) Authorised service Short message service (in regional constellation, station and user can exchange short messages)
Navigation with Indian Constellation (NAVIC)	India	National and adjoining areas	Operational space segment	Standard positioning service (civilian use) Precision service Messaging interface, which makes it possible to send warnings to specific geographic areas
Quasi-Zenith Satellite System (QZSS)	Japan	National and adjoining areas	Operational since November 2018	Satellite positioning, navigating and timing service Satellite Report for Disaster and Crisis Management (transmission of disaster-related information) Positioning technology verification service (new positioning technologies can use satellites for testing verification) QZSS Safety Confirmation Service (under elaboration, for the transmission of information from evacuation shelters to control stations) Public regulated service (authorised government users)
Korean Positioning System (KPS)	Korea	National and adjoining areas	Early development phase, deployment expected in 2030s	

The accuracy and integrity of the (civil) signals emitted by these GNSS constellations can be further enhanced by both terrestrial and satellite-based augmentation systems (SBAS). SBAS systems consist of networks of precisely located terrestrial reference stations that collect (mainly) GPS satellite measurements which are transmitted to a central processing facility. Messages on satellite signal accuracy and integrity (e.g. detection of satellite faults and anomalies) are then communicated via geostationary satellites across the service area (European GNSS Agency, 2018[41]). In the case of the European Geostationary Navigation Overlay (EGNOS), location accuracy is reportedly improved from 17 metres (using a standard GPS receiver) to 3 metres (European GNSS Agency, 2018[41]). These systems play an important role in aviation, but there are also other applications (e.g. precision agriculture, marine and land transport, mapping/surveying).

Operational SBAS systems include the Wide Area Augmentation System (WAAS) in the United States, the Multi-functional Satellite Augmentation System (MSAS) in Japan, EGNOS in Europe and the GPS Aided GEO Augmented Navigation system (GAGAN) in India. Systems are also being developed in Korea (KASS) and the Russian Federation (European GNSS Agency, 2016[42]; Korean Ministry of Land, Infrastructure and Transport, 2018[43]; FAA, 2018[44]). Australia and New Zealand are currently conducting an SBAS test bed project on both countries' territories, with testing until 2019 (LINZ, 2017[45]). Table 7.6 summarises these findings.

Table 7.6. Satellite-based augmentation systems for positioning, navigation and timing

As of June 2018

System	Country	Coverage	Operational status
Wide Area Augmentation System (WAAS)	United States	Regional (United States, Canada and Mexico)	2003 (activated for general aviation)
Multi-functional Satellite Augmentation System (MSAS)	Japan	National (and neighbouring areas)	Operational since 2007
European Geostationary Navigation Overlay Service (EGNOS)	Europe	Regional (European Union). Ongoing projects to extend to other areas in Eastern Europe and Africa	2009 (open service) 2011 (safety of life service)
GPS Aided GEO Augmented Navigation (GAGAN)	India	National	Operational since 2015
System of Differential Correction and Monitoring (SDCM)	Russian Federation	National	In development
Korean Augmentation Satellite System (KASS)	Korea	National	In development, planned deployment in 2020 for public service, 2022 for safety of life service
Satellite-Based Augmentation System test bed project	Australia, New Zealand	Regional	Under trial, tests 2017-19

The growing importance of data hosting, processing and analytics

The last decade has seen the emergence of new types of space downstream services and companies, to a large extent fuelled by the increased availability and quality of government data and signals, advances in data processing and computing capacity, as well as the decreased cost of satellite manufacturing and launch, which has paved the way for more customised commercial constellations.

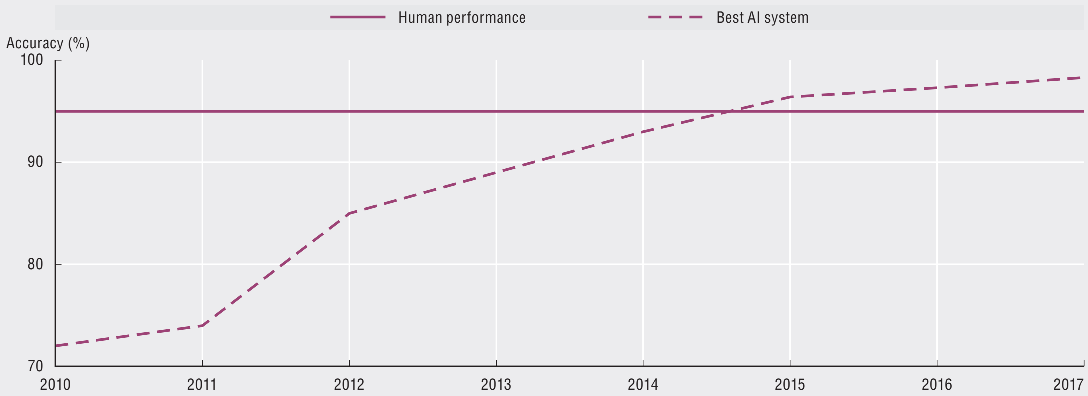
Activity has been particularly strong in earth observation and positioning, navigation and timing. The number of recorded companies with earth observation activities in Europe and Canada doubled between 2008 and 2016, from about 250 to 500 companies (EARSC, 2017[46]). Commercial applications are diverse, ranging from the surveillance of remote infrastructures and installations, precision agriculture, naval vessel tracking, and land management and planning. Earth observation data are also increasingly combined with other data to create value-added products and services, e.g. different weather products for the maritime and agro-business industries to optimise vessel routes and adapt fertiliser use, or economic predictions. Some of this is linked to recent developments in artificial intelligence (see Box 7.3), which are lowering the barriers and costs of analysing huge amounts of data.

It is also important to note the growth in intermediate service providers. These are firms that offer data hosting or processing services to other firms and in that way significantly facilitate the storage, processing and distribution of (earth observation) data.

Box 7.4. Artificial intelligence and satellite data

Until recently, the analysis of satellite imagery was a costly, time-consuming and mainly manual exercise, but several technological advances, artificial intelligence (AI) technologies in particular, not only ensure that a lot of this work can be automated, but also open up new opportunities of trend prediction and forecasting. Machine-learning algorithms are quickly becoming more performant, sometimes surpassing human skills. Figure 7.6 shows the progress of AI systems in solving the object detection task in the Large Scale Visual Recognition Challenge (LSVRC) Competition that evaluates algorithms for object localisation/detection and image/scene classification from large scale images and videos. The best AI systems are more accurate than (average) human performance.

Figure 7.6. Improved object detection accuracy of AI systems



Notes: The LSVRC competition was organised by the Stanford University Vision Lab between 2010 and 2017.

Source: Shoham et al. (2017[47]), *Artificial Intelligence Index: 2017 Annual Report*, *http://cdn.aiindex.org/2017-report.pdf.*

AI algorithms and software currently contribute to geospatial analysis in multiple ways. Algorithms can be trained to identify, detect and/or count specific objects such as moving cars or marine vessels, and contribute to the monitoring of illegal fishing or estimating retail activity. They can also be helpful in land cover management and agriculture, by using multispectral satellite imagery to monitor the health and yield of agricultural crops, levels of deforestation (counting trees), identify land use (heat detection from commodity production facilities, and track changes in urban infrastructure) (Yates, 2017[48]).

In addition to automating formerly human tasks, algorithms exposed to millions of images can potentially identify patterns and correlations unidentifiable to the human brain and contribute to forecasting and planning. This typically involves linking satellite data with other types of data (socio-economic, social networks, media). A combination of satellite data, social networks, professional networks, online retailers, blogs, e-commerce, meteorological data, and data from air, marine and road traffic can be used to predict, for instance, energy or manufacturing trends (Huynh, 2017[49]).

Data storage and processing powered by cloud computing are some of the key technologies that are transforming the earth observation sector and enabling new activities. Several big cloud computing firms are playing a significant role in this. One example is Amazon Web Services (AWS) (see also Box 7.2). Data from the US earth observation satellite Landsat 8 have been available for free on AWS since 2015. Within the first 150 days of operations, the AWS Landsat 8 site hosted some 200 000 scenes and had more than 560 million hits from 167 countries. After a year, the number of hits had doubled to more than 1 billion (Sundwall, 2016[50]). Currently, the Earth on AWS platform hosts multiple earth observation datasets in addition to Landsat 8, e.g. Sentinel-2 (Europe), CBERS (China/Brazil), MODIS and GOES (United States), in addition to a dedicated labelled dataset for training machine learning algorithms (SpaceNet) (AWS, 2018[51]).

Cloud computing firms also support commercial earth observation activities. Table 7.7 shows a selection of earth observation data platforms for development of applications, including start-ups, space sector incumbents and non-space newcomers (EARSC, 2017[46]).

Table 7.7. Selected earth observation data platforms

Company	Country	Platform	Country/activity
Airbus Defence and Space	Europe	Geostore	Developers and sale
Amazon	United States	AWS	Developers
Atos	France	SparkInData	Developers
CloudEO	Germany	CloudEO store	Sales
DigitalGlobe	United States	GBDX (migrated to AWS)	Developers
ESRI	United States	ArcGIS on-line	Developers
Earth Observation Data Centre for Water Resources Monitoring (EODC)	Austria	EODC Platform	Developers
GeoCento	United Kingdom	EO Data Store	Developers (and sales)
Google	United States	Google Earth Engine	Developers and sales
Hexagon Geospatial	United States	Hexagon M. App	Developers
Planet	United States	Planet Platform	Developers (and sales)
Urthecast	Canada	Urthecast Platform	Developers

Source: EARSC (2017[46]), *A Survey into the Health of the European EO Services Industry*, *http://earsc.org/news/results-eo-industry-survey-september-2017*.

As satellite data become more plentiful and easier to process and use, they contribute to innovative applications in an increasing number of fields. Box 7.5 provides examples of interesting applications in the development of socio-economic indicators, where satellite data in certain cases can be used as proxies for economic variables in areas with limited data coverage.

As a final note and as seen in Chapter 1, there is also considerable growth and company creation in sectors dependent on GNSS technology. This includes services provided to other businesses (e.g. freight management, surveying) and the wider public (e.g. Uber and similar applications). Some 5 billion smartphones currently have GNSS chips (European GNSS Agency, 2017[54]), which represents a large potential market for location-based services and applications.

Box 7.5. Satellite data feeding into new economic indicators: Night lights as a proxy for economic activity

Satellite data are increasingly used in the field of economics, where different types of earth observation data, combined with other socio-economic data, are used to develop indicators. The information derived from satellite data can be used as proxies for economic variables that are impossible to get from areas with limited or no data availability (e.g. no census, border areas, conflict zones, very small geographical units, etc).

Positive correlations have been found for instance between night lights data, mainly provided by meteorological polar-orbiting satellites, and various socio-economic variables, including GDP per capita, manufacturing value-added, electricity consumption, and urban population (Addison and Stewart, 2015[52]). This allows to build up original socio-economic indicators.

An interesting illustration of the use of night lights data is a recent econometric analysis of the impact of trade liberalisation and regional trade integration policies on the development of border regions in East Africa (Brülhart, Cadot and Himbert, 2017[53]). High-resolution night lights data were used as proxies for levels of economic activity and population density. The study analysed the light intensity of 10 x 10 km geo-referenced cells along cross-border highways or major roads up to 200 km away from the border as well as a 5 km 'buffer' area on each side of the road (consistent with sub-Saharan habitation patterns), and regressed it on the distance to the nearest border and the interaction of distance with trade intensity. It found that night light intensity consistently decreased when approaching international inland borders, a pattern that

Box 7.5. Satellite data feeding into new economic indicators: Night lights as a proxy for economic activity *(cont.)*

was repeated in other inland border regions in the world. This contributed to identifying a socio-economic "border shadow effect", by which border regions are, on average, less developed than other regions. However, the study's econometric simulations showed that trade liberalisation (e.g. lower tariffs) could mitigate this border shadow effect and contribute to a spatially balanced development in the region.

Research on trade and spatial concentration in developing countries has traditionally relied on case studies with limited external applicability or cross-sectional approaches using aggregate proxies (e.g. trade-openness indices and spatial concentration indices). This approach, using satellite night lights, made it possible to conduct an analysis with more granular and robust data.

Sources: Addison and Stewart (2015[52]), "Nighttime lights revisited: The use of nighttime lights data as a proxy for economic variables", *World Bank Policy Research Working Paper*, No. 7496, *https://openknowledge.worldbank.org/handle/10986/23460* and Brülhart, Cadot and Himbert (2017[53]), "Trade integration and spatially balanced development implications for Uganda and Rwanda", *IGC Working Paper,* No. F-43406-CCP-1, *https://www.theigc.org/wp-content/uploads/2017/08/Brulhart-et-al-2017-Working-paper.pdf.*

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COUNTRY PROFILES: ACTORS IN THE SPACE ECONOMY

The following chapters presents selected country profiles, focussing on members of the OECD Space Forum and selected OECD countries and partner economies with space programmes. The countries covered are (in alphabetical order): Australia, Canada, People's Republic of China, France, Germany, India, Italy, Korea, Mexico, the Netherlands, New Zealand, Norway, Switzerland, the United Kingdom, and the United States.

8. Guide to the Profiles

Using a common framework to present information, country profiles provide facts and indicators for a selected number of countries with space programmes (i.e. members of the OECD Space Forum, as well as Australia, the People's Republic of China (hereafter "China"), India and New Zealand). The country profiles provide a quick, at-a-glance, overview of important activities and trends, and include both long-standing and new indicators developed by the OECD Space Forum.

Each profile provides information on the state of the country's space sector; space-related government budgets, recent policy developments, as well as key commercial activities. These findings are supported by a selection of internationally comparable indicators, subject to data availability:

- "Fast facts" indicators
- Space budget trends and main programmes
- Scientific production in space literature
- Top applicants of space-related patents
- Penetration of satellite telecommunications technologies
- Space-related official development assistance commitments.

Throughout the country profiles, three-letter ISO country name abbreviations have been used. A list of country codes is provided at the beginning of the report, under Acronyms and abbreviations.

"Fast facts" indicators

The Fast Facts boxes summarise indicators found in different chapters of the publication.

- The per capita space budget (in current USD) is intended as a quick and intuitive comparative indicator of the investments in institutional space programmes. The demographic data come from OECD databases.
- The country's institutional space budget (in current USD) as a share of Gross domestic product (GDP) is based on government sources and OECD calculations.
- The space R&D share of civil government budget appropriations for R&D (GBARD) is provided for the last available year. This indicator uses budget estimates (not actual spending) and focuses on the socio-economic objective "exploration and exploitation of space". This excludes military space programmes, which are included in a specific, aggregated "defence" category in the *Main Science and Technology Indicators* database.
- The launch year of the first (successfully launched) satellite is a high-visibility marker of a country's space programme. The satellite can be domestically developed or purchased from abroad; in both cases, it represents significant investments and new technical capabilities.
- The share of graduates in science, technology, engineering and mathematics (STEM) subjects in tertiary education is an indicator of the available talent pool for space sector development and growth. The data come from the OECD Education at a Glance database and comprises graduates from three fields of education: natural sciences, mathematics and statistics; information and communication technologies; and engineering, manufacturing and construction.

Space budget trends and main programmes

The indicator on institutional budget provides a conservative estimate of the inflation-adjusted evolution of space programmes over the last ten years between 2008 and 2017. Also included is an overview of main space agency programmes for 2017 or the latest available year, which may indicate some of the key national priorities. Data come from government sources.

Budget trends are provided in both constant national currencies and in constant US dollars in order to give an indication of the currencies' fluctuations, as many space budgets are often affected by exchange rates. For calculations, this report makes use of the consumer price index (all items) as a deflator and exchange rates from the *OECD Main Economic Indicators (MEI)* database.

In the country profile for China, the space budget is an estimate, based on the analysis of other R&D intensive sectors, experiences in OECD and non-OECD space programmes and infrastructure development.

Scientific production in space literature

The indicator on the share of global space-related scientific production in space literature tracks innovation activities in the space sector. Authors of scientific papers are most likely found in higher education institutions and research organisations.

The analysis is based on a custom-built “Space literature” dataset of scientific publications extracted from Elsevier’s Scopus Custom Data database. The Space literature dataset includes papers from 124 journals, comprising all journals in the Elsevier Scopus space and planetary science classification, a selection of relevant journals belonging to the aerospace engineering field, and journals dedicated to specific space applications (e.g. GPS, GNSS, satellite remote sensing and navigation). Estimates of scientific production are based on whole counts of documents (i.e. papers in scientific journals and conference papers) by authors affiliated to institutions.

The Scopus Custom Data database is a global database of peer-reviewed scientific articles, with bibliometric records of more than 25 million articles published in more than 18 000 journals. Papers are allocated to scientific fields using the All Science Journal Classification (ASJC). It includes scientific publications in English (the majority) as well as other languages.

Top applicants of space-related patents

Space-related patent applications is another indicator that serves as a proxy for innovation activities. Patent applicants are often business firms, but can also be based in higher education institutions and research organisations.

Space-related patent applications are identified using a combination of codes from the International Patent Classification (IPC) and keyword searches in the patent title. Data refer to IP5 patent families (inventions patented in the five top IP offices) filed between 2002-05 and 2012-15, by first filing date and according to the inventor’s residence, using fractional counts.

Penetration of satellite telecommunications technologies

Two indicators, satellite TV subscriptions and satellite broadband subscriptions per 100 inhabitants, track the uptake of satellite telecommunications technologies across the world. They have been extracted from the OECD *Broadband database* and the International Telecommunication Union’s (ITU) *World Telecommunication/ICT Indicators database (WTID)*.

While data availability for subscriptions varies from year to year, data are on average available for all major actors and leading global economies.

Space-related official development assistance commitments

This new indicator identifies the main thematic purpose and donors/recipients of space-related official development assistance (ODA) over the period 2000-16, as reported in the databases of the OECD Development Assistance Committee (DAC). It contributes to tracking the actual use of space technologies to address socio-economic challenges in developing countries.

The OECD’s Development Co-operation Directorate has been in charge of measuring resource flows to developing countries since 1961, with particular attention given to the official and concessional part of this flow, defined as “official development assistance”.

In close collaboration DAC colleagues, the OECD Space Forum Secretariat has explored the databases using keyword searches. The original dataset has been manually checked and cleaned in order to identify and retain only the projects effectively dealing with space-related initiatives. Almost 2 100 ODA projects featuring satellite applications or technologies were identified over the 16-year period.

Data are reported by donor and recipient country and/or region. In some cases, the recipient cannot be identified, either because it was not specified by the donor country or because the ODA was delivered via an international organisation (e.g. the World Bank). The list of thematic purposes (e.g. business development, telecommunications, biodiversity) is defined by DAC and attributed to a project when it is entered into the DAC database.

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In view of its location, Australia is an important partner in international space vehicle tracking activities as the host of NASA and ESA deep space communications earth stations. The country furthermore plays a key role in fundamental research with several large radio astronomy observatories. The Australian Space Agency, established in July 2018, acts as the principal co-ordinator of governmental activities on civil space matters and advises the government on civil space policy issues. It is under the responsibility of the Department of Industry, Innovation and Science. Other important government actors include the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Geoscience Australia.

In the 2018-19 government budget, the Australian Space Agency was allotted AUD 26 million (some USD 20 million) over four years. From 2019-20, the Agency will also be able to draw from a pool of AUD 15 million (USD 12 million) dedicated to partnering with international space organisations. Australia intends to build on its niche industry capabilities and strategically develop new commercial opportunities to compete in the global space economy.

Other recent policy initiatives include the four-year AUD 220 million (USD 170 million) funding package for GNSS-augmenting infrastructure, for a satellite-based augmentation system and a complementary National Positioning Infrastructure Capability with an even higher accuracy (Australian Department of Industry, Innovation and Science, 2018[1]).

The Australian government announced in the 2017-18 budget the creation of a digital analysis platform for satellite imagery and other earth observations, Digital Earth Australia. The objective is to increase the efficiency and effectiveness of Australian government programmes and policies which rely on accurate and timely spatial data. The platform will also provide Australian industry with access to stable, standardised data and imagery products.

Research is conducted at a number of universities and research organisations, such as the government-funded Co-operative Research Centre for Spatial Information (GNSS and satellite imagery applications) and Space Environment Research Centre (space environment, space situational awareness).

The Australian space industry has activities in manufacturing, in particular ground stations and equipment, satellite operations and downstream applications, with several start-ups. Start-ups such as Fleet Space and Myriota are developing applications for the Internet of Things (IoT), planning to provide precision agriculture in remote areas, end-to-end goods tracking, assets and environmental monitoring, etc. Both companies launched their first satellites in 2018. Fleet Space now has four cubesats in orbit, out of a planned 100.

Important downstream activities include satellite operations and telecommunications, positioning, navigation and timing, and earth observation. Many companies cater to the maritime, extractive and agriculture industries. Space industry revenues have been estimated at some AUD 3 billion (USD 2.3 billion) (Australian Department of Industry, Innovation and Science, 2017[2]).

Australia's share in scientific publications in OECD's space literature dataset (see guide to the profiles) is comparable to that of Canada and the Russian Federation and has been stable since 2000. The country's share in space-related patent applications decreased between 2002-05 and 2012-15, mainly due to increased activity of other countries.

Satellite broadband penetration is one of the highest in the OECD area. The number of subscriptions is currently increasing after a dip between 2009 and 2015. This may be connected to the rollout of the National Broadband Network, a government scheme to provide high-speed and affordable (mainly fibre) broadband to all Australians. Two nbn™ Sky Muster satellites, launched in 2015-16, cover rural and remote areas without access to terrestrial technologies, representing more than 200 000 potential subscribers (Joint Standing Committee on the National Broadband Network, 2017[3]).

Space-related official development assistance projects in the period 2000-16 have mainly focussed on telecommunications and disaster risk management, with the majority of the recipients located in the Pacific region.

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Figure 9.1. Australia – Fast facts

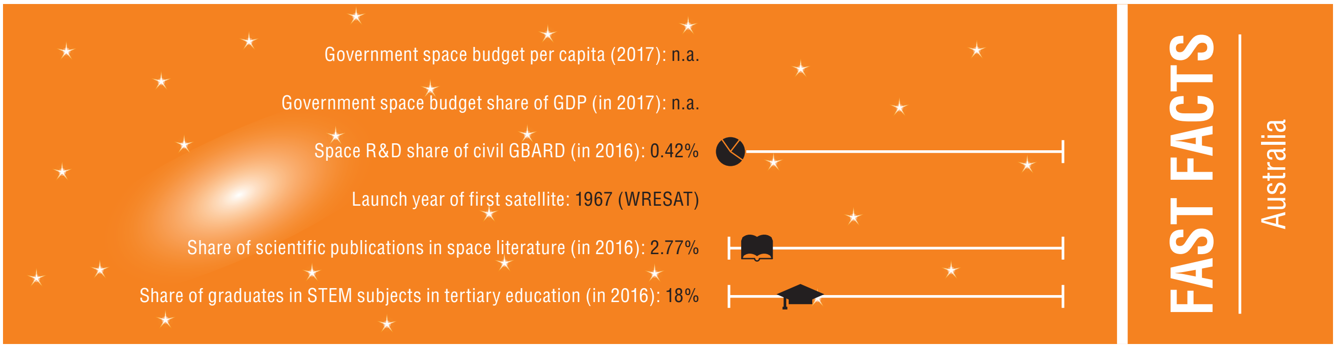
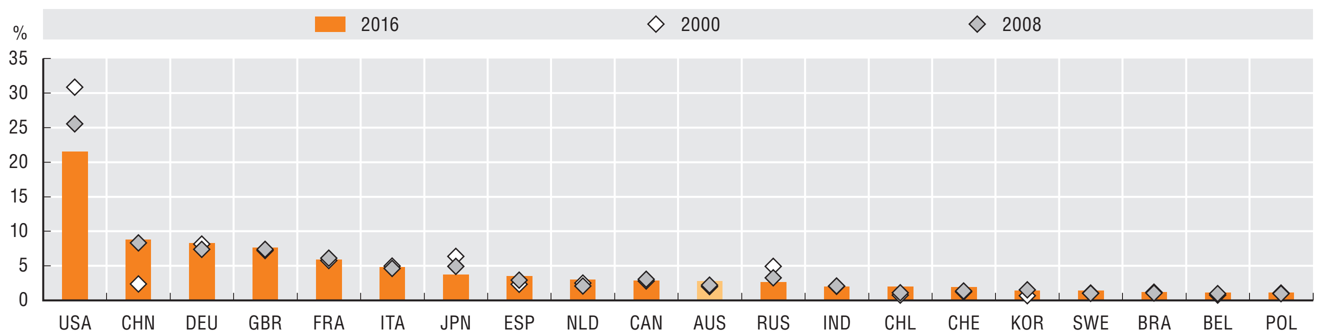


Figure 9.2. Scientific production in space literature, per country

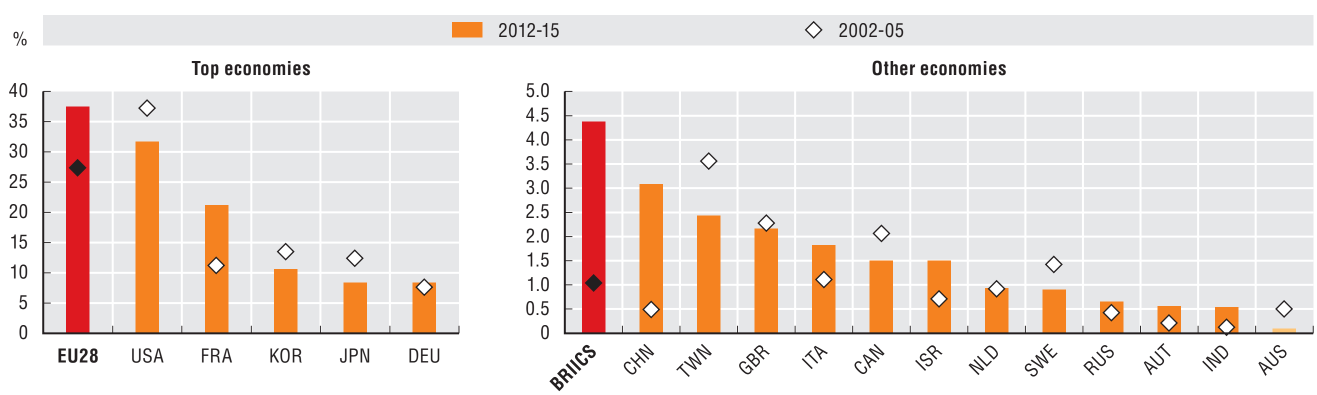
Share of total space publications, 2000, 2008 and 2016



Source: OECD analysis based on Scopus Custom Data, Elsevier, July 2018.

Figure 9.3. Top applicants of space-related patents

IP5 patent families, by priority date and applicant's location, using fractional counts, 2002-05 and 2012-15

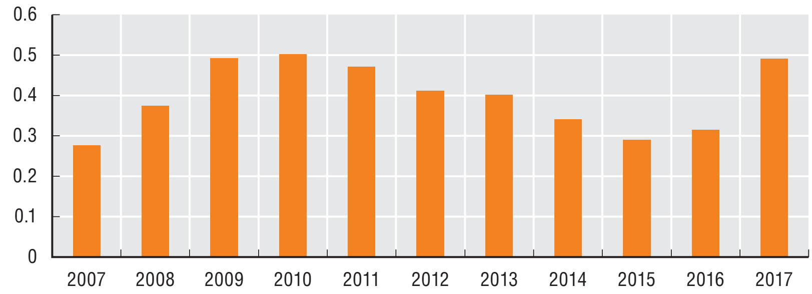


Note: Patent families are compiled using information on patent families within the Five IP offices (IP5). Figures are based on incomplete data from 2014.

Source: OECD STI Micro-data Lab: Intellectual Property Database, *http://oe.cd/ipstats*, March 2018.

Figure 9.4. Penetration of satellite telecommunication technologies in Australia

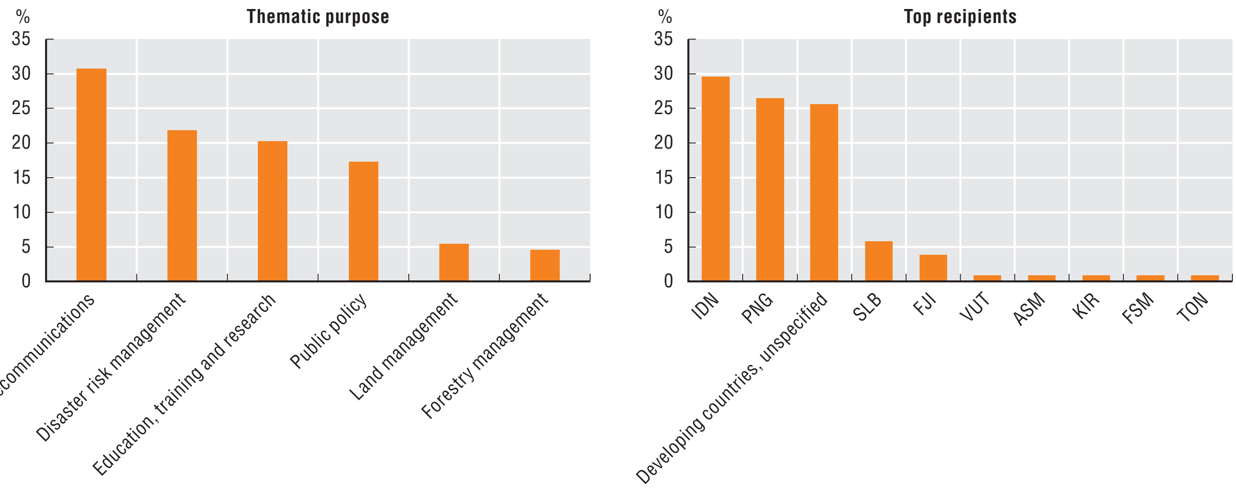
Satellite broadband subscriptions per 100 inhabitants, 2007-16



Source: OECD analysis based on OECD Broadband database, *https://www.oecd.org/sti/broadband/broadband-statistics/*, and ITU World Telecommunication/ ICT Indicators database.

Figure 9.5. Australian space-related official development assistance commitments

Share of total Australian space-related commitments, 2000-16



Source: Calculations based on OECD DAC database (2018).

10. Canada

Canada has strong capabilities in telecommunications, earth observation, synthetic aperture radar (SAR) and computer vision systems, aerospace manufacturing and robotics. In the 1960s, it was the third country to launch a satellite into space (Alouette-1) and it is currently an active member of international science and earth observation missions. It is one of the partnering countries on the International Space Station and has also announced its participation in NASA's *Gateway* initiative, a manned outpost orbiting the Moon. Under the authority of the Department of Innovation, Science and Economic Development (ISED), the Canadian Space Agency (CSA) is responsible for the co-ordination of space policies and programmes in Canada.

The 2014 Space Policy Framework offers five core principles that help to guide the Canadian government's priorities for its space programme. These core principles include a need to ensure Canadian interests and private sector competitiveness are supported through the space programme, and a focus on leveraging partnerships and Canada's excellence in key capabilities through its space activities. A government space strategy was released in March 2019, highlighting the importance of space science and exploration, industry support and innovation and the use of space technologies to address societal challenges (e.g. bringing connectivity to remote areas, climate change research).

Important long-term Canadian priorities are the Radarsat earth observation missions (first satellite launched in 1995), which provide synthetic aperture radar imagery for maritime surveillance, disaster management and ecosystem monitoring. The country has also had formal co-operation agreements with the European Space Agency since the late 1970s, which give Canadian companies access to the European market.

In 2017, the budget of the Canadian Space Agency amounted to CAD 339 million (USD 249 million), a 3% decrease in real terms compared with 2008. 36% of the budget was devoted to 'space data, information and services' (including the Radarsat constellation), 30% to space exploration (mainly the International Space Station) and 19% to 'future Canadian space capacity'. Subscriptions to ESA programmes accounted for about 10% of the budget (Canadian Space Agency, 2016[1]).

Important research and innovation actors include the Canadian Space Agency and the National Research Council, which support several laboratories and centres across the country. Furthermore, Natural Resources Canada and Defence Research and Development Canada play an important role in earth observation data storage and processing and military technology innovation. Thirty-six universities across Canada carry out an important share of space-related R&D.

The Canadian space sector has activities in many industry segments. In 2017, the sector generated some CAD 5.6 billion (USD 4.1 billion) in revenues, 84% of which was generated in the downstream segment (i.e. satellite operations, value-added products and services including direct-to-home broadcasting) (Canadian Space Agency, 2019[2]). The space sector workforce comprised some 9 942 FTEs (full-time equivalents), with a 50-50 distribution between upstream and downstream segment organisations. Government employees are not included in space workforce data. The biggest industry clusters can be found in Ontario and Québec, which together accounted for 80% of revenues and 74% of the workforce in 2017.

Sales to domestic and foreign government actors accounted for only 13% of revenues, but public procurement remains very important in some upstream segments such as science and space exploration. Exports accounted for 38% of total revenues, with the United States and Europe as the most important foreign markets (Canadian Space Agency, 2019[2]).

Canada's share in scientific publications in the OECD "Space literature" dataset (see guide to the profiles) has remained stable since 2000. Canada's share of space-related patent applications decreased between 2002-05 and 2012-15, mainly due to increased activity of other countries.

The penetration of satellite television has gradually decreased since 2010, after an increase between 2000 and 2010. Canada has several funding mechanisms for providing rural broadband, including that provided by satellite (OECD, 2018[3]). The Arctic Inuvik Satellite Station Facility (opened in 2010) was recently linked to the main telecommunications network via a 1 000 km high-speed optical cable, to attract ground station operators and benefit from the growing numbers of polar-orbiting satellites in low-earth orbit.

Space-related development assistance activities over the period 2000-16 focussed mainly on enabling and facilitating local business development (tele-training) and developing tele-communication networks.

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Figure 10.1. Canada – Fast facts

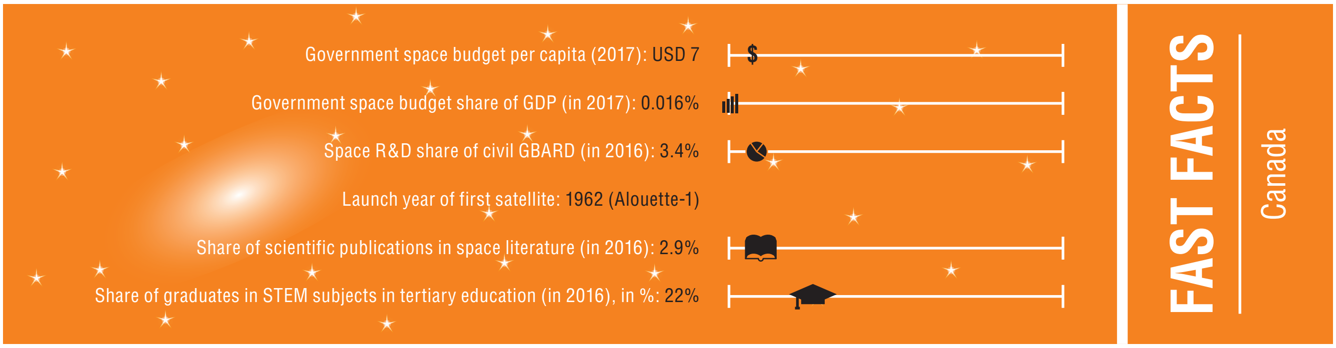
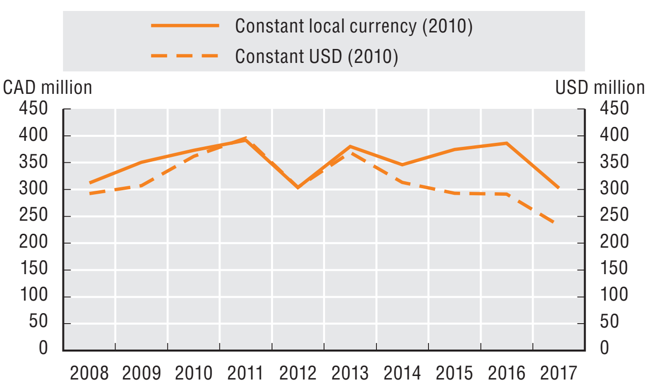
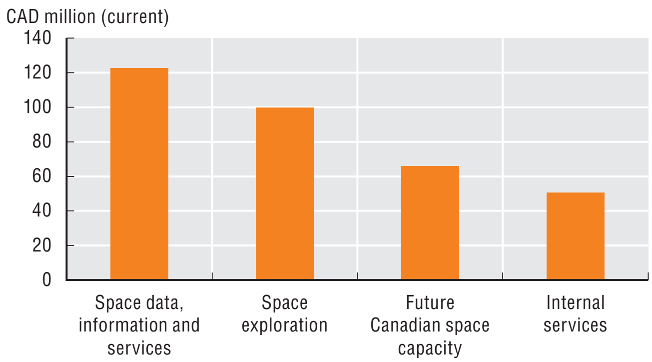


Figure 10.2. Space budget trends and main programmes

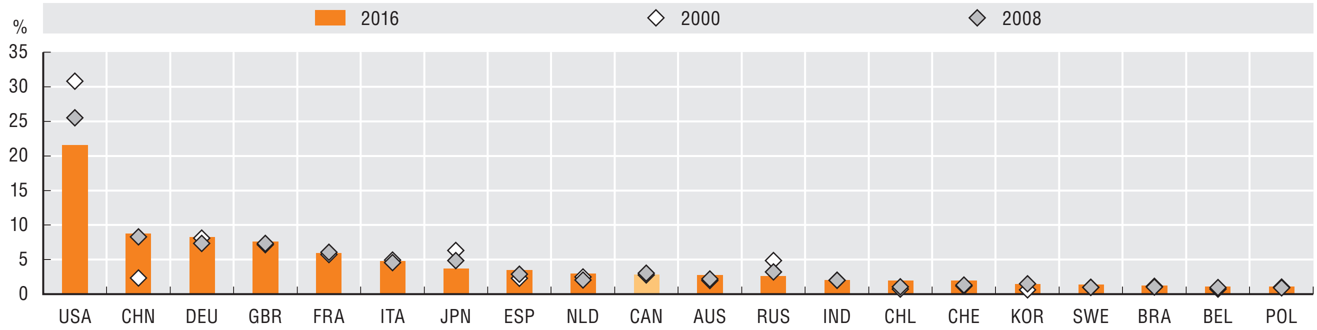




Source: OECD analysis based on institutional sources.

Figure 10.3. Scientific production in space literature, per country

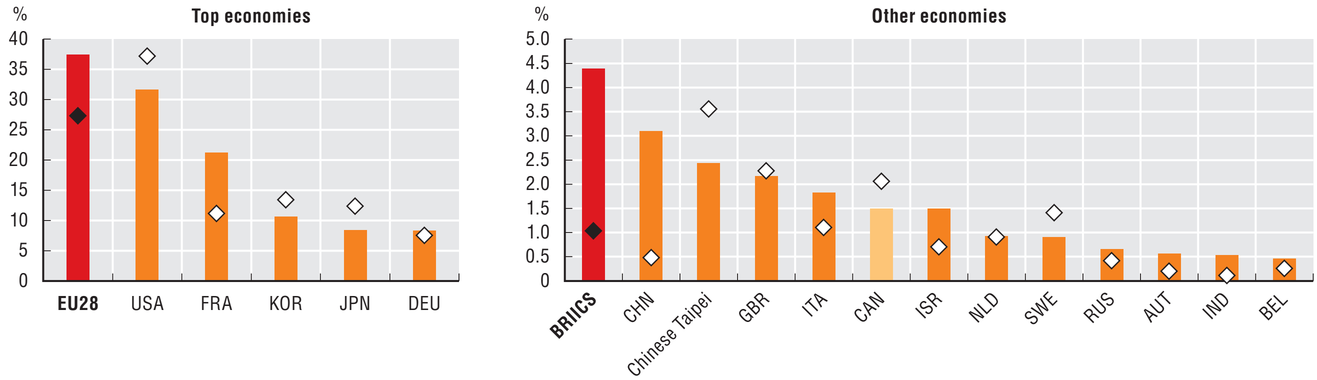
Share of total space publications, 2000, 2008 and 2016



Source: OECD analysis based on Scopus Custom Data Elsevier, July 2018.

Figure 10.4. Top applicants of space-related patents

IP5 patent families, by priority date and applicant's location, using fractional counts

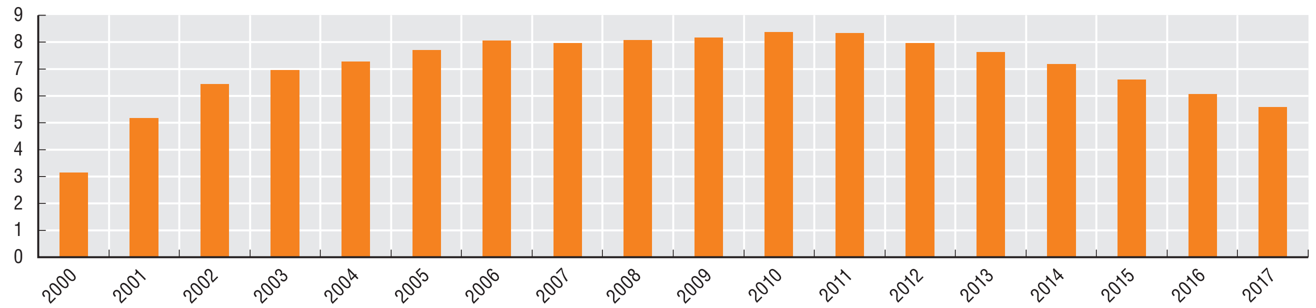


Note: Patent families are compiled using information on patent families within the Five IP offices (IP5). Figures are based on incomplete data from 2014.

Source: OECD STI Micro-data Lab: Intellectual Property Database, *http://oe.cd/ipstats*, March 2018.

Figure 10.5. Penetration of satellite telecommunication technologies in Canada

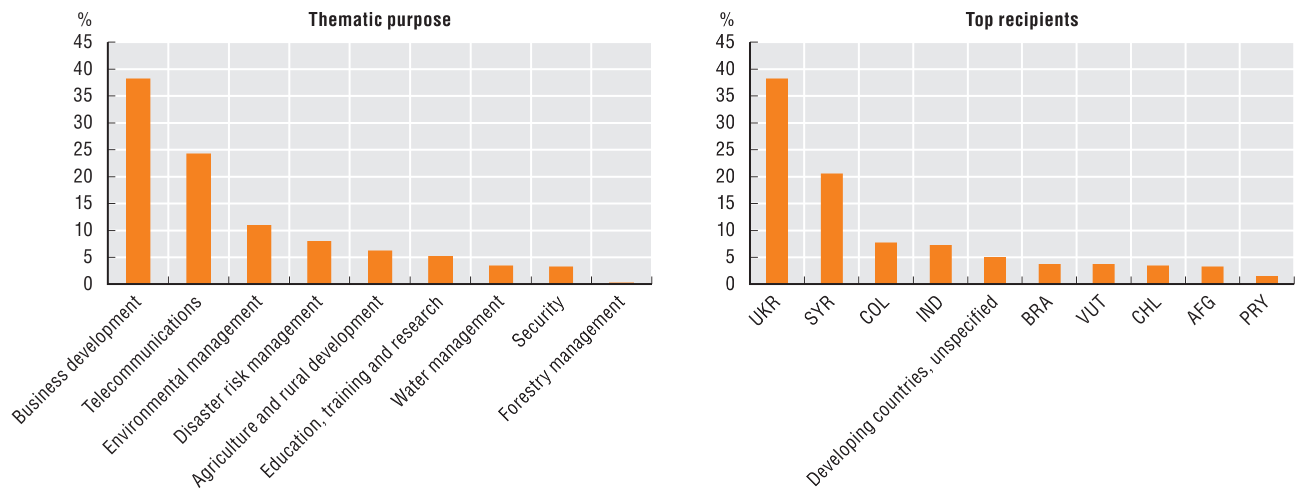
Satellite TV subscriptions per 100 inhabitants, 2000-2016



Source: OECD analysis based on OECD Broadband database, *https://www.oecd.org/sti/broadband/broadband-statistics/*, and ITU World Telecommunication/ICT Indicators database.

Figure 10.6. Canadian space-related official development assistance commitments

Share of total Canadian space-related commitments, 2000-16



Source: Analysis based on OECD DAC database (2018).

11. People's Republic of China

Since its first successful launch in 1970, the People's Republic of China (hereafter "China") has extended its capabilities in all types of space activities. It is one of only three countries to have sent humans into orbit. While traditionally government-controlled, an increasing number of private actors are appearing in the sector. The China National Space Administration, under the Ministry of Industry and Information Technology, and the People's Liberation Army (PLA) are responsible for civil and military space activities, respectively. Other important actors include the National Space Science Centre of the Chinese Academy of Sciences as well as the state-owned enterprises China Aerospace Science Technology Corporation (CASC) and the China Aerospace Science and Industry Corporation (CASIC).

It is conservatively estimated that China allocated some USD 9.3 billion to space activities in 2017 (guide to the profiles). This takes into account considerable investments in spacecraft technologies and human spaceflight, such as the work to finalise the Chinese Space Station, planned to be operational in 2022, and developing the super-heavy launcher Long March 9, destined for Mars and lunar missions in the 2030s. With thirty-nine orbital launches in 2018, a third of all 2018 worldwide launch events, the country conducted more annual space launches than ever before.

Downstream application programmes and science activities are also increasingly ambitious. China now has the second-highest number of operational earth observation missions, after the United States (some twenty national and multilateral missions), and will soon finalise the global extension of the Beidou GNSS constellation. In 2018, it became the first country to successfully land a rover on the far side of the Moon. Also, the quantum physics satellite Micius successfully transmitted entangled photon pairs between ground stations in China and Austria, a first step to ensure long-distance encrypted communications. China's first mission to Mars may launch in 2020.

China's most recent five-year plan for economic and social development for 2016-20 sets as priorities the accelerated construction of a national civil space infrastructure for earth observation, broadband mobile communications and GNSS, and space technology development (People's Republic of China State Council, 2016[1]). There is also an increased focus on socio-economic returns of space investments with reinforced efforts to develop space applications for government, civil and commercial use (People's Republic of China State Council, 2016[2]).

China has government-led activities in all segments of the space industry. CASC and CASIC are the major actors in manufacturing and in the commercialisation of products and services abroad. The commercialisation of space activities is a growing priority in China. In 2014, the government opened the space sector to private capital. Dozens of companies have been created, mainly targeting the growing market of very small satellites. This includes for instance the launch vehicle manufacturers LandSpace, iSpace and OneSpace and the nanosatellite manufacturers MinoSpace and Spacety. Funding is provided both by private venture capital funds and local and regional government administrations. LandSpace made its first orbital launch attempt in October 2018, with the small satellite launcher Zhuque-1, carrying a payload manufactured by MinoSpace. This was China's first private space launch. In 2016, the Chinese manufacturing sector, dominated by state-owned and state-controlled enterprises, reported some CNY 22.9 billion (USD 3.4 billion) in revenues (Chinese National Bureau of Statistics, 2017[3]).

In the downstream segment as well, China has seen a growth in the number of private actors, such as the earth observation satellite operator Chang Guang Satellite Technology, with the Jilin constellation. Start-ups are also active in other downstream segments, including data analytics. In satellite telecommunications, the CASC subsidiary China Satcom is a key actor, with some USD 220 million in revenues recorded in 2016 (Henry, 2017[4]).

China's share of scientific production in the OECD space literature dataset and space-related patent applications (see guide to the profiles) has significantly increased in the last 10-15 years, and is surpassed only by that of the United States. This is part of a more general trend of increased Chinese scientific publishing and patenting activity in all domains at the same time. China was the recipient of several space-related official development assistance projects between 2000 and 2016, mainly focussing on environmental management and agriculture and rural development. The main donors were the United Kingdom and Germany.

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Figure 11.1. People's Republic of China – Fast facts

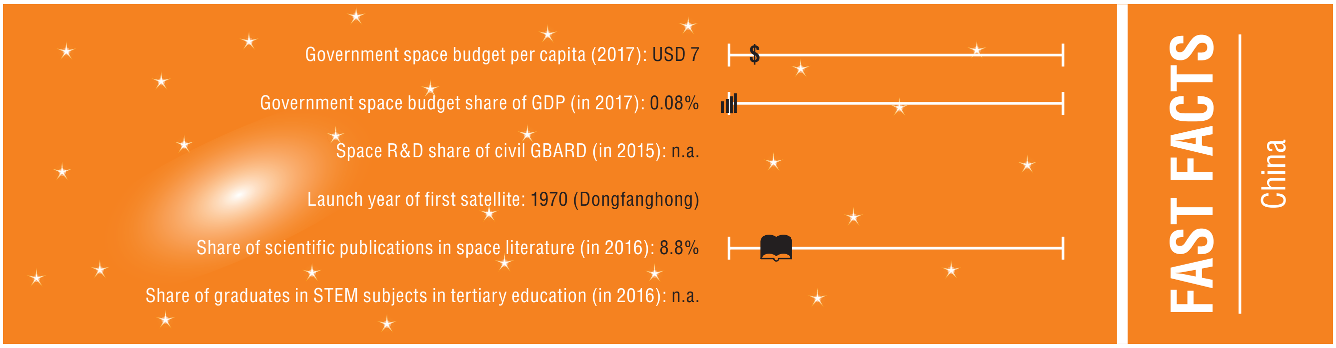
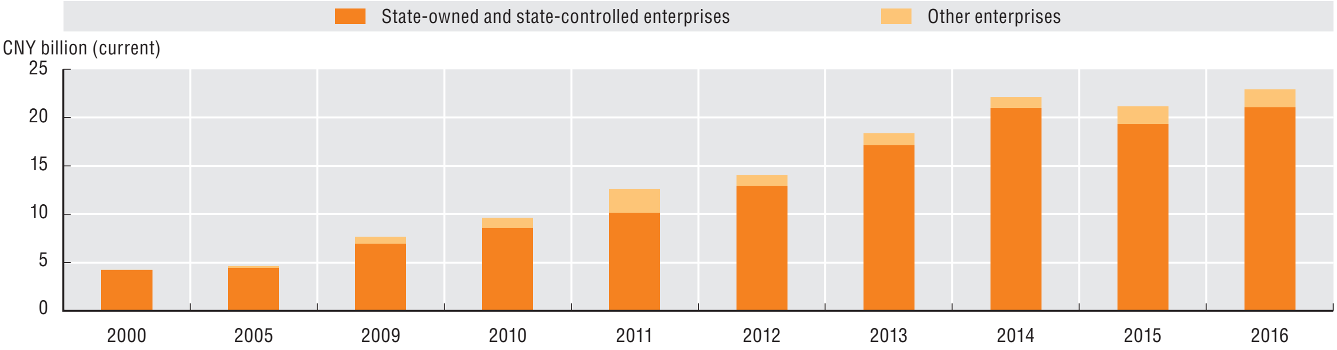


Figure 11.2. Revenues of Chinese companies involved in spacecraft manufacturing

In CNY billion (current), 2000-16

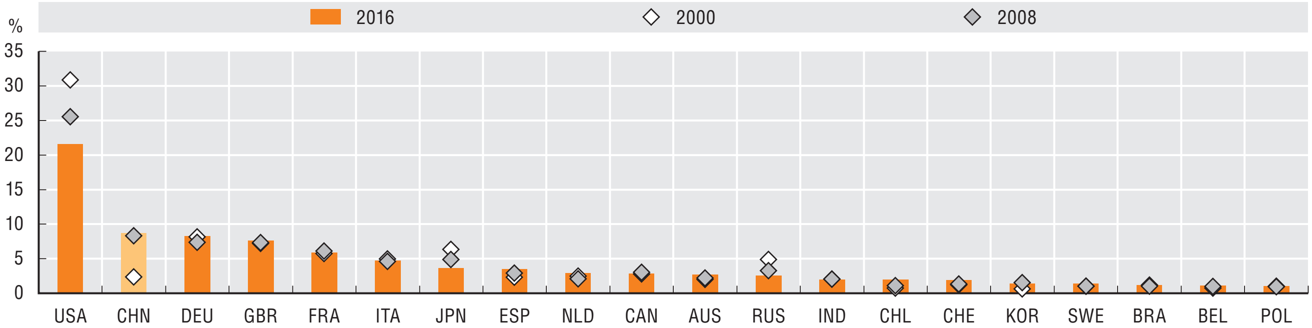


Note: Revenues are not adjusted for inflation.

Source: Chinese National Bureau of Statistics (2017), China Statistics Yearbook on High Technology Industry: 2017.

Figure 11.3. Scientific production in space literature, per country

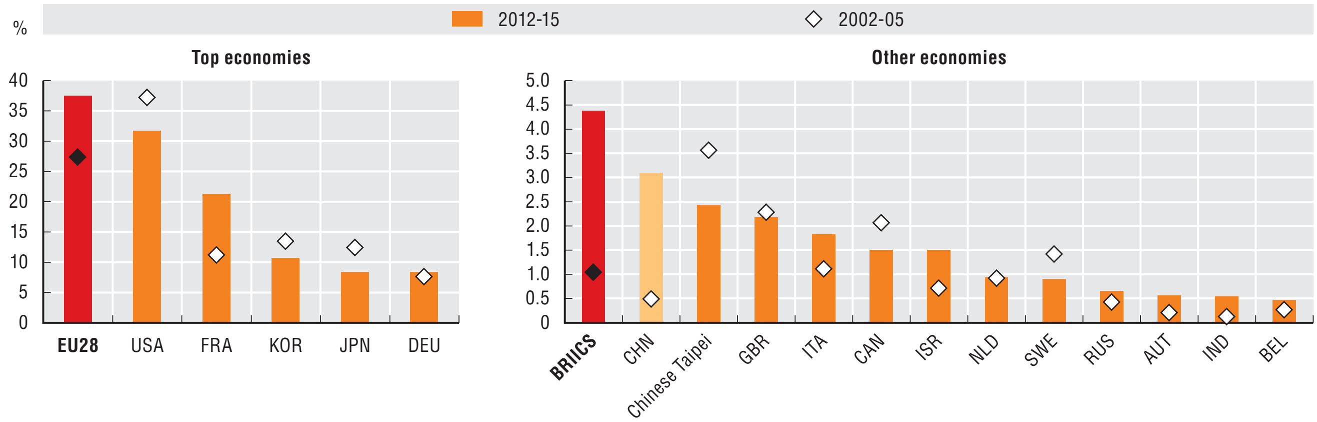
Share of total space publications, 2000, 2008 and 2016



Source: OECD analysis based on Scopus Custom Data, Elsevier, July 2018.

Figure 11.4. Top applicants of space-related patents

IP5 patent families, by priority date and applicant's location, using fractional counts, 2002-05 and 2012-15

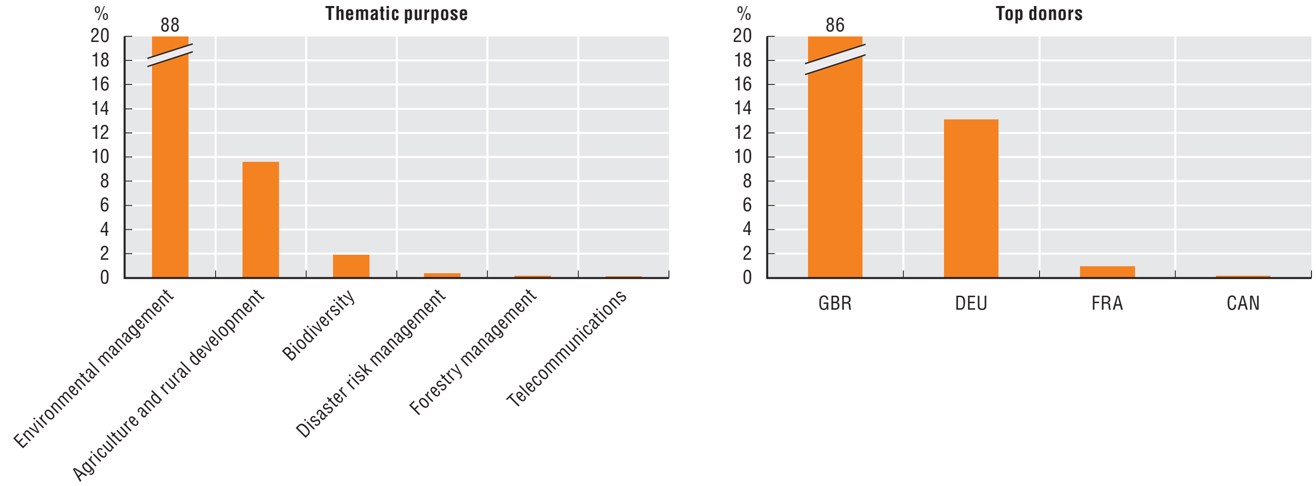


Note: Patent families are compiled using information on patent families within the Five IP offices (IP5). Figures are based on incomplete data from 2014.

Source: OECD STI Micro-data Lab: Intellectual Property Database, *http://oe.cd/ipstats*. March 2018.

Figure 11.5. Space-related official development assistance projects conducted in China

Share of space-related commitments directed to China, 2000-16



Source: Calculations based on OECD DAC database (2018).

12. France

France has the largest space budget in Europe and is, with Germany, one of the top contributors to the European Space Agency (ESA). It is home to the Guiana Spaceport, with excellent conditions for launch to the geostationary orbit. The French space agency CNES, under the joint supervision of the Ministry of Higher Education and Research and the Ministry of Defence, is responsible for formulating and executing space policies. France also hosts the headquarters of the European Space Agency (ESA) and several centres and services for the European navigation programme Galileo.

Recent policy activities aim to strengthen technology development and innovation in downstream activities. The cross-ministerial government Future Investment Plan (PIA), established in 2010, is providing additional funding for the development of next-generation satellites and downstream products and services.

Downstream services and product development and commercialisation were further supported by the 2016 creation of four 'boosters', or accelerators, near existing regional non-space clusters (maritime, transport, energy, agriculture, environment). These boosters have so far created more than 35 promising projects that have been selected for further funding and support. Following this initial success, another three boosters were designated in 2018, including a cluster in French Guiana, addressing themes such as natural hazards and resources management, future mobility, agriculture and tourism (French Ministry of Higher Education, Research and Innovation, 2018[1])

France is also in the process of formulating a new military space strategy, focussing on reinforcing surveillance and offensive capabilities as well as the resilience of individual satellites and systems. In an effort to guide long-term policy decisions, CNES has launched the Space'ibles project, a multidisciplinary foresight exercise uniting both space and non-space actors.

In 2017, the French institutional budget estimates for space activities totalled some EUR 2.4 billion (USD 2.7 billion), a 26% increase in real terms since 2008. Of this, 61% funded the French multilateral programme, while 36% was dedicated to ESA and 3% to EUMETSAT. Almost half of the commitments funded the launcher programme (46%), followed by earth observation (14%), defence (11%) and science (10%).

Government research institutes and laboratories play an important role in R&D and innovation activities, with dedicated organisations such as CNES, the National Aerospace Research Centre (ONERA) and CNRS, the National Centre for Scientific Research. A lot of research is conducted at universities and in the highly-regarded aerospace and mechanical engineering schools.

The French space industry has activities in all segments of the space sector. Both upstream and downstream sectors are strongly export-oriented. It is estimated that French manufacturers accounted for some 75% of European space manufacturing exports in 2017 (French Ministry of Higher Education, Research and Innovation, 2019[2]).

There are systems integrators in both satellite and launcher production, including Airbus and Thales Alenia Space, and a multitude of companies producing subsystems and equipment. Airbus is part of the OneWeb Manufacturing consortium and in 2017, it opened a facility near Toulouse to produce prototypes for the satellites in the planned mega-constellation for satellite broadband. The bulk of the satellites will be produced in Florida. Important industry segments include launch services (Ariane Group), launcher and satellite manufacturing (in particular earth observation satellites). In 2017, space manufacturing activities in France generated some EUR 7.9 billion (USD 8.9 billion) in unconsolidated revenues, with military space orders accounting for 27% of the total. It employed 15 000 persons, mainly in the Southwest and Ile de France regions. (GIFAS, 2018[3]).

Satellite operations and earth observation are some of the most significant downstream activities, with a growing number of start-ups providing value-added services for sectors such as maritime, energy, agriculture and finance. Satellite operator Eutelsat reported revenues of EUR 1.4 billion (USD 1.5 billion) in 2017-18, with some 560 persons employed in France (Eutelsat, 2018[4]).

France ranks among the leading countries worldwide in space scientific production in the OECD space literature dataset, with a stable share in global space publications since 2000. France's share in space-related patent applications has doubled between 2002-05 and 2012-15. Space-related official development assistance projects in the period 2000-16 focussed on environmental management and fisheries, with Viet Nam and Indonesia as top recipient countries.

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Figure 12.1. France – Fast facts

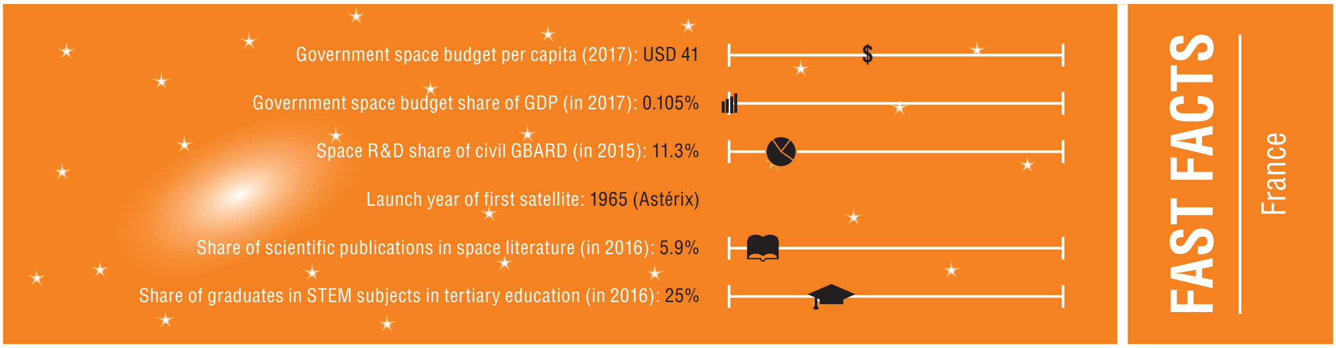
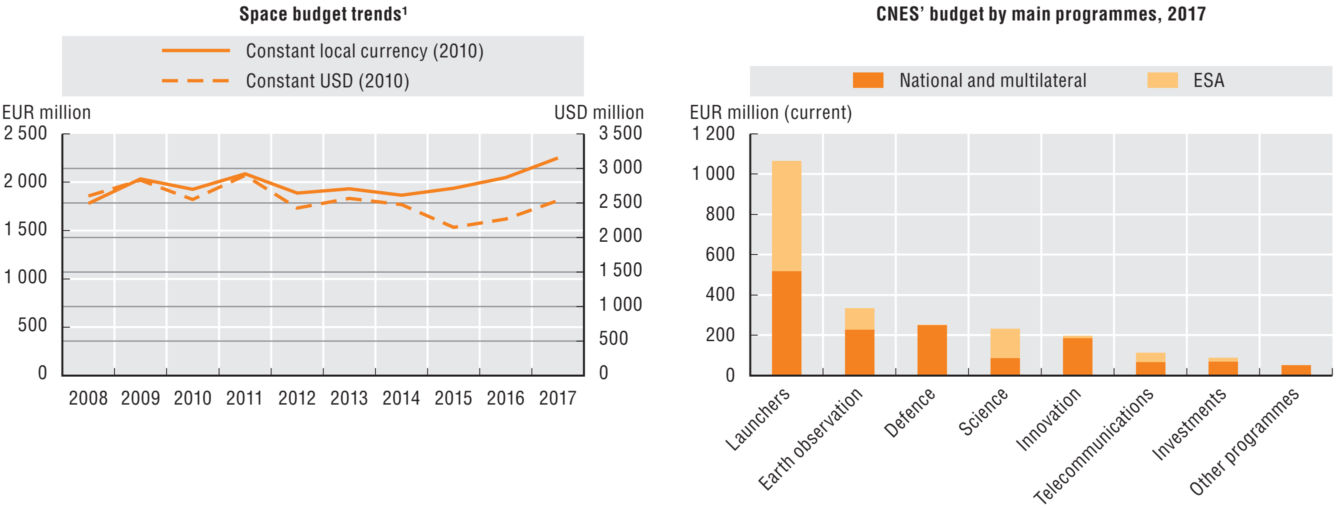


Figure 12.2. Space budget trends and main programmes

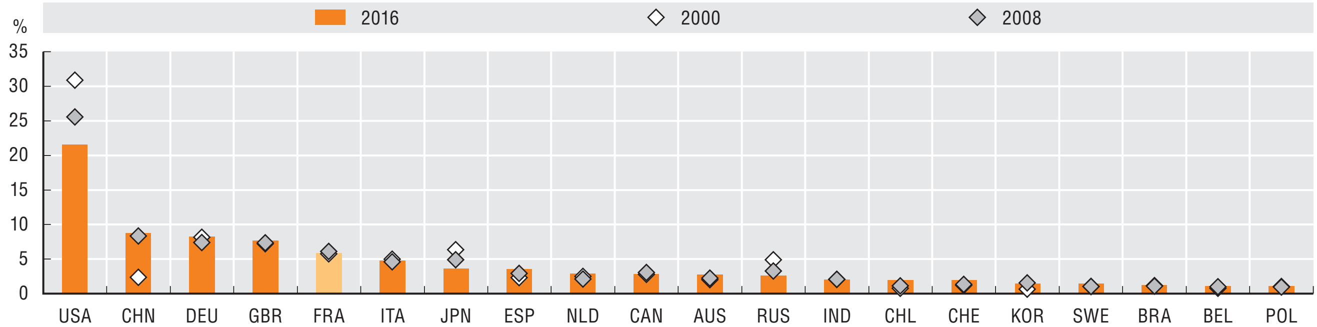
In constant EUR and USD, 2008-17 and in EUR (current), 2017



Note: 1.The institutional space budget includes contributions to the national/multilateral programme, EUMETSAT and the European Space Agency.
Source: OECD analysis based on institutional sources.

Figure 12.3. Scientific production in space literature, per country

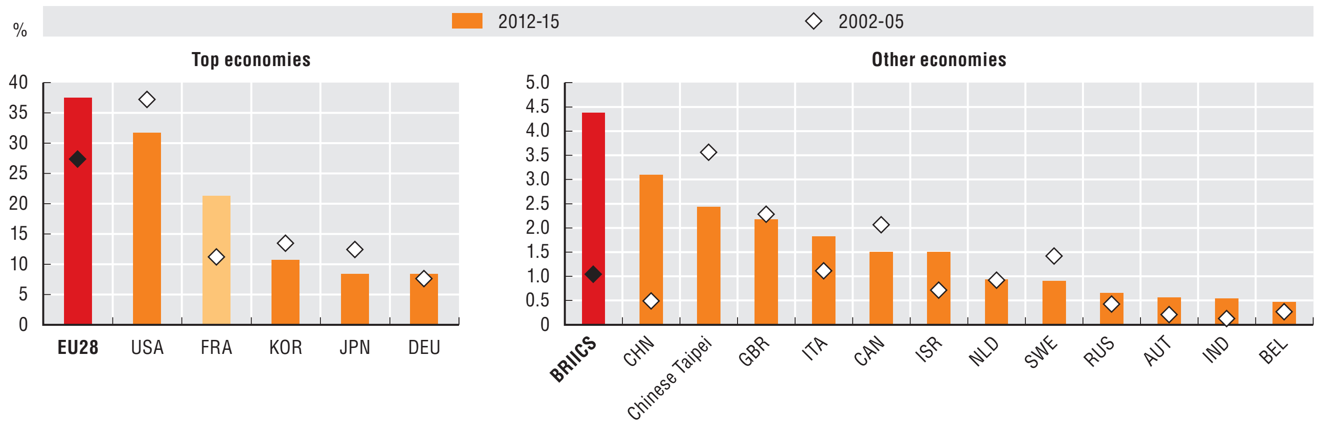
Share of total space publications, 2000, 2008 and 2016



Source: OECD analysis based on Scopus Custom Data, Elsevier, July 2018.

Figure 12.4. Top applicants in space-related patents

IP5 patent families, by priority date and applicant's location, using fractional counts, 2002-05 and 2012-15

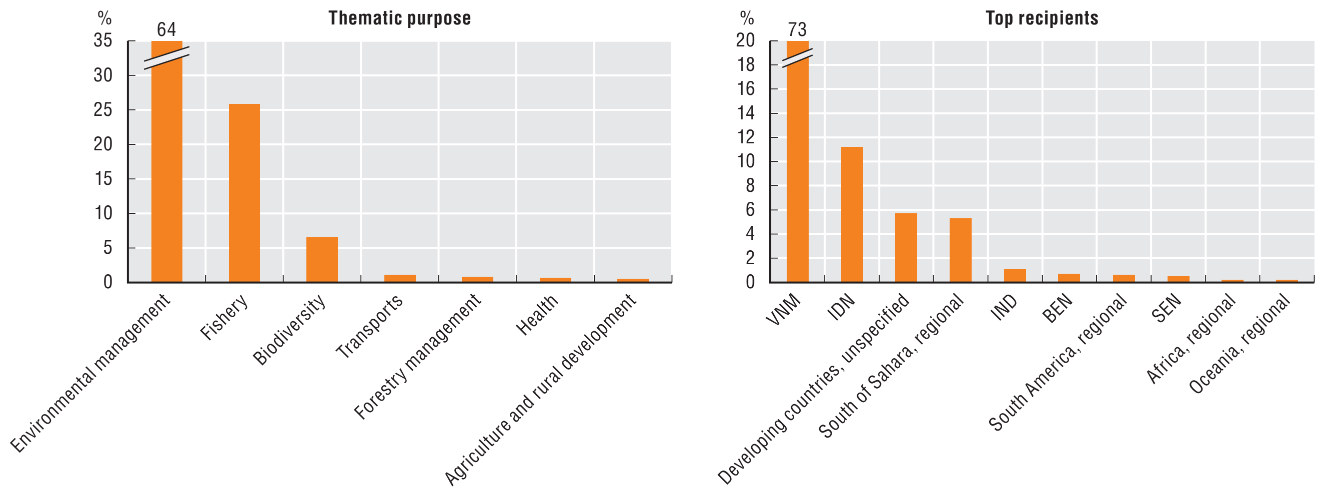


Note: Patent families are compiled using information on patent families within the Five IP offices (IP5). Figures are based on incomplete data from year 2014.

Source: OECD STI Micro-data Lab: Intellectual Property Database, *http://oe.cd/ipstats*, March 2018.

Figure 12.5. French space-related official development assistance commitments

Share of total French space-related commitments, 2000-16



Source: Analysis based on OECD DAC database (2018).

13. Germany

Germany is a major player in the European space sector and, with France, the top contributor to the European Space Agency (ESA). DLR, the German Aerospace Centre, under the responsibility of the Federal Ministry of Economics and Energy, is in charge of national and international space activities

The most recent national space strategy was formulated in 2010, focussing on the use of space for the benefit of society, research and supporting commercial activities (BMWI, 2010[1]). An evaluation of the national strategy is currently underway, including a major socio-economic impact assessment of German space activities. A 2015 preliminary estimate of the German space sector's impact on the economy found a direct influence on economic sectors covering 22% of German GDP, which is for 2016 equivalent to EUR 584 billion, or USD 645 billion, (DLR, 2015[2]). Several policy initiatives, such as the Space Components Initiative, are addressing the major changes taking place in the global space sector (e.g. constellations) and are supporting German industry capabilities and adaptation to evolving markets. DLR has also carried out a foresight study to identify the possible future role of the space sector in Germany and inform policies and planning.

Germany allocated an estimated EUR 1 522 million (USD 1 716 million) in 2017 to civil space activities, a 44% increase in real terms compared with 2008. Almost 60% of funding was dedicated to the European Space Agency, while some 30% was allocated to the national space programme and research and technology (R&T). The biggest programme priorities of DLR include earth observation and launchers (each accounting for about 30% of total funding in 2016), followed by technology development, space science and human space flight.

DLR is the biggest space-related research centre in the country, comprising laboratories and facilities in several locations across the country. Other important R&D actors include universities, other Helmholtz centres and the Max Planck and Fraunhofer research centres. Several international organisations and centres are also based in Germany, including the ESA centres for space operations and astronaut training, as well as the headquarters of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and the European Southern Observatory.

The German space industry is active in almost all space business segments, from upstream to downstream activities. The space manufacturing segment has experienced significant economic growth between 2009 and 2017, with a 36% increase in inflation-adjusted revenues and 45% in employment (BDLI, 2018[3]; BMWI, 2010[1]).

Space manufacturing relies on several big space system integrators in satellite production and orbital systems (e.g. Airbus Space & Defence, OHB). There have traditionally been close links to the defence and aerospace industries. The industry is otherwise characterised by a high number of small- and medium-sized enterprises, which supply high-technology materials, components, equipment and multiple launcher and satellite subsystems, with an emphasis on precision engineering and optics. For example, NASA's Orion Crew Capsule is assembled in Germany (at Airbus' facilities in Bremen), as well as the Vinci upper-stage engine for Ariane 6. In 2017, the German space manufacturing sector generated some EUR 3.0 billion (USD 3.4 billion) in revenues and employed 9 000 people (BDLI, 2018[3]). Important industrial clusters can be found in the north-western part of Germany (e.g. Bremen), as well as in the southern-most federal states Bavaria and Baden-Württemberg.

In the downstream sector, the commercialisation of high-resolution earth observation imagery products and services plays an important role. Another important activity is the production of satnav and telecom equipment, e.g. GNSS receivers and clocks for positioning, navigation and timing (PNT).

Germany is one of the top-ranking countries with respect to its share in scientific publications in the OECD space literature data set and space-related patent activity (see guide to the profiles), a position that has remained stable since 2000. Satellite TV penetration has slowly grown in Germany between 2007 and 2016, while satellite broadband penetration has decreased. Space-related development assistance projects in the period 2000-16 focussed mainly on environmental management, agriculture and rural development and biodiversity, with the Sub-Saharan region and China being the top recipients of German space-related assistance.

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Figure 13.1. Germany – Fast facts

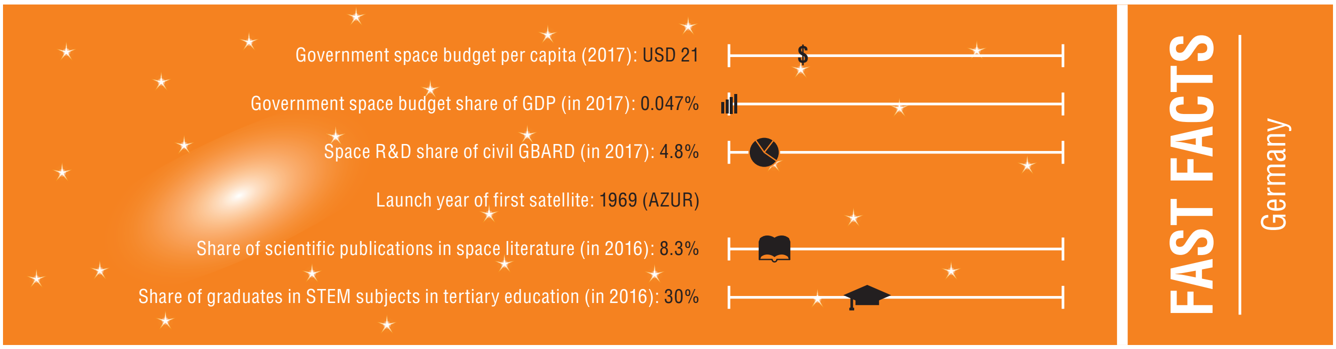
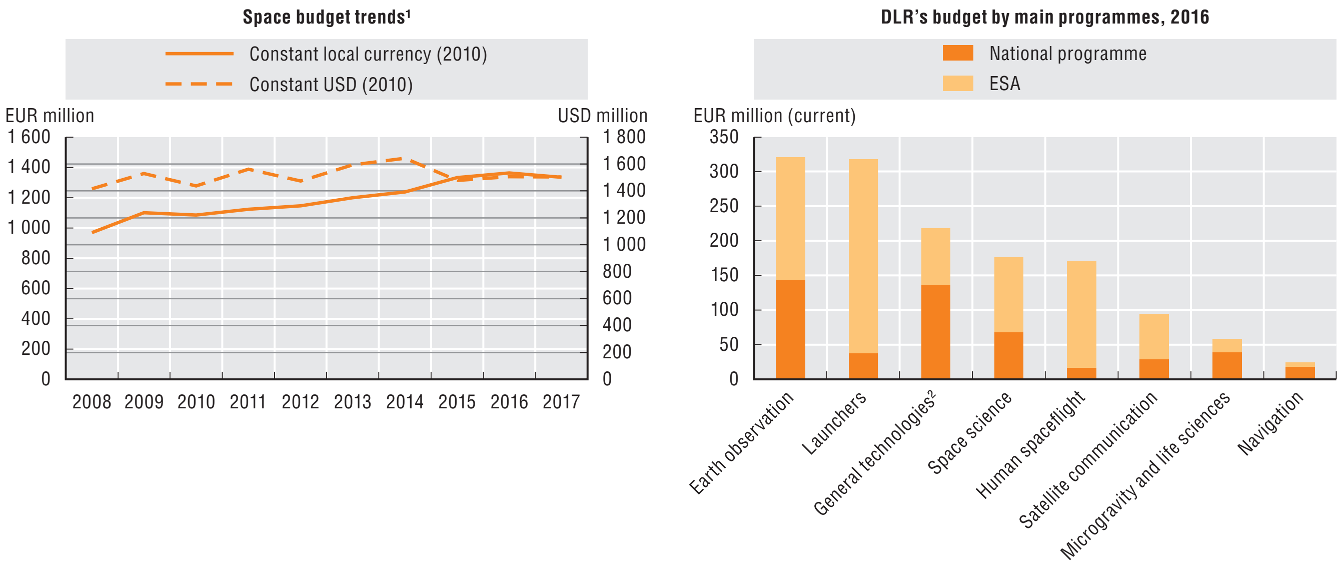


Figure 13.2. Space budget trends and main programmes

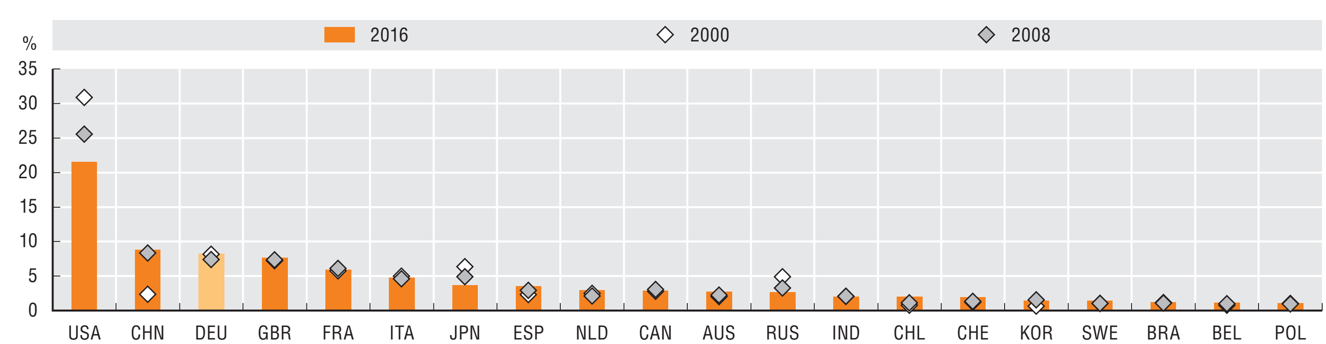


Note: 1.The institutional space budget includes national R&T funding and allocations to ESA, EUMETSAT and other national/multilateral programmes. 2. This category also includes robotics and other programmes.

Source: OECD analysis based on institutional sources.

Figure 13.3. Scientific production in space literature, per country

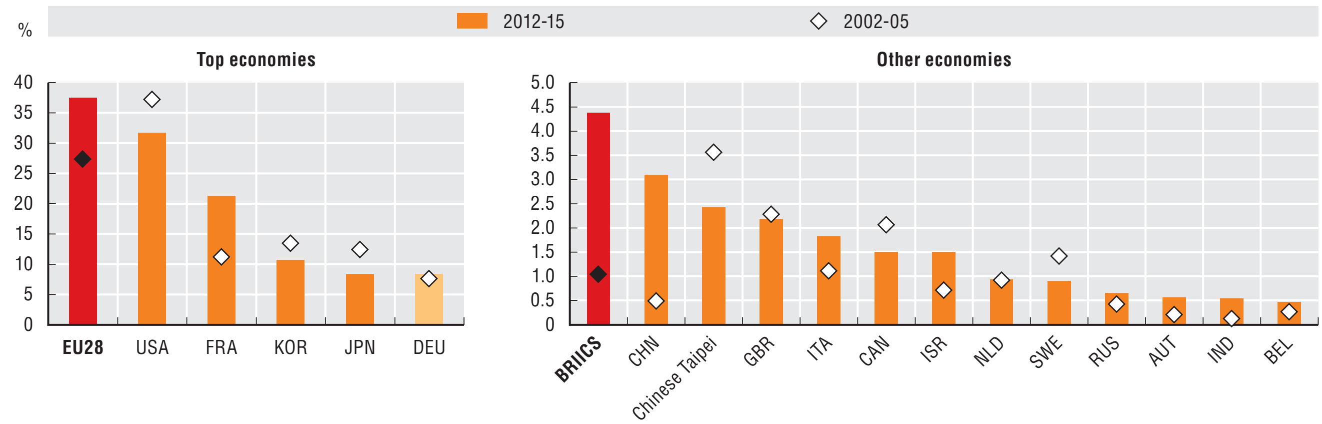
Share of total space publications, 2000, 2008 and 2016



Source: OECD analysis based on Scopus Custom Data, Elsevier, January 2018.

Figure 13.4. Top applicants of space-related patents

IP5 patent families, by priority date and applicant's location, using fractional counts, 2002-05 and 2012-15

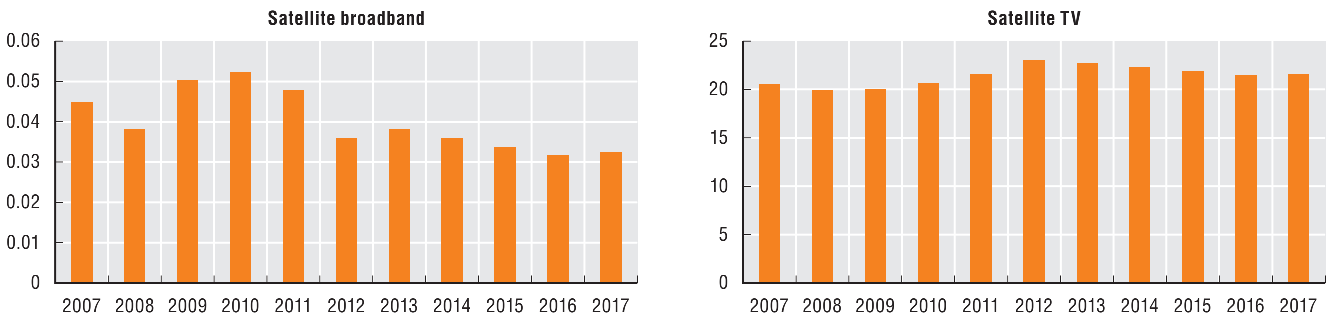


Note: Patent families are compiled using information on patent families within the five IP offices (IP5). Figures are based on incomplete data from year 2014.

Source: OECD STI Micro-data Lab: Intellectual Property Database, *http://oe.cd/ipstats*, March 2018.

Figure 13.5. Penetration of satellite telecommunication technologies in Germany

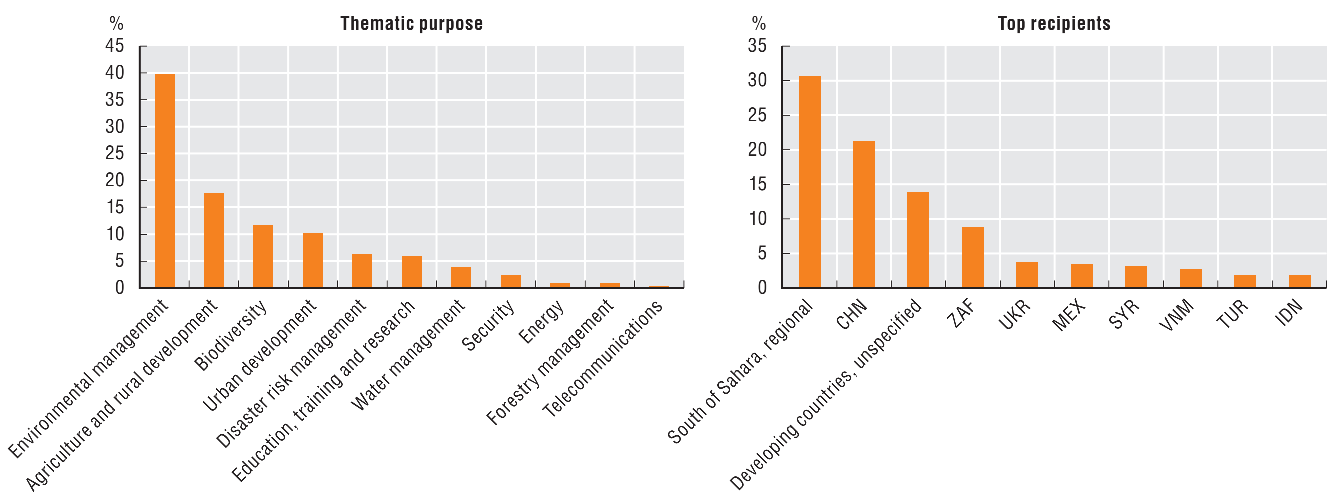
Subscriptions per 100 inhabitants, 2007-16



Source: OECD analysis based on OECD Broadband database, *https://www.oecd.org/sti/broadband/broadband-statistics/*, and ITU World Telecommunication/ ICT Indicators database.

Figure 13.6. German space-related official development assistance commitments

Share of total space-related commitments, 2000-16



Source: Analysis based on OECD DAC database (2018).

14. India

India has an ambitious programme in technology development, space applications and science. The country launches its own satellites from the Satish Dhavan Space Centre in Sriharikota, and operates a significant fleet of earth observation and satellite communications satellites for civil applications such as emergency management, tele-education and tele-health. The Indian Space Research Organisation (ISRO), under the Department of Space, is responsible for R&D, operations as well as manufacturing, and has laboratories and facilities spread across the country. ISRO employed some 16 000 persons in 2017/18 (ISRO, 2018[1])

In 2017, the Department of Space allocated an estimated INR 91.6 billion (USD 1.4 billion) to space activities. The biggest programmes include space technology and space applications, accounting for 65% and 17% of the budget, respectively. Between 2008 and 2017, the budget grew notably by some 30% in real terms.

In the last years, India has successfully deployed the space segment of its regional GNSS system NavIC as well as the satellite-based augmentation system GAGAN. In 2017, the domestically developed GSLV-MkIII launcher, India's most powerful launcher to date, had a successful orbital demonstration flight, launching a communications satellite to the geosynchronous orbit. The launcher will be instrumental in India's human spaceflight programme. After many years of technology development, the Indian government approved in 2018 INR 100 billion (USD 1.5 billion) for India's first manned space mission. The project foresees two unmanned flights of the Gaganyaan spacecraft in 2020 and 2021, followed by a manned flight with a three-member crew to the low-earth orbit in 2022.

Several science missions are also coming up. This includes a second Mars orbiter, MOM-2, following India's first successful interplanetary mission to Mars in 2013, and a second lunar mission, Chandrayaan-2, comprising an orbiter, lander and rover. A mission to Venus is also planned.

Recent policy initiatives have focussed on space sector commercialisation and increasing the capabilities of the domestic space industry. ISRO is currently collaborating with private consortia for the manufacturing of satellites and the Polar Satellite Launch Vehicle. In response to the growing national and international demand for Indian space products and services, as well as increasing start-up activity, a new legal framework, the "Space Activities Bill", is under elaboration (ISRO, 2017[2]).

India has capabilities in several industry segments, including manufacturing, launch, satellite operations and downstream activities. Most of these activities are government-led, with ISRO assembling subsystems provided by private companies.

Antrix, the commercial branch of ISRO, provides launch services for polar-orbiting LEO satellites and the geostationary satellite market. The Polar Satellite Launch Vehicle is an affordable choice for nanosatellites. In 2017, it launched 130 foreign satellites, more than half of all international customer satellites launched during the 1999-2018 period. In the downstream sector, the company leases transponders on Indian INSAT and GSAT satellites and on foreign satellites to private service providers, and it commercialises satellite data products (Antrix Corporation, 2017[3]). In the 2016-17 fiscal year, transponder leasing accounted for 80% of Antrix's INR 18.7 billion (USD 280 million) operational revenues (Antrix Corporation, 2017[3]).

India's share in scientific publicatons in space literature (see guide to the profiles) is comparable to that of the Russian Federation and Switzerland and has remained stable since 2000. India's share in space-related patent applications has significantly increased between 2002-05 and 2012-15. The penetration of satellite TV has significantly increased in the last 10 years. The subscription rate for satellite broadband is low, but growing. In the 2000-16 period, India was the recipient of several space-related official development assistance projects, most notably in the context of transport, biodiversity and disaster risk management. The United States and France were the main donor countries over the period.

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Figure 14.1. India – Fast facts

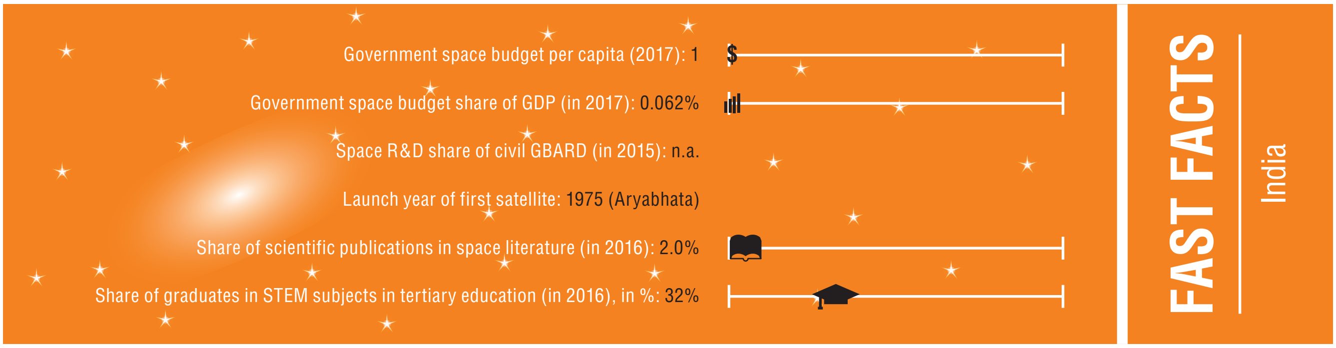
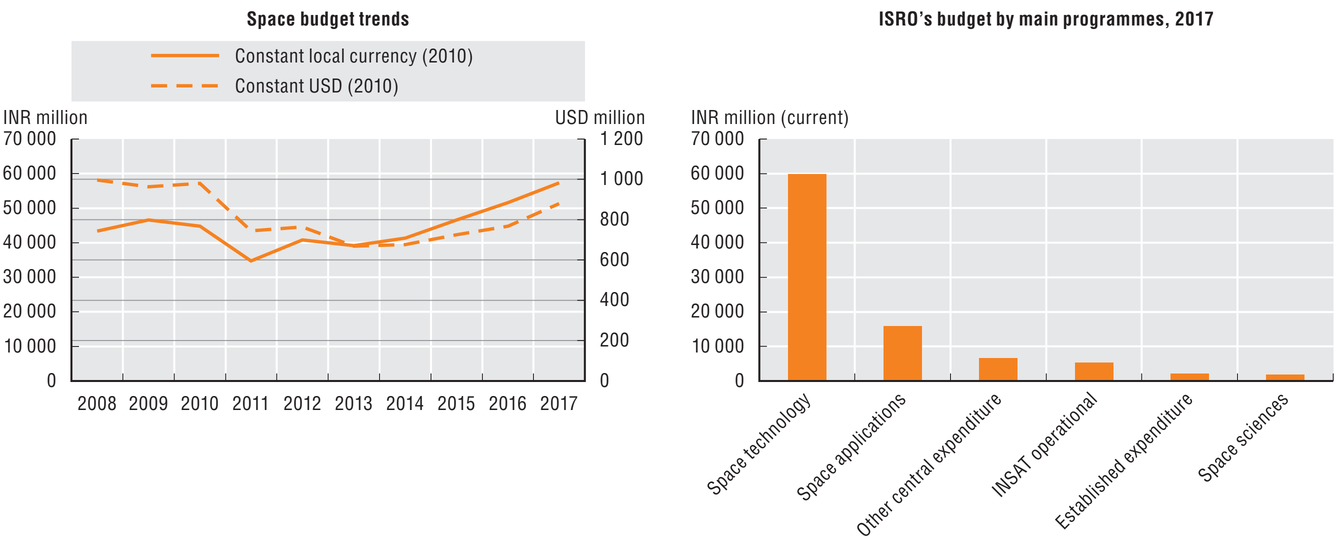


Figure 14.2. Space budget trends and main programmes

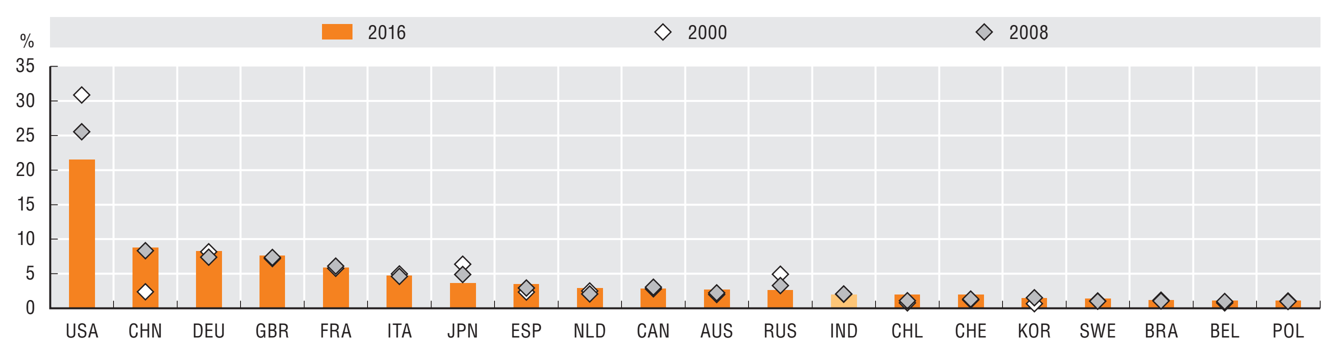
In constant INR and USD million, 2008-17 and INR million (current), 2017



Source: OECD analysis based on institutional sources.

Figure 14.3. Scientific production in space literature, per country

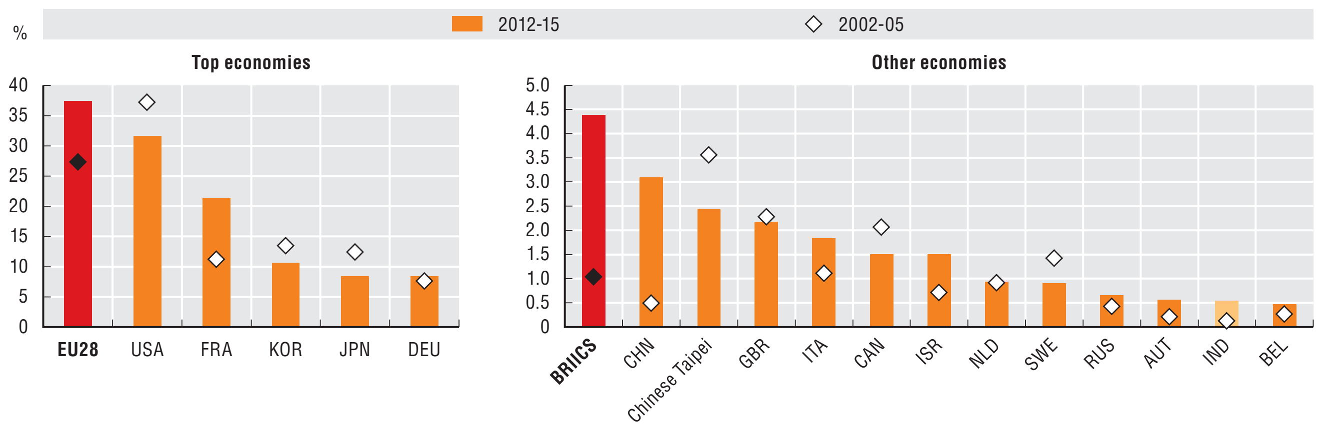
Share of total space publications, 2000, 2008 and 2016



Source: OECD analysis based on Scopus Custom Data, Elsevier, July 2018.

Figure 14.4. Top applicants of space-related patents

IP5 patent families, by priority date and applicant's location, using fractional counts, 2002-05 and 2012-15

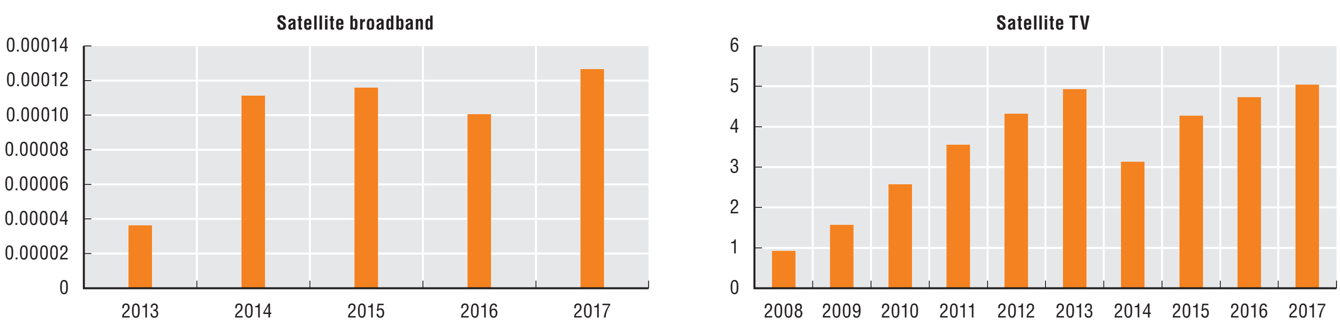


Note: Patent families are compiled using information on patent families within the Five IP offices (IP5). Figures are based on incomplete data from 2014.

Source: OECD STI Micro-data Lab: Intellectual Property Database, *http://oe.cd/ipstats*, March 2018.

Figure 14.5. Penetration of satellite telecommunication technologies in India

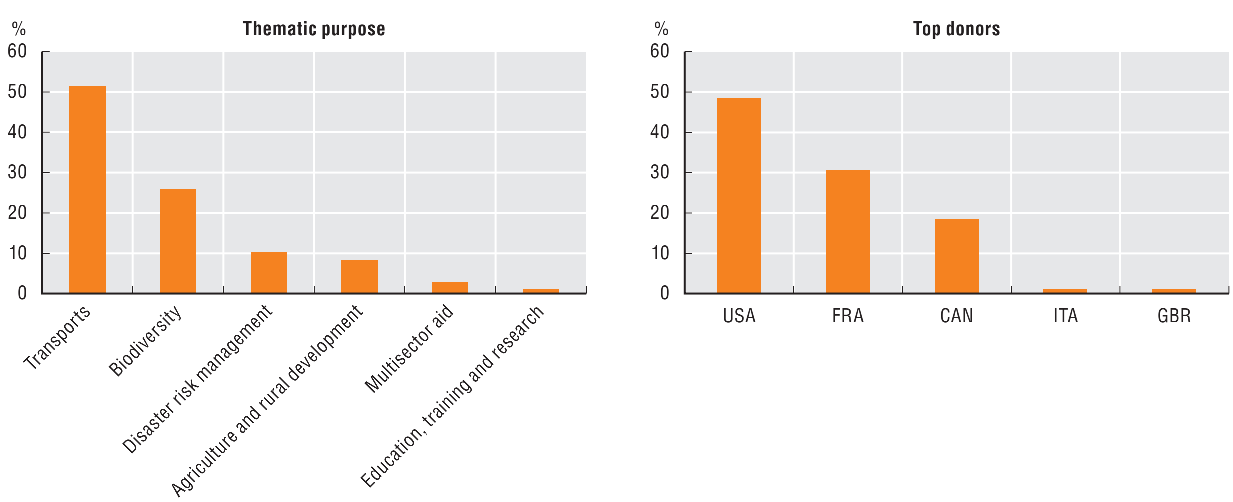
Satellite broadband and satellite TV subscriptions per 100 inhabitants, 2013-16 and 2008-16



Source: OECD analysis based on OECD Broadband database, *https://www.oecd.org/sti/broadband/broadband-statistics/*, and ITU World Telecommunication/ ICT Indicators database.

Figure 14.6. Space-related official development assistance projects funded in India

Share of space-related commitments directed to India, 2000-16



Source: Calculations based on OECD DAC database (2018).

15. Italy

Italy is a founding member and the third-highest contributor to the European Space Agency (ESA). The Italian Space Agency, Agenzia Spaziale Italiana (ASI), defines, coordinates and manages national space programmes and the Italian participation to European and international space projects, under the supervision of the Ministry of Education, University and Research.

Italy's space policy guidelines are formulated in the latest Strategic Vision Document for 2016-2025, which puts an increased emphasis on socio-economic returns of space activities, in particular, on the development of downstream activities (ASI, 2016[1]) .

In 2018, Law No. 7 established a new national space governance, entrusting the Prime Minister with the overarching responsibility for space and aerospace policies supported by an inter-ministerial Committee composed of twelve Ministers and the President of the Regional Conference (COMINT), to the Presidency of the Council of Ministers (Italian Parliament, 2018[2]).

In 2017, Italy allocated some EUR 837 million (USD 944 million), to space activities, which is a 1% increase in real terms over the last 10 years since 2008. 66% of the funding was directed towards ESA, and some 30% allocated to national and bilateral activities. Key priorities of the Italian Space Agency budget includes earth observation (30%), launchers and space transportation (26%), and human spaceflight and microgravity (20%). In addition to the ASI budget, the "Italian Space Economy Strategic Plan", foresees an additional multi-annual investment of some EUR 4.7 billion, half of which is to be funded by the private sector. An initial part of this has already been allocated to telecommunications (ASI, 2016[3]).

Space-related research in aerospace engineering and space sciences is carried out in both national research organisations and at universities, such as the Italian Aerospace Research Centre (CIRA), Sapienza University of Rome and the polytechnic universities in Milano and Torino. ASI's Space Geodesy Centre "Giuseppe Colombo" is one of the most important space geodetic observatories in the international network. ESRIN, ESA's headquarters for earth observation activities, is located in Frascati, near Rome.

Italy has strong capabilities in almost all segments of the space industry, upstream and downstream. The sector currently encompasses some 200 companies, employs more than 6 200 people and, in 2015, generated more than EUR 1.6 billion in revenues (ASI, 2016[1]). While the majority of Italian space companies are small and medium-sized companies (SMEs), four companies, Avio, Selex ES, Telespazio and Thales Alenia Space Italia, account for about 80% of total employment (ASI, 2016[1]).

Italian manufacturing companies are active in satellite, launcher and orbital system production and are important suppliers of high-technology subsystems, components, equipment and instruments, with strong links to the defence and automotive industries. Important aerospace clusters are located in the centre of the country (Lazio, Toscana, Abruzzo). The second most important area is the northwest (Piemonte and Lombardia), while the south and the Islands are increasing their share in revenues (Campania, Puglia).

The Taranto-Grottaglie Airport in Puglia has been formally designated as Italy's first spaceport by the Ministry of Infrastructures and Transport and ENAC, the civil aviation authority. In 2018, Virgin Galactic and Virgin Orbit announced a series of agreements with the Italian Space Agency and Italian companies to further the development of commercial launch activities in southern Italy.

In the downstream sector, space operations are an important activity, with Telespazio accounting for a major share of employment and revenues. Many companies also provide satellite data products and services, for instance for synthetic aperture radar (SAR) satellite imagery. Applications typically cater to government and commercial users in the areas of land cover management (agriculture, forestry), maritime activities and geo-hazard monitoring.

Italy's share in scientific publications in OECD's space literature dataset (see guide to the profiles) is comparable to that of France and Japan and has remained stable since 2000. In space-related patenting, Italy's share in patent applications has significantly increased between 2002-05 and 2012-15. The penetration of satellite television has remained stable in the last years after an increase in subscriptions after 2000. Space-related development assistance activities in the 2000-16 period have focussed mainly on disaster risk management, followed by education, research and training.

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Figure 15.1. Italy – Fast facts

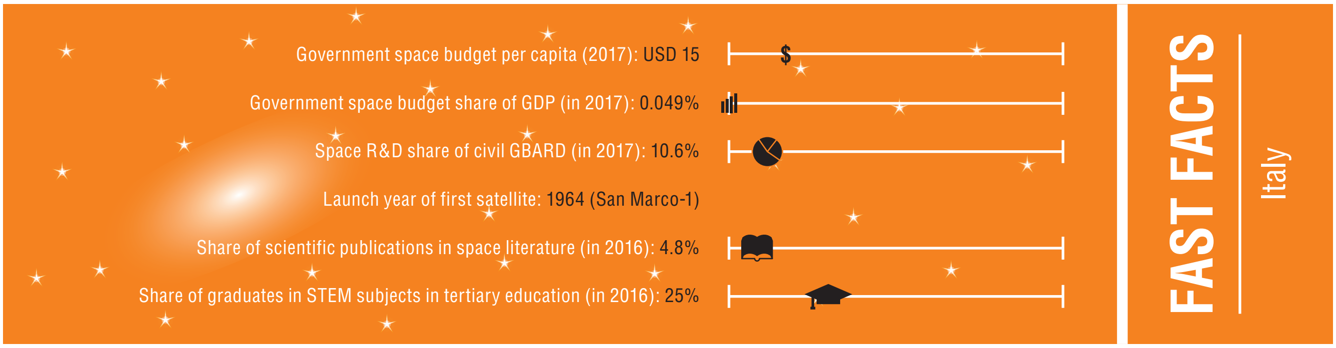
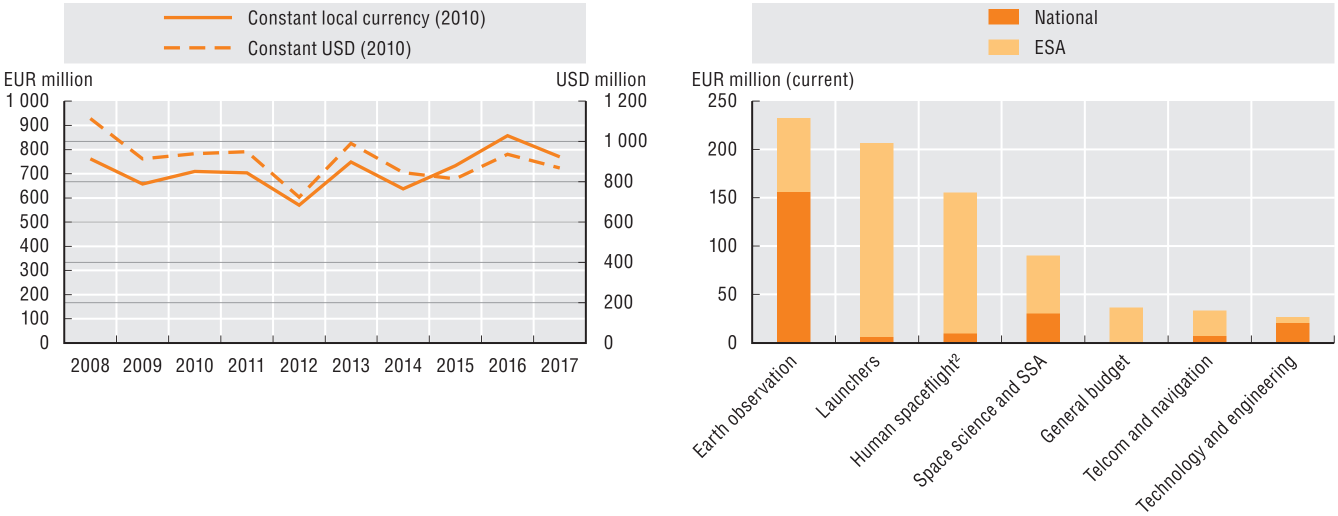


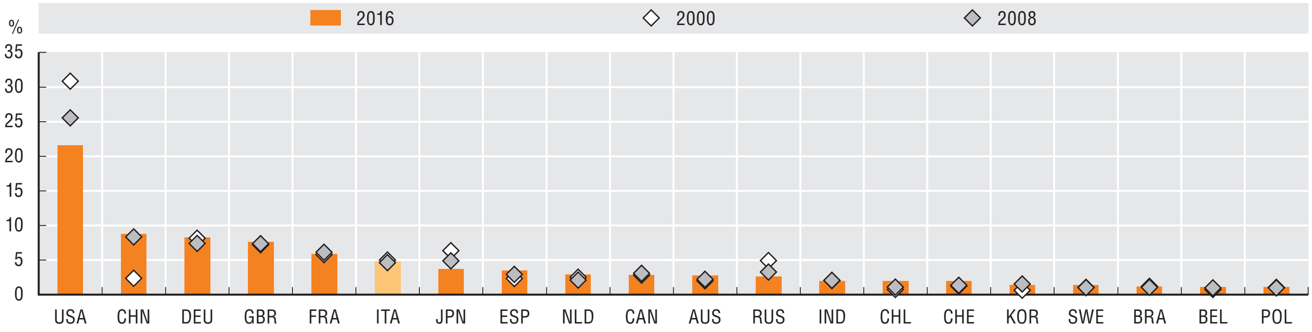
Figure 15.2. Space budget trends and main programmes



Note: 1. The institutional space budget includes data for national and bilateral activities, ESA and EUMETSAT. 2. Also includes microgravity.
Source: OECD analysis based on institutional data.

Figure 15.3. Scientific production in space literature, per country

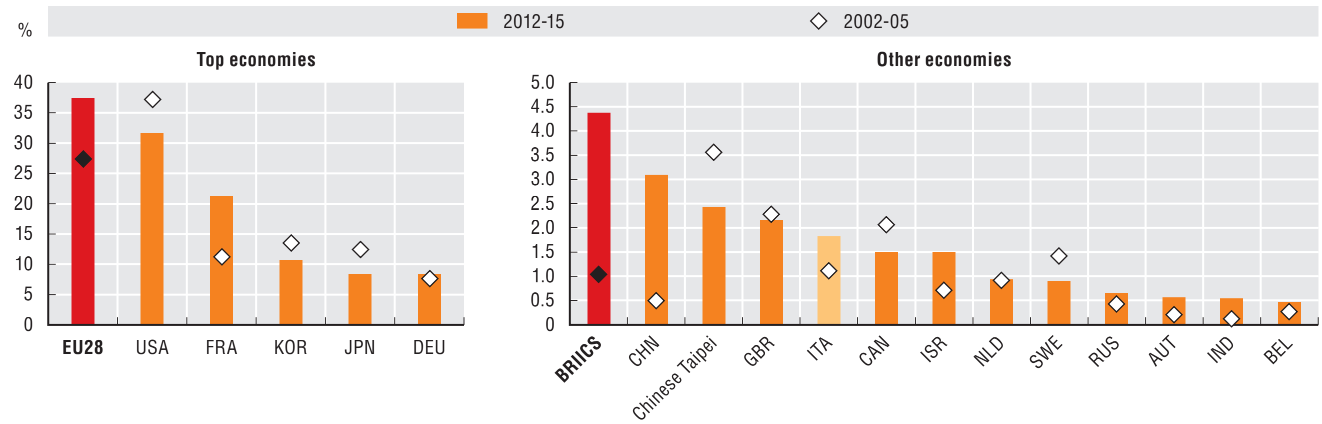
Share of total space publications, 2000, 2008 and 2016



Source: OECD analysis based on Scopus Custom Data, Elsevier, July 2018.

Figure 15.4. Top applicants of space-related patents

IP5 patent families, by priority date and applicant's location, using fractional counts, 2002-05 and 2012-15

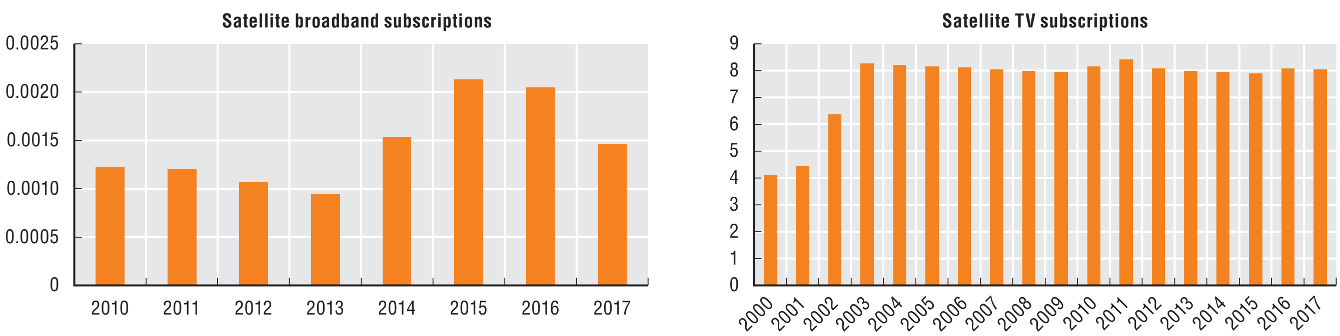


Note: Patent families are compiled using information on patent families within the Five IP offices (IP5). Figures are based on incomplete data from 2014.

Source: OECD STI Micro-data Lab: Intellectual Property Database, *http://oe.cd/ipstats*, March 2018.

Figure 15.5. Penetration of satellite telecommunication technologies in Italy

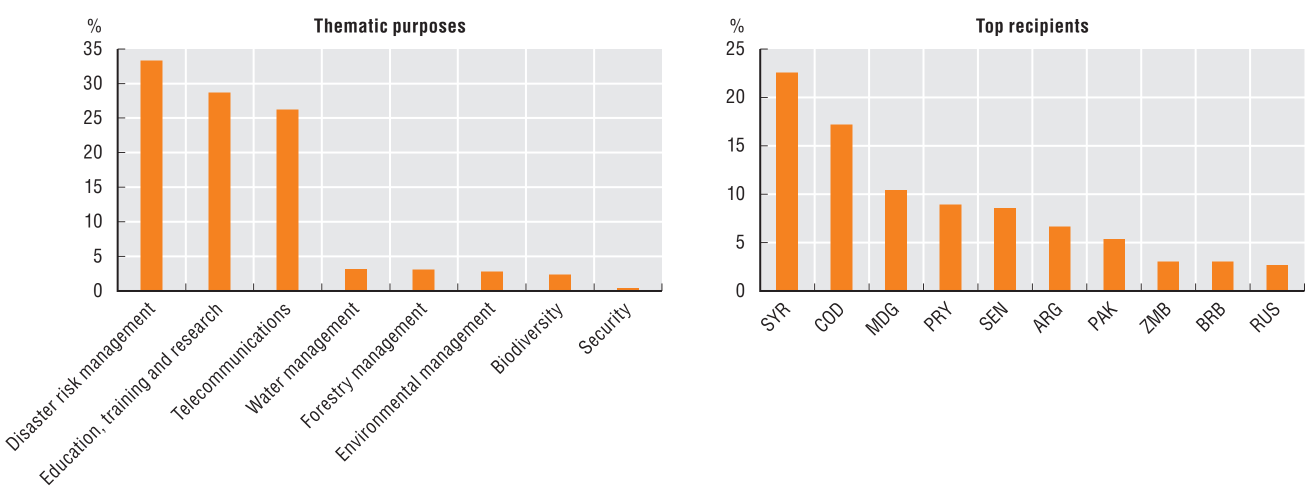
Satellite broadband and satellite TV subscriptions per 100 inhabitants, 2010-16 and 2000-16



Source: OECD analysis based on OECD Broadband database, *https://www.oecd.org/sti/broadband/broadband-statistics/*, and ITU World Telecommunication/ICT Indicators database.

Figure 15.6. Italian space-related official development assistance commitments

Share of total Italian space-related commitments, 2000-16



Source: OECD analysis based on OECD DAC database (2018).

16. Korea

Korea's first space programme dates back to the late 1980s with its first successful launch using the domestic KSLV-1 launcher in 2013. It is one of a small number of countries with independent access to space from the Naro Space Centre. The Korea Aerospace Research Institute (KARI) manages the Korean space programme, under the responsibility of the Ministry of Science, ICT and Future Planning.

In 2018, the Third Space Development Plan identified the key space policy objectives, with six focus areas: indigenous development of launcher technologies; development of satellite technologies and increased use of data and applications for society; lunar space exploration; establishment of the Korea Positioning System (KPS); strengthening of the national innovation capacity through public-private-academic collaboration; and space industry promotion and space sector job creation, through more private participation in space development and commercialisation activities (Government of Korea, 2018[1]).

Korea sees space exploration as an important stepping stone for developing national capabilities. A lunar orbiter is scheduled for 2020, which will carry five domestic payloads and one payload developed by NASA. Objectives include, for instance, to test lunar exploration technologies, demonstrate a "space internet", conduct scientific investigations of the lunar environment and surface, and identify potential landing sites for future missions. A lunar lander mission is planned for 2030. In May 2019, the Korea Astronomy and Space Science Research Institute and NASA agreed to jointly build a payload device for NASA's lunar landers scheduled for launch in the 2020s.

Korea is also reinforcing its positioning, timing and navigation infrastructure. A satellite-based GPS augmentation system is to be deployed in 2022. As mentioned above, this will be followed by a regional satellite navigation system (KPS) in the 2030s.

It is a priority to increase the utilisation of Korean government satellite data. KARI's Satellite Operation Centre was in 2015 designated as a National Satellite Operation and Application Centre. The objective is to create an integrated management system and to improve and facilitate the distribution of data to both public and private actors.

In 2017, the Korean government allocated some KRW 670.3 billion (USD 593 million) to space activities in KARI, a 77% increase in real terms compared with 2008. The biggest budget posts were launchers and the space centre (36% of the total), followed by satellite and ground infrastructure development (33%).

Space-related research activities are carried out in several government research agencies (e.g. KARI, Korea Astronomy and Space Science Institute (KASI), Electronics and Telecommunications Research Institute (ETRI)), and many universities also have aerospace and space science programmes, notably Korea Advanced Institute of Science and Technology (KAIST) and Seoul National University.

The Korean space industry has capabilities in most space industry segments, including space vehicle and equipment manufacturing, satellite launch, satellite operations and downstream applications. The Korean space industry generated some KRW 2 779.3 billion (USD 2.4 billion) in revenues 2016 and employed almost 6 000 persons (KARI, 2017[2]). Research centres are generally found in Daejeon in conjunction with KARI, while companies are mostly located in the Seoul metropolitan area.

Space manufacturing companies have contributed to government programmes for decades and produce components, parts and equipment. There are important links to other sectors such as aerospace and defence, ICT, automotive and maritime industries. While KARI remains the main driver of space manufacturing activities in Korea, it increasingly transfers activities and capabilities to private sector companies and consortiums (Kim, 2015[3]). Downstream applications and equipment play an important role in terms of commercial revenues and exports. This includes in particular the manufacturing of equipment for satellite telecommunications and navigation (e.g. direct-to-home set-top boxes, antennas, GNSS receivers). In 2016, the satellite services and equipment segment accounted for 87% of space industry revenues and 98% of exports (KARI, 2017[2]).

Korea's share in scientific publications in the OECD "Space literature" dataset has increased since 2000 and is comparable to that of Switzerland and Sweden (see guide to the profiles). It ranks among the top countries in space-related patent applications. Satellite TV penetration in Korea has increased significantly since 2002, although growth has slowed down in the last years. Satellite broadband penetration is very low, with the country mainly connected by high-speed fibre. Space-related official development assistance projects in the 2000-16 period focussed on telecommunications and agriculture and rural development, with recipients located mainly in the sub-Saharan region.

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Figure 16.1. Korea – Fast facts

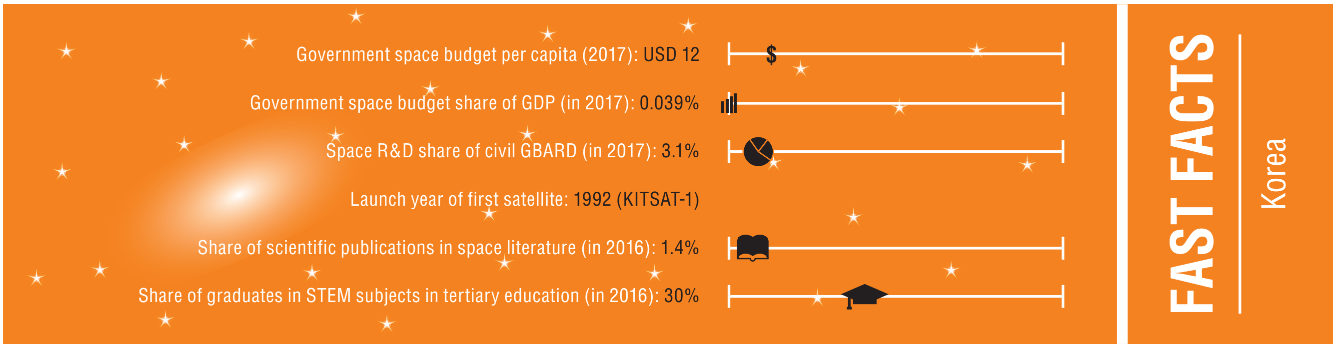
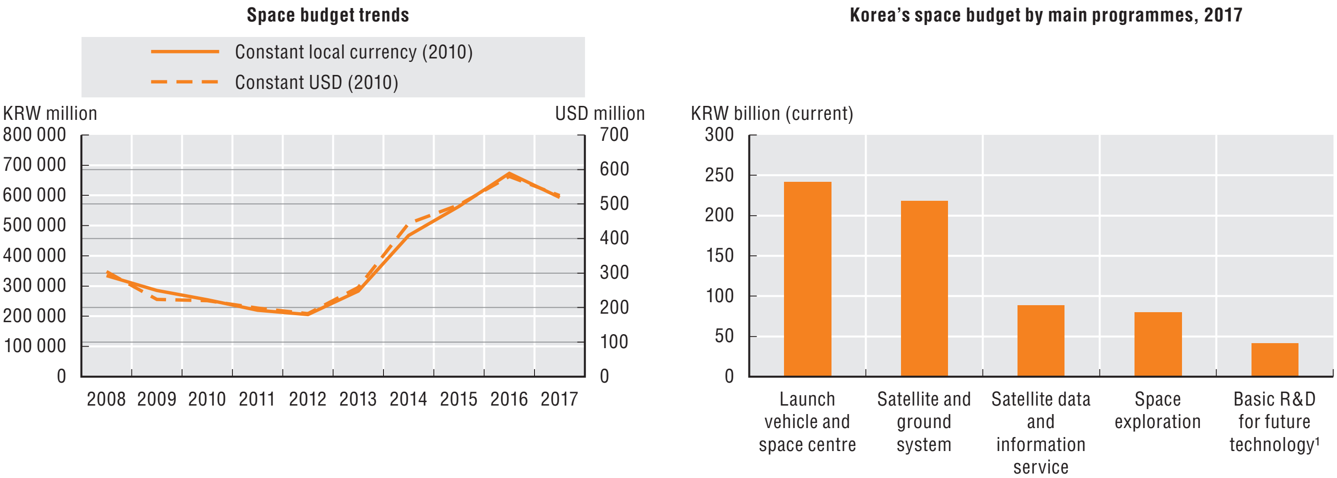


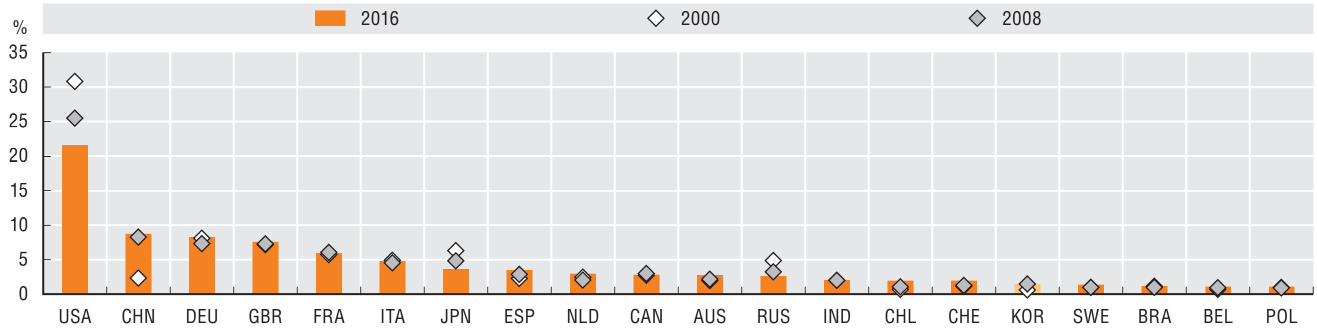
Figure 16.2. Space budget trends and main programmes



Note: 1. Also includes education activities and other activities.
Source: OECD analysis based on institutional sources.

Figure 16.3. Scientific production in space literature, per country

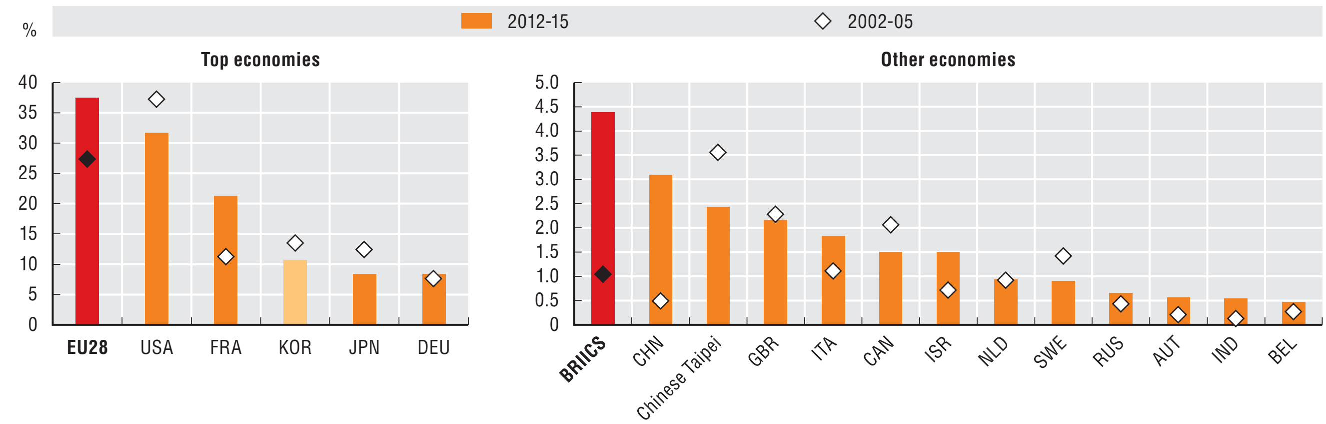
Share of total space publications, 2000, 2008 and 2016



Source: OECD analysis based on Scopus Custom Data, Elsevier, July 2018.

Figure 16.4. Top applicants of space-related technologies per country

IP5 patent families, by priority date and applicant's location, using fractional counts, 2002-05, 2012-15

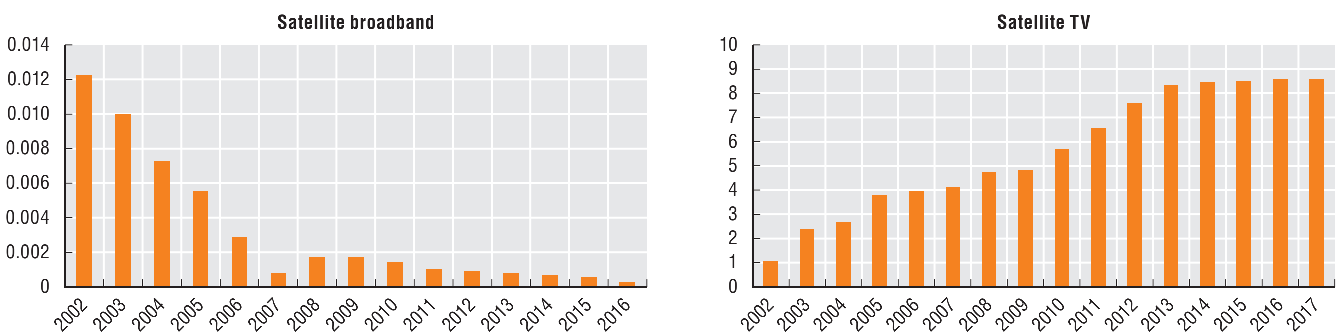


Note: Patent families are compiled using information on patent families within the Five IP offices (IP5). Figures are based on incomplete data from 2014.

Source: OECD STI Micro-data Lab: Intellectual Property Database, *http://oe.cd/ipstats*, March 2018.

Figure 16.5. Penetration of satellite telecommunication technologies in Korea

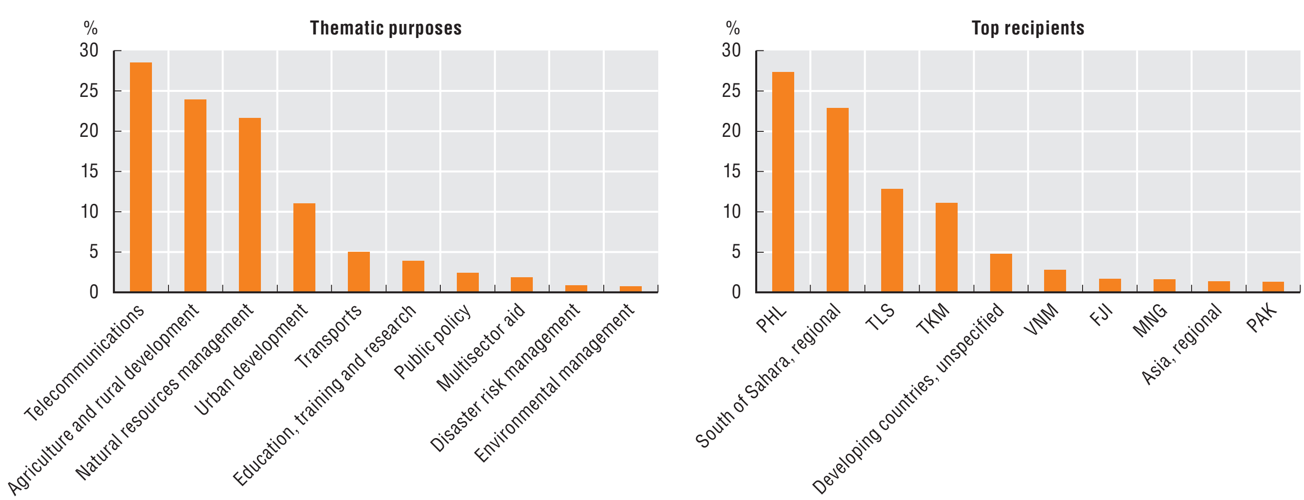
Satellite broadband and satellite TV subscriptions per 100 inhabitants, 2002-16



Source: OECD analysis based on OECD Broadband database, *https://www.oecd.org/sti/broadband/broadband-statistics/*, and ITU World Telecommunication/ICT Indicators database.

Figure 16.6. Korean space-related official development assistance commitments

Share of total Korean space-related commitments, from 2000-16



Source: Calculations based on OECD DAC database (2018).

Building on its growing aerospace manufacturing industry, Mexico is developing new capabilities in space technologies and satellite applications. Government space activities are carried out in several federal ministries, including the ministries of Defence, Fisheries and Natural Resources; and Transportation and Communications. The Mexican Space Agency (AEM) is based in the Ministry of Transportation and Communications and is responsible for promoting the uses of space science and technology and supporting the growth of the national space sector.

In 2017, the budget for government space activities amounted to some MXN 1 228 million (USD 80 million), when taking into account the biggest government space programmes in Mexico: the MEXSAT infrastructure, the Agro-alimentary and Fisheries Information Service (SIAP), and the programmes of the Mexican Space Agency (Mexican Secretariat of Finance and Public Credit, 2017[1]). This estimate is lower than for previous years, principally due to the high costs involved in purchasing and launching the MEXSAT satellites. The main priorities are telecommunications for rural internet, emergency response and remote fixed and mobile communications (MEXSAT); and earth observation for agriculture and defence purposes (SIAP). Total yearly expenditure may well exceed USD 100 million, when taking into account satellite operations and terminals, the purchase of satellite imagery, GNSS services, etc.

The industry development strategy is spelled out in the 2017 space industry roadmap: *Orbit Plan 2.0*. The plan ambitiously targets a 1% market share of the global space market for components, products and services by 2026, equivalent to USD 3 billion. By the same year, the country should have developed the necessary infrastructure to extend connectivity coverage in Latin America by 25% (ProMexico, 2017[3]).

The Mexican Space Agency uses capacity-building and partnerships to reach these goals. It supports capacity development in small satellite technology, through regional technology development centres (Gutierrez, 2017[4]) and via international co-operation. The agency also works to increase the availability of R&D funding (e.g. the AEM-CONACYT Sectoral Fund) (National Council of Science and Technology (CONACYT), 2018[5]). Important research actors include the centres of the National Council of Science and Technology (CONACYT) and multiple universities.

The space manufacturing sector, consisting mainly of subsidiaries for large international companies producing lower-tier components, is tightly linked to the rapidly growing and increasingly sophisticated Mexican aerospace industry, located mainly in the federal states of Baja California and Jalisco. The aerospace industry provides systems, parts and equipment for several major North American and European aerospace manufacturers (Mexican Federation of Aerospace Industries, 2012[6]). Telecommunications is an important downstream activity. The commercial satellite operator Satmex was acquired by Eutelsat in 2014. In June 2017, the company reported EUR 134.6 million in revenues (Eutelsat, 2017[7]).

Mexico's share in scientific publications in the OECD "Space literature" database (see guide to the profiles) has increased since 2000 and is comparable to that of Brazil and Belgium. Satellite TV penetration has grown exponentially in Mexico since 2010, while the number of satellite broadband subscriptions decreased between 2007 and 2015 before increasing again in 2016. As part of Mexico's digital strategy, the project *Mexico Conectado* works to bring internet access to public spaces throughout the country, using satellite technologies in remote areas. Satellite accounted for some 30% of sites connected by 2016 (OECD, 2017[2]).

Mexico has received space-related official development assistance from Germany, the United States and Spain in the period 2000-16, with projects mainly related to biodiversity.

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Figure 17.1. Mexico – Fast facts

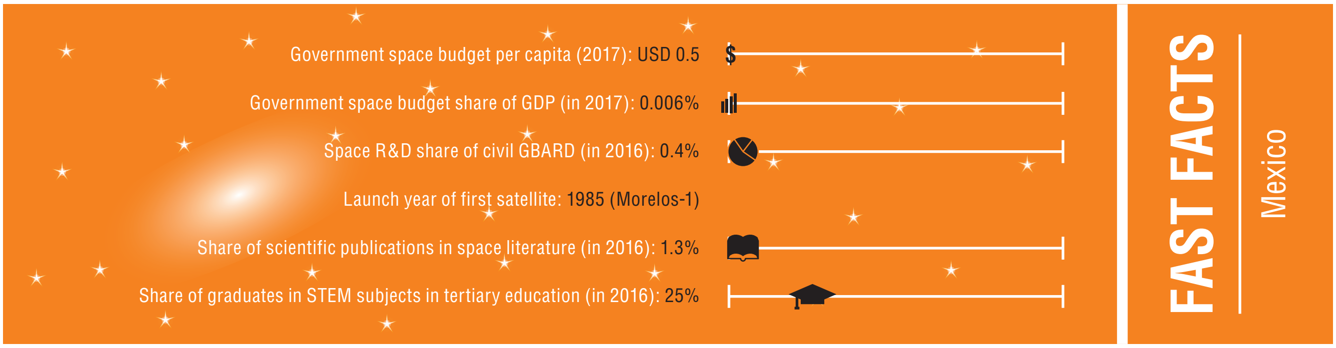
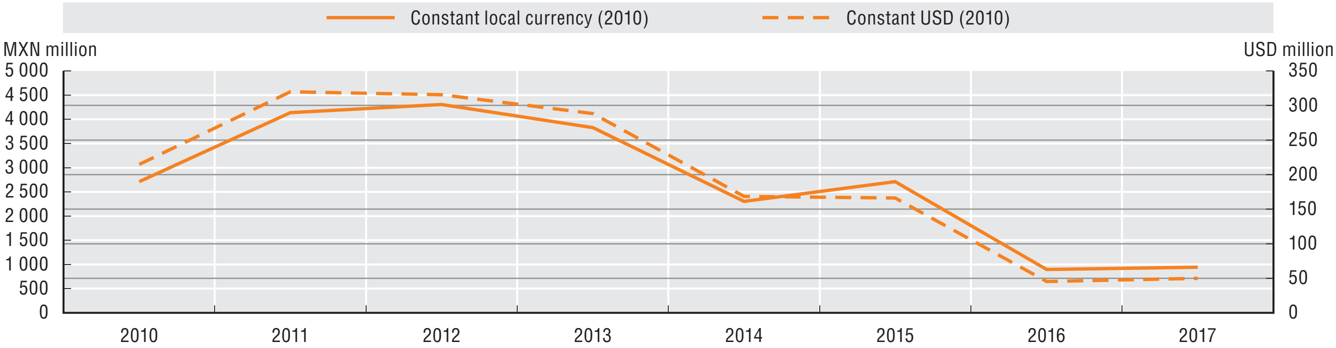


Figure 17.2. Space budget trends

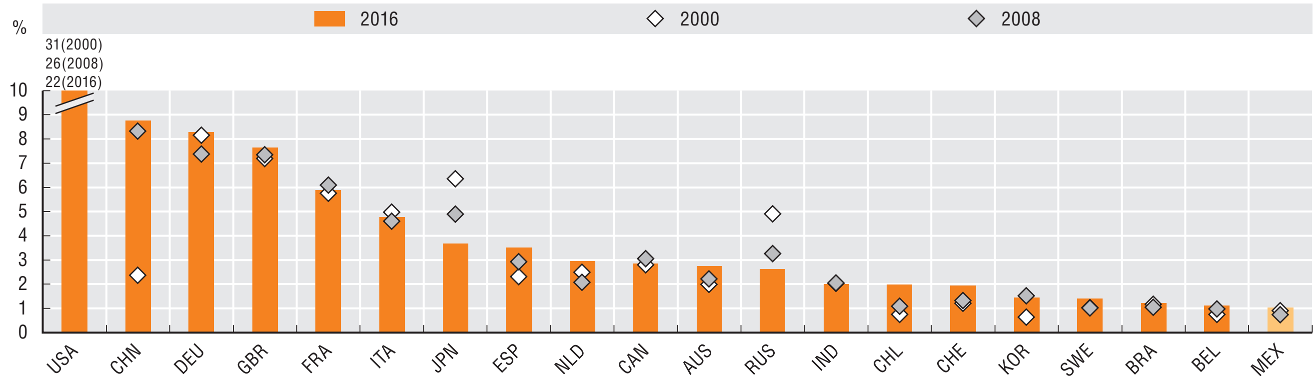


Note: The institutional space budget includes allocations for the Mexsat satellite system and the Mexican Space Agency.

Source: OECD analysis based on institutional sources.

Figure 17.3. Scientific production in space literature, per country

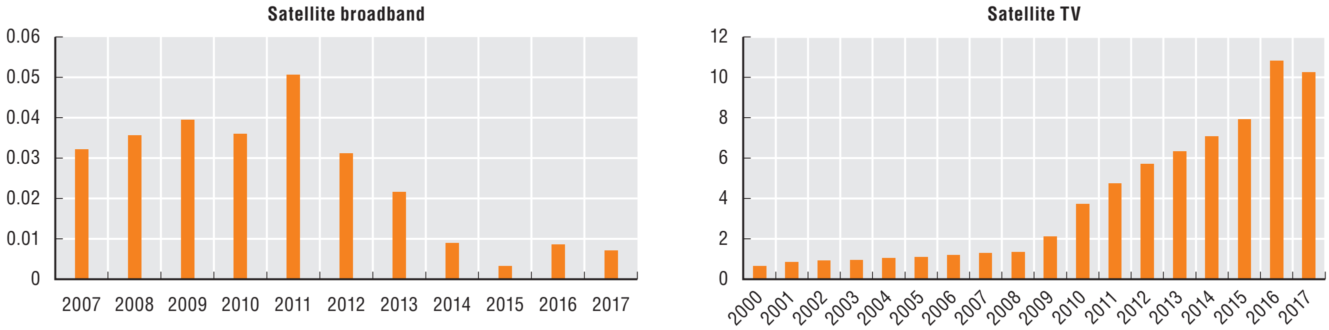
Share of total space publications, 2000, 2008 and 2016



Source: OECD analysis based on Scopus Custom Data, Elsevier, July 2018.

Figure 17.4. Penetration of satellite telecommunication technologies in Mexico

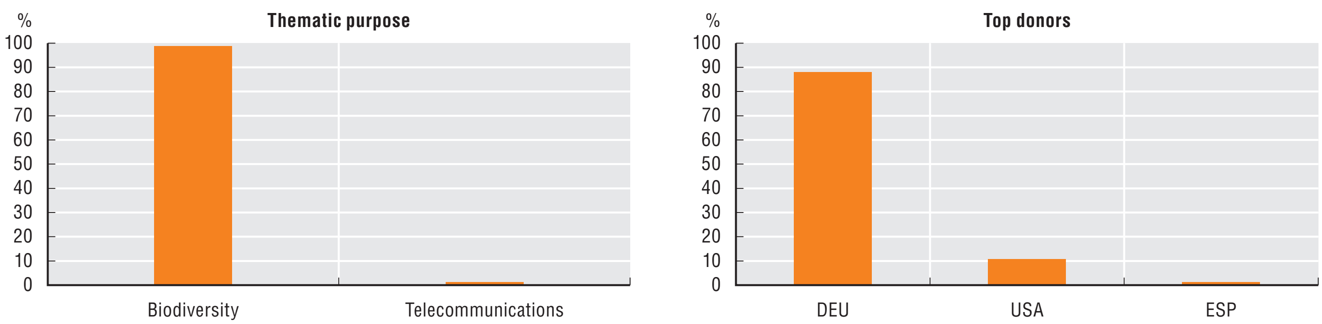
Satellite broadband and satellite TV subscriptions per 100 inhabitants, 2007-16 and 2000-16



Source: OECD analysis based on OECD Broadband database, *https://www.oecd.org/sti/broadband/broadband-statistics/*, and ITU World Telecommunication/ICT Indicators database.

Figure 17.5. Space-related official development assistance projects carried out in Mexico

Share of space-related commitments directed to Mexico, 2000-16



Source: Calculations based on OECD DAC database (2018).

18. The Netherlands

The Netherlands has participated in international and European space activities for more than 50 years. The Netherlands Space Office (NSO) is the space agency of the government, advising and implementing the national space policy. NSO reports to the ministries of Economic Affairs and Climate Policy; Education, Culture and Science; Infrastructure and Water Management; and the Netherlands Organisation for Scientific Research (NWO).

Important national activities and recent policy initiatives include the creation of the Satellite Data Portal in 2012, which contains earth observation data covering the Netherlands' territory from several commercial satellite missions. The main purpose of the data portal is to offer the user community data complementary to Copernicus satellite data, and develop national downstream capabilities. It provides free access to national actors for civil and commercial use.

In 2017, the Netherlands allocated some EUR 128 million (USD 145 million) to space activities, a 15% decrease in real terms compared with 2008. 65% of the funding was allocated to ESA and 18% to EUMETSAT. 37% of the ESA funding was devoted to science, followed by 22% to the launchers programme. Other priorities include the satellite communications and technology development programmes.

Important national space technology and research actors include several public research institutes (e.g. Netherlands Institute for Space Research (SRON), and Netherlands Organisation for Applied Scientific Research (TNO), several universities with capabilities in astronomy, earth observation and aerospace engineering, in addition to private companies (like Airbus Netherlands) and many small and medium-sized enterprises (SMEs). The country also hosts the European Space Technology and Research Centre (ESTEC), the largest establishment of the European Space Agency (ESA), which develops and tests many of the Organisation's projects and missions, as well as the Galileo Reference Centre, operated by the European GNSS Agency.

The Netherlands space industry has strong capabilities in several industry segments, including manufacturing subsystems and downstream applications. The space manufacturing sector provides subsystems (e.g. instruments and solar panels) and components to European satellites and launchers, such as sensors, structures and igniters. The Netherlands currently has two domestically-built instruments in orbit. The air-quality measuring instrument TROPOMI, flying on the Copernicus satellite Sentinel-5P, launched in 2017, and the ozone monitoring instrument OMI, on the US satellite AURA. The Royal Netherlands Meteorological Institute processes and analyses the scientific data from these two instruments. Several companies in the Netherlands are also important actors in the growing small and very small satellite industry (e.g. cubesats) as manufacturers and launch service providers, including for instance Innovative Solutions in Space (ISIS) and Hiber).

Important downstream/value-adding activities include earth observation products and services for precision farming, infrastructure modelling (incl. pipelines, deformation) and water management, and navigation (e.g. GNSS devices). Furthermore, a number of satellite operators have ground stations (Inmarsat) or their main office (SES Networks, Leosat) in the Netherlands. Annual turnover of the Netherlands space industry is estimated at some EUR 600 million (USD 663 million) (Holland High Tech, 2018[2]).

The Netherlands' share in scientific publications in the OECD space literature dataset (see guide to the profiles) is comparable to that of Canada and Spain and has increased since 2000. In space-related patent applications, Netherlands' share has remained stable.

Disbursements on space-related ODA projects over the period 2002-16 focussed mainly on agriculture and rural development (including food production) and water management. Since 2013, the Netherlands Space Office runs the Geodata for Agriculture and Water programme (G4AW), which funds projects and partnerships in developing countries in Africa and Asia, developing satellite-based information services for smallholder farmers and pastoralists and providing useful and timely agro-meteorological advice as well as financial/insurance products. An important objective is to improve sustainable food production, with an effective use of inputs (water, seeds, pesticides, etc.) (Netherlands Space Office, 2016[1]). Positive impacts of this programme have already been registered, with programme participants reporting 10-15% harvest increases as well as a reduced use of inputs

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Figure 18.1. Netherlands – Fast facts

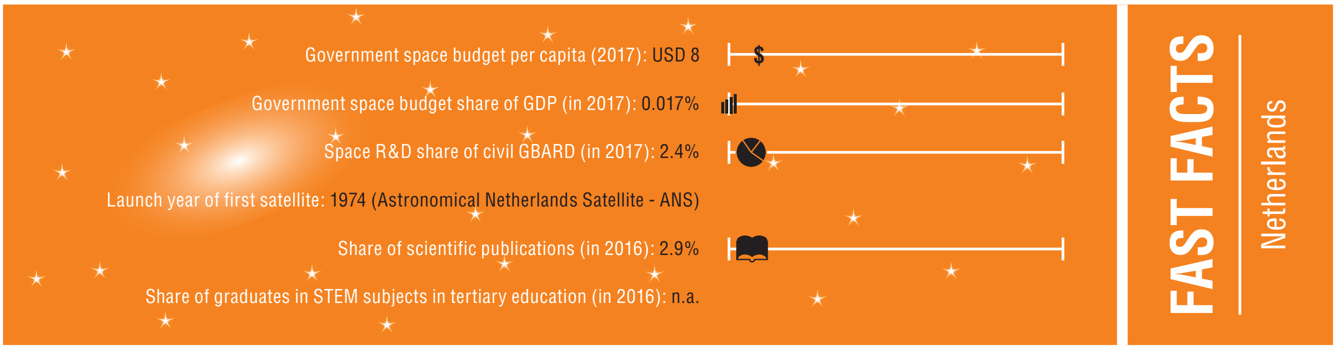
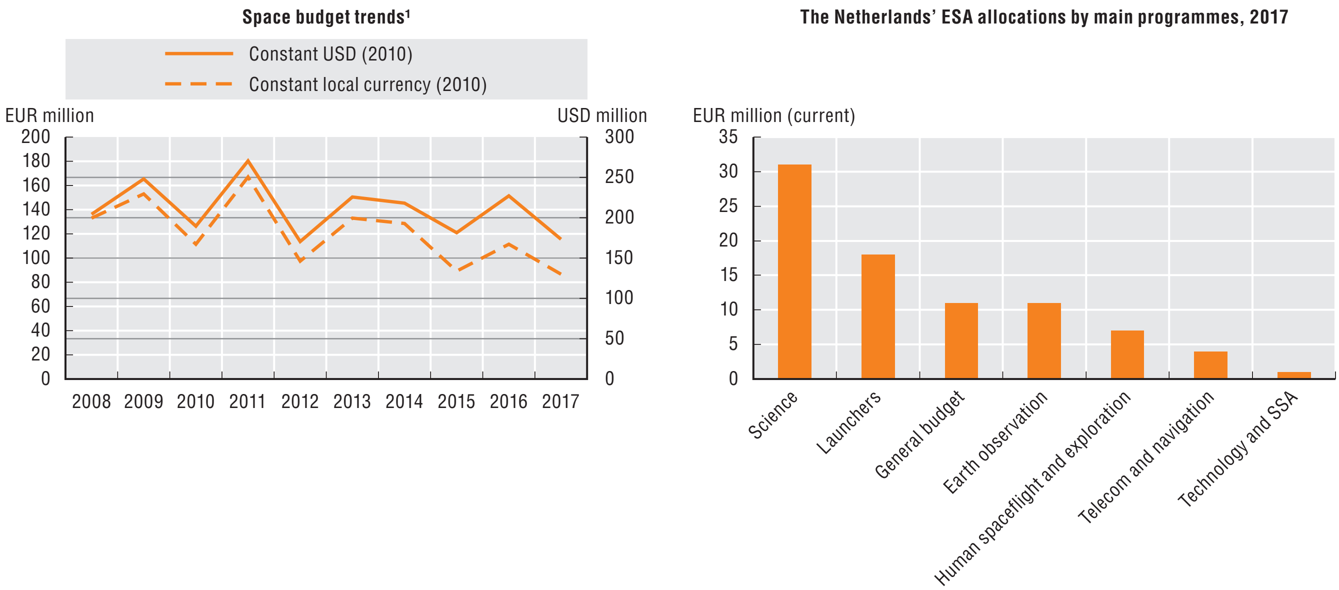


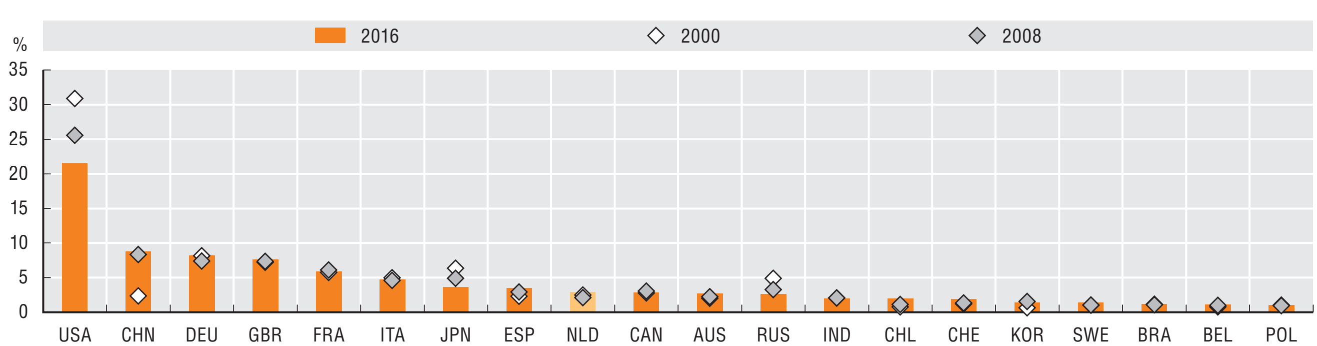
Figure 18.2. Space budget trends and main programmes



Note: 1.The institutional space budget includes allocations to ESA, EUMETSAT, ECMWF, WMO and national/multilateral programmes.
Source: OECD analysis based on institutional sources.

Figure 18.3. Scientific production in space literature, per country

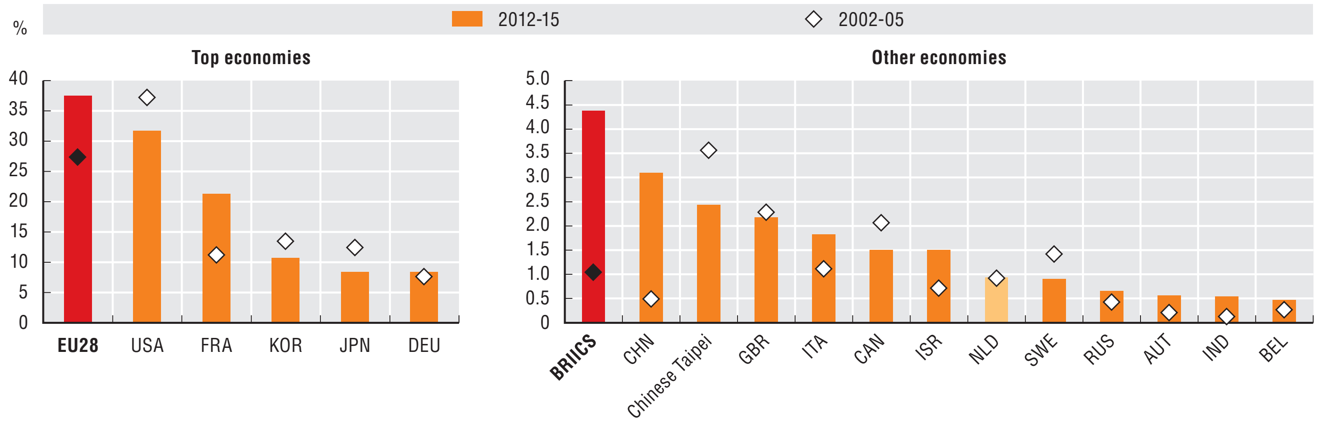
Share of total publications in space literature, 2000, 2008 and 2016



Source: OECD analysis based on Scopus Custom Data, Elsevier, July 2018.

Figure 18.4. Top applicants of space-related patents

IP5 patent families, by priority date and applicant's location, using fractional counts, 2002-05 and 2012-15

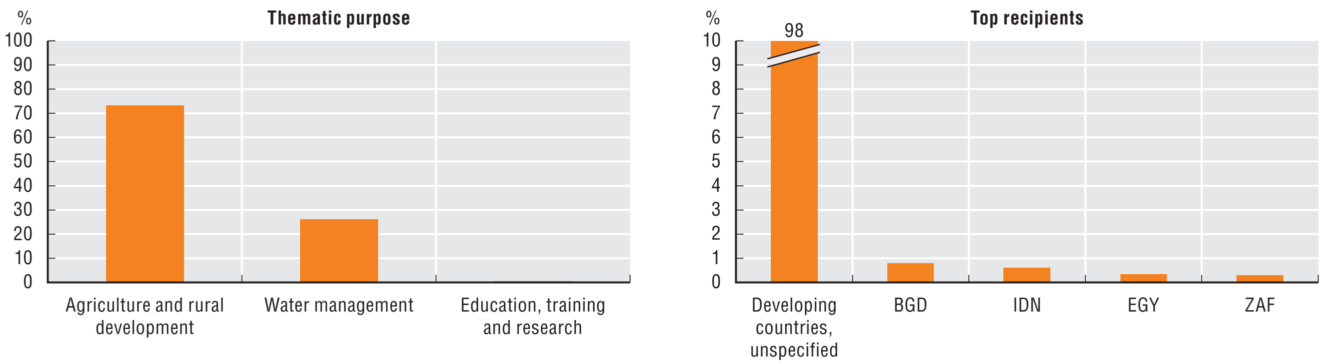


Note: Patent families are compiled using information on patent families within the Five IP offices (IP5). Figures are based on incomplete data from 2014.

Source: OECD STI Micro-data Lab: Intellectual Property Database, *http://oe.cd/ipstats*, March 2018.

Figure 18.5. Netherlands' space-related official development assistance disbursements

Share of total Netherlands' space-related disbursements, 2002-16



Note: The vast majority of Netherlands' space-related ODA projects in the OECD DAC dataset display information about disbursements rather than commitments (due to reporting procedures). For this reason, the figure shows the total disbursements by thematic purpose and by top recipients, instead of total commitments.

Source: Analysis based on OECD DAC database (2018).

19. New Zealand

New Zealand is a new and dynamic actor in the space sector with a focus on "new space". The New Zealand Space Agency in the Ministry of Business, Innovation and Employment, was set up in 2016 as the official government institution in charge of space policy, regulation and business development. New Zealand's location provides access to some of the largest numbers of launch azimuths in the world, and low air traffic enables high-frequency launch.

In 2017 the Outer Space and High-altitude Activities Act was passed, which regulates orbital launch vehicles, launch facilities and satellites, as well as high-altitude activities (New Zealand Ministry of Business, Innovation and Employment, 2017[1]). New Zealand also has a Technology Safeguards Agreement with the United States, enabling the transfer of technology necessary to operate a New Zealand-based launch industry.

New Zealand's spending on space activities and R&D is broad and spread across several government departments. New Zealand's departmental space budget is NZD 3.7 million per year (USD 2.7 million). In addition to this, New Zealand spent NZD 3.9 million supporting space science and research in 2017-18. That will rise to NZD 6.02 million for 2018-19. Substantial R&D occurs within industry, and space-related companies like Rocket Lab have received government R&D grants of up to NZD 5 million per year to supplement their R&D budgets. From 2018, companies can apply for a tax credit for R&D activities and this will apply across all sectors, including space.

New Zealand has also been investing in skills and R&D capability including through the establishment of the Space Systems Institute based at the University of Auckland and an agreement with NASA for internships at their Ames Research Centre in California. A programme of space science investments will begin in 2018-19, including under a Letter of Intent signed with DLR.

New Zealand has several publicly-funded research institutions contributing to the development and use of space science and technologies across a variety of areas, such as Land Information New Zealand (LINZ). Universities also play an active role in global space science research, for instance the University of Auckland's Space Science Institute (SSI).

Key emerging areas of expertise include the development of capabilities in responsive launch, smallsats, high-tech manufacturing, data analysis and integration, earth observation application development and ground stations. The country hosts the world's first fully private orbital launch facility at Mahia Peninsula, owned and operated for their sole use by Rocket Lab. Rocket Lab, a US company with a subsidiary in New Zealand, is the leading commercial actor in the New Zealand space industry, and had its first successful test launch in 2018. New Zealand also has upstream business activity in components and materials, for instance C-Tech (carbon fibre), Rapid Advanced Manufacturing (3-D printing), and subsystems, for instance Hyperion Technologies and Rakon.

In the downstream space sector, strong transport and telecommunications infrastructure in southern latitudes means New Zealand also hosts ground stations supporting international space programmes and some of the biggest commercial players of 'new space'. The Awarua Satellite Ground Station hosts antennas for both public and private satellite operators (e.g. Planet, Spire, ESA) and has a high-speed fibre optic link to the main telecommunications network (Venture Southland, 2018[2]). Furthermore, a number of companies provide and export space-related services and products in areas such as land management, precision agriculture, atmospheric and oceanographic research, geosciences and hazard management.

Since 2017, Land Information New Zealand (LINZ) and Geoscience Australia have trialled a satellite-based augmentation system for Australia and New Zealand to improve GNSS signal accuracy. Furthermore, the Centre for Space Science Technology was funded to help industries access and use space-derived data, with an initial NZD 15 million funding over three years (Centre for Space Science Technology, 2017[3]).

New Zealand's share in scientific publications in the OECD space literature dataset (see guide to the profiles) is comparable to that of Ireland and has remained stable since 2000, with a small increase in the last years. The penetration of satellite television has remained stable since 2010, while the satellite fixed broadband subscription rate has decreased. This decrease is related to the progressive introduction of mainly terrestrial ultra-fast broadband in New Zealand.

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Figure 19.1. New Zealand – Fast facts

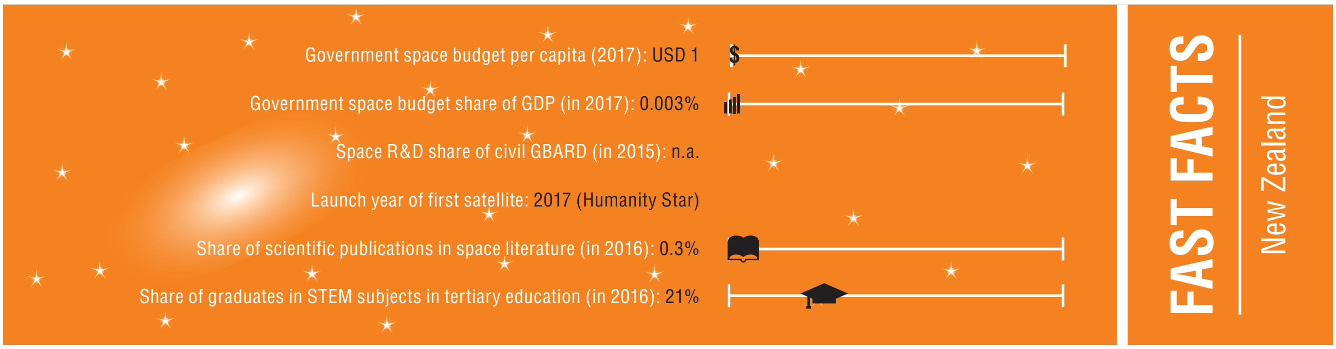
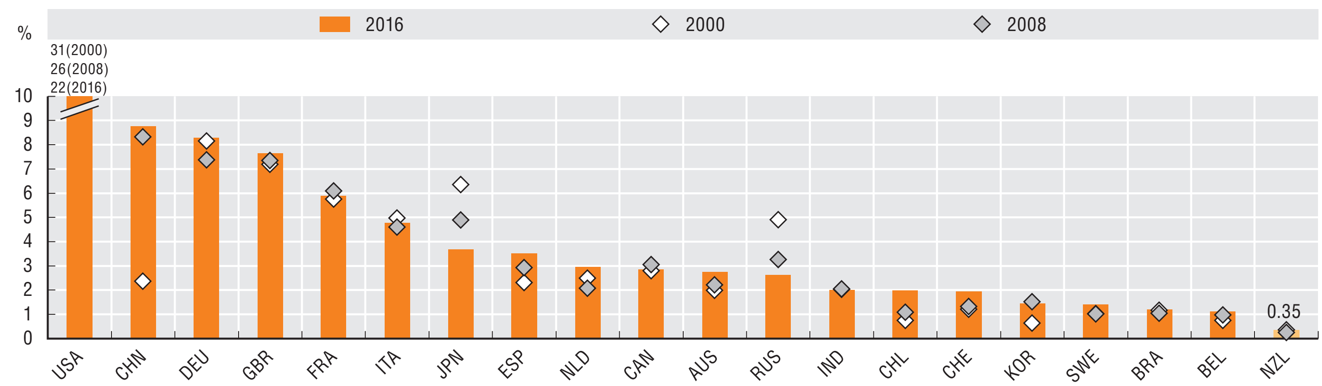


Figure 19.2. Scientific production in space literature, per country

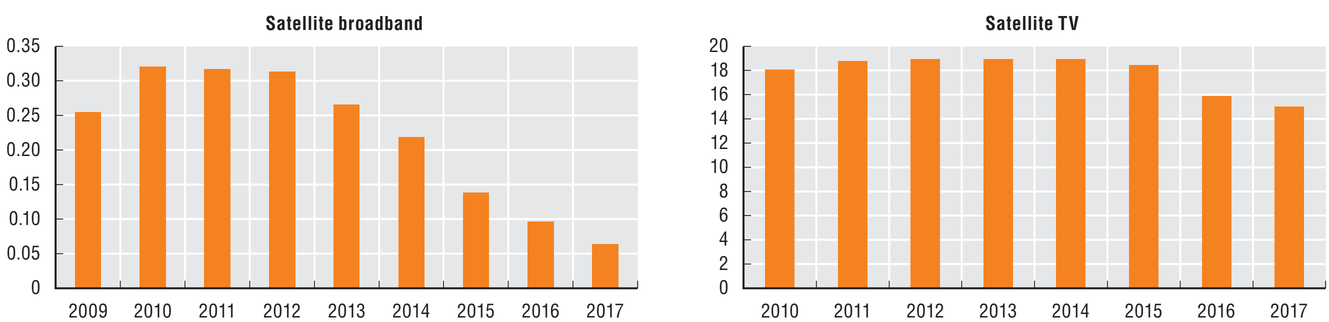
Share of total space publications, 2000, 2008 and 2016



Source: OECD analysis based on Scopus Custom Data, Elsevier, July 2018.

Figure 19.3. Penetration of satellite telecommunication technologies in New Zealand

Satellite broadband and satellite TV subscriptions per 100 inhabitants, 2009-16



Source: OECD analysis based on OECD Broadband database, *https://www.oecd.org/sti/broadband/broadband-statistics/*, and ITU World Telecommunication/ICT Indicators database.

Norway is a long-term participant in international space activities. The Norwegian Space Agency is a government agency under the Ministry of Trade, Industry and Fisheries. The Agency carries out Norwegian space policy, co-ordinates all space-related activities and represents the country in the European Space Agency.

A new government space strategy is currently being prepared, as well as an update of the Norwegian space legislative framework. The Norwegian government is also planning an Arctic satellite broadband communication system for government use, which would consist of two satellites, with a planned launch in 2022. Other recent policy activities include the creation of a national ground segment portal (Satellittdata.no) for data from the Sentinel satellites in the Copernicus programme.

In 2017, Norway allocated some NOK 1 154 million (USD 140 million) to space activities, a doubling of funding in real terms compared with 2008. Contributions to the European Space Agency (ESA), European Union (EU), 25%, and EUMETSAT accounted for some 90% of funding. Contributions to EU programmes for Galileo and Copernicus have increased over the years and now account for about 25% of the Norwegian institutional space budget. Norway contributes to all ESA voluntary programmes, in particular to the programmes for science (36%), telecommunications (20%) and earth observation (18%). The country also has a bilateral agreement with Canada for access to imagery from the Radarsat constellation. Since 2010, Norway has launched several very small and small satellites (AISSAT-1 and -2 and NorSat-1 and -2), detecting Automatic Identification System (AIS) signals from vessels, for the monitoring of fisheries, oil spills and maritime traffic.

Norway hosts satellite ground stations at both the Arctic and Antarctic poles. The world's biggest commercial ground station for reading and distributing satellite data is located on the Norwegian archipelago Svalbard, linked to the European mainland with high-speed fibre optical cables. Both European and US agencies use the Svalbard station to downlink data from their polar-orbiting satellites.

There are also several suborbital launch and research facilities located above the Arctic Circle, notably the Andøya Space Centre and the ALOMAR Arctic atmosphere observatory. An important development in 2018 was the launch of the first sounding rocket fully developed and built in Norway by the Norwegian company Nammo in partnership with the Norwegian Space Agency and ESA. The rocket Nucleus, using innovative environmentally-friendly propulsion technology, was launched from the Andøya Space Centre and reached an altitude of 104 km.

The Norwegian space industry has capabilities in space manufacturing, satellite operations and downstream applications. Norwegian space manufacturing companies supply components, equipment and subsystems to several European satellites and launchers. Norwegian space manufacturers benefit greatly from ESA membership. An evaluation of the impact on Norway's participation in ESA programmes between 2000 and 2017, including a cumulative 3-year delay, found an impact factor (multiplier) of 4.8 in company sales (Norwegian Space Agency, 2018[1]).

Important downstream activities include satellite ground station operations, broadcast and maritime telecommunications (Marlink, Telenor). Kongsberg is a leading supplier of satellite data download and processing services. Several companies also provide products and services related to positioning, navigation and timing and value-added services, often catering to businesses in the maritime and extractive industries. In 2015, the Norwegian space industry conservatively generated some NOK 7 billion (USD 868 million) in revenues (Norwegian Space Agency, 2016[2]).

Norway's share in scientific publications in OECD's "Space literature" dataset (see guide to the profiles) is comparable to that of Belgium and Brazil and has remained stable since 2000. Like in many other countries, Norway's share of space-related patent applications has decreased between 2002-05 and 2012-15, mainly due to increased activity of new and emerging economies. Satellite TV and satellite broadband penetrations are above the OECD median. Satellite TV subscriptions have been steadily decreasing since 2007, while satellite broadband subscription rates remain stable. Space-related official development assistance projects in the period 2000-16 have focussed mainly on environmental management and telecommunications.

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Figure 20.1. Norway – Fast facts

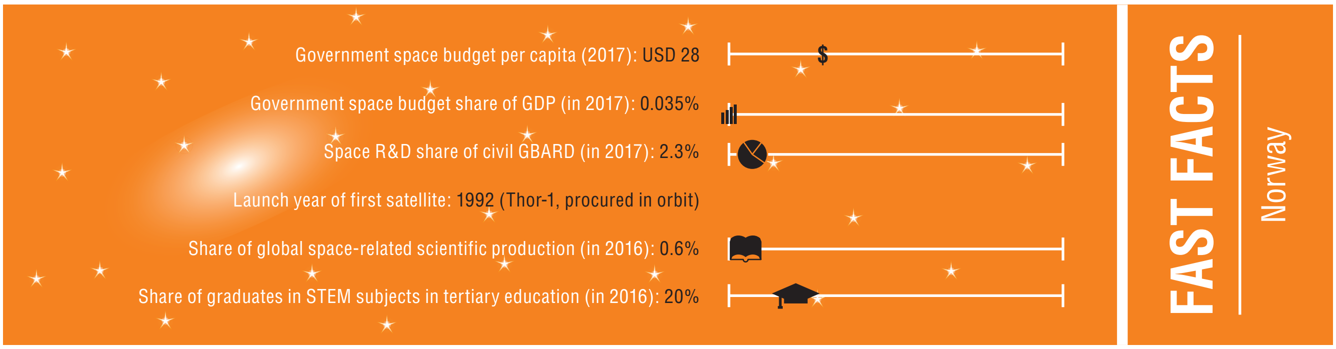
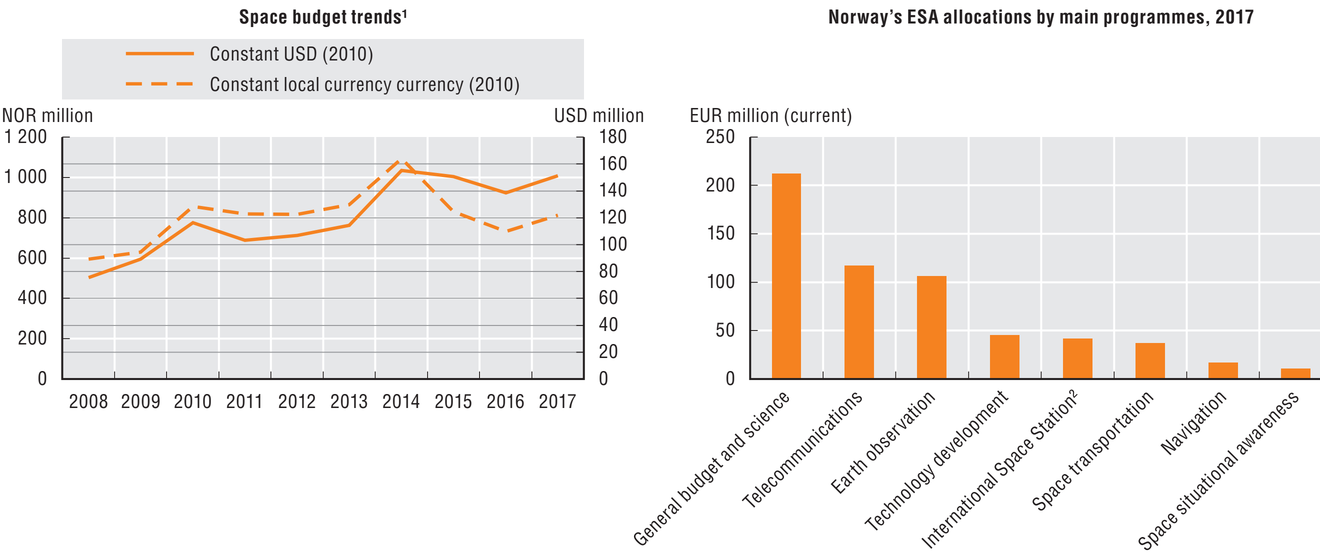


Figure 20.2. Space budget trends and main programmes

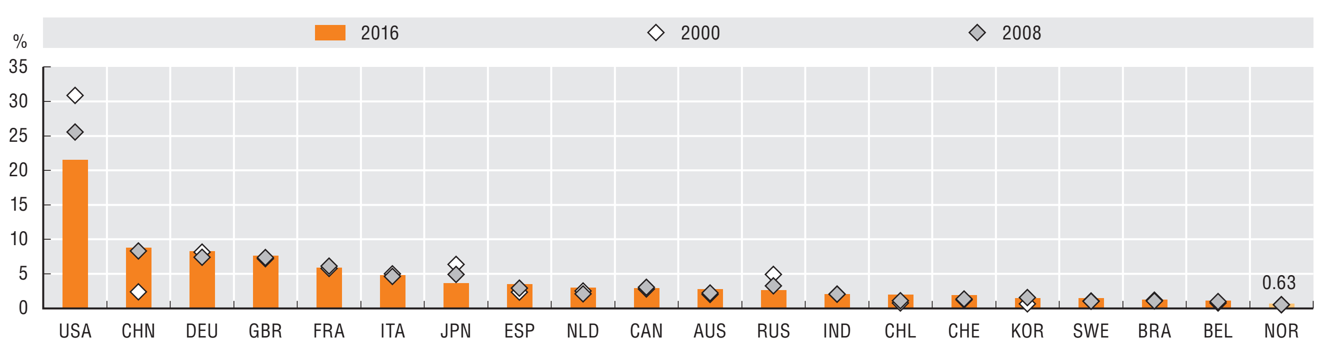


Note: 1. Norwegian space budget trends includes allocations to ESA, EU, EUMETSAT and national and multilateral programmes.2. This category also includes microgravity and exploration.

Sources: OECD analysis based on institutional sources.

Figure 20.3. Scientific production in space literature, per country

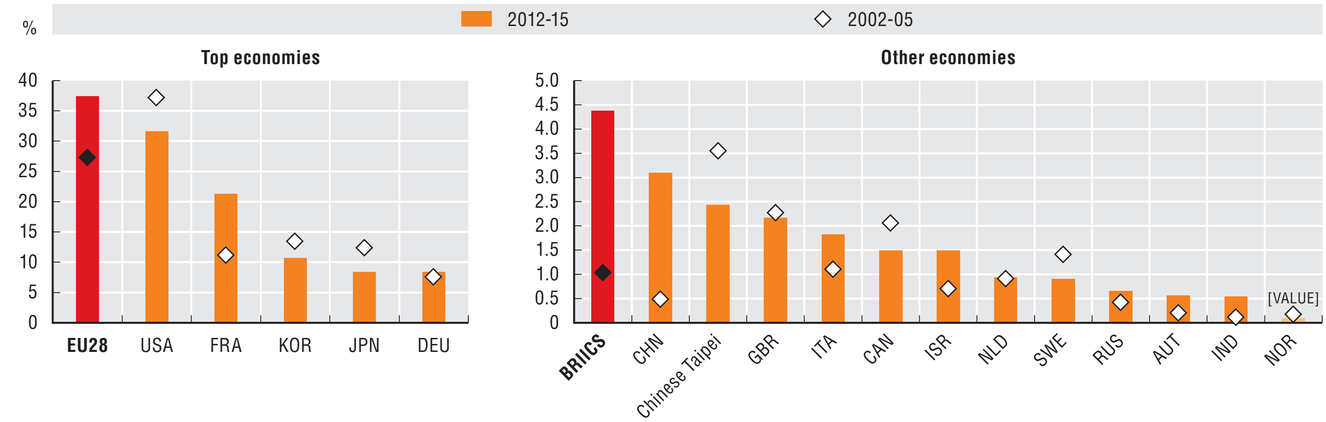
Share of total space publications, 2000, 2008 and 2016



Source: OECD analysis based on Scopus Custom Data, Elsevier, July 2018.

Figure 20.4. Top applicants of space-related patents

IP5 patent families, by priority date and applicant's location, using fractional counts, 2002-05 and 2012-15



Note: Patent families are compiled using information on patent families within the Five IP offices (IP5). Figures are based on incomplete data from year 2014.

Source: OECD STI Micro-data lab: Intellectual Property Database, *http://oe.cd/ipstats*, March 2018.

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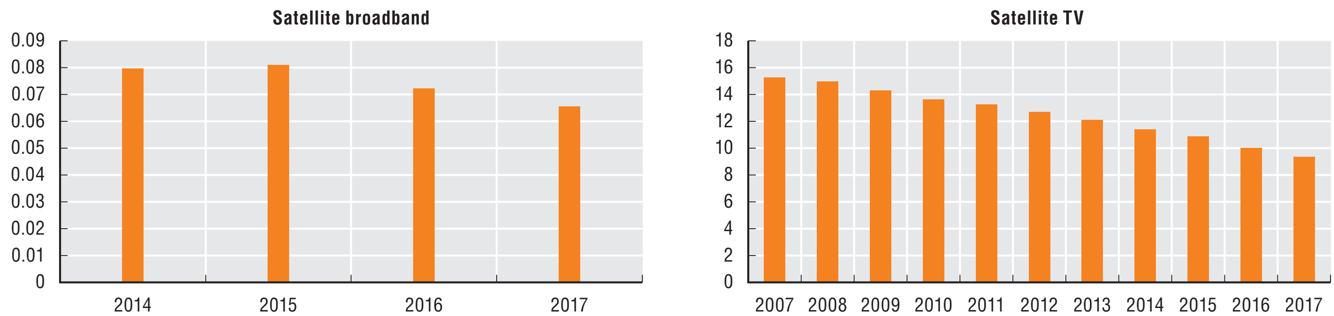
Satellite broadband and satellite TV subscriptions per 100 inhabitants



Source: OECD analysis based on OECD Broadband database, *https://www.oecd.org/sti/broadband/broadband-statistics/*, and ITU World Telecommunication/ICT Indicators database.

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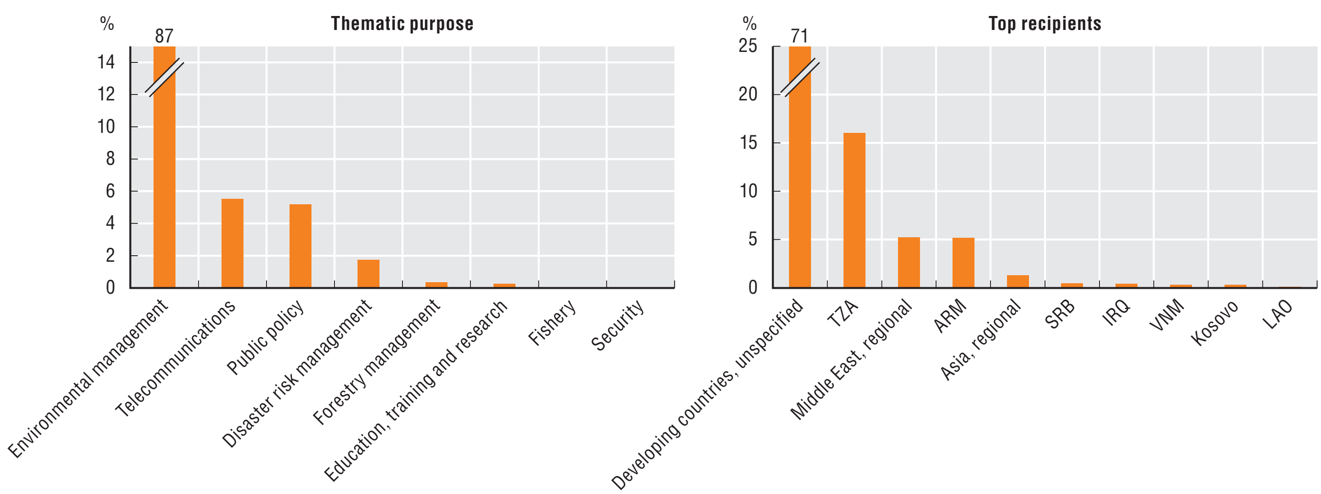

Source: Analysis based on OECD DAC database (2018).

21. Switzerland

Switzerland has a dynamic space sector and is one of the founding members of the European Space Agency (ESA). The Swiss Space Office, in the Federal Department of Economic Affairs, Education and Research, is in charge of implementing Swiss space policy.

Policy focusses on the development of civil space applications, the long-term commitment to space exploration and the competitiveness of national actors (SERI, 2008[1]). The revised 2018-20 policy implementation plan recommends measures to continue to the implementation of these space policy priorities, specifically to support academic and private space actors, contribute to the digital transformation of Switzerland, further strengthen networks and clusters and develop space-related skills through education and training (Swiss Space Office, 2017[2]). An ESA business incubation centre opened at the Federal Institute of Technology ETH Zurich in 2016.

Switzerland allocated an estimated CHF 242 million (USD 246 million) in 2017 to civil space activities, a 67% increase in real terms compared with 2008. Most of the funding is dedicated to international activities, with the European Space Agency (ESA) accounting for 72% of the budget, European Union programmes Galileo and Copernicus 17% and EUMETSAT 8%. The largest programme priorities include science (including the participation in PRODEX), launchers, earth observation and telecom.

Higher education institutions play an important role in space-related R&D, with the Federal Institute of Technology EPF Lausanne hosting the Swiss Space Centre, and the University of Bern hosting the International Space Science Institute (ISSI). Other important space research organisations are the Swiss Federal Laboratories for Materials Science and Technology (EMPA), the Paul Scherrer institute (PSI) as well as all institutes in charge of scientific instruments developed under the ESA PRODEX Programme.

The Swiss space industry has strong links to the aerospace and mechanics industries. It produces subsystems for satellites and launchers (e.g. atomic clocks), instruments and sensors. Fairings developed for the European Ariane 5 and Vega launchers are also used for US Atlas launcher. More than 50% of companies are SMEs with the main actors being the subsystem suppliers RUAG and APCO. An increasing number of actors are also active in the downstream segment, with several start-ups created through the ESA Business Applications Programme and the Business Incubation Centre. Altogether, space sector employment represents more than 2 500 FTEs in Switzerland, according to the Swiss Space Industry Group (SSIG) (Meier, 2018[3]). Most companies are located close to universities and research centres and/or urban centres, with a concentration near Zurich and in the French-speaking cantons (Geneva, Lausanne). A 2015 evaluation of Swiss R&D funding instruments for space activities found that the industry was one of the most innovative and research-intensive industries in Switzerland, with a high share of exports, mostly to Europe (Swiss Space Office, 2015[4]).

Several international organisations are based in Switzerland and have space-related activities. The Group on Earth Observations (GEO) has the most direct link to the space sector, but the World Meteorological Organisation (WMO), with links to the Physical Meteorological Observatory (PMOD)/World Radiation Centre (WRC) in Davos, the International Union for Conservation of Nature (IUCN), and the International Telecommunication Union (ITU) also have space-related activities. CERN, the European Organization for Nuclear Research, signed a co-operation agreement with the European Space Agency in 2014.

Switzerland's share in scientific publications in OECD's "Space literature" dataset (see guide to the profiles) is comparable to that of India and Korea and has slightly increased since 2000. Switzerland's share of space-related patent applications has decreased between 2002-05 and 2012-15, mainly due to increased activity of new and emerging economies. Satellite broadband penetration remains low, but has significantly increased since 2015. Swiss space-related development assistance projects in the period 2000-16 focussed mainly on agriculture and rural development in Asia.

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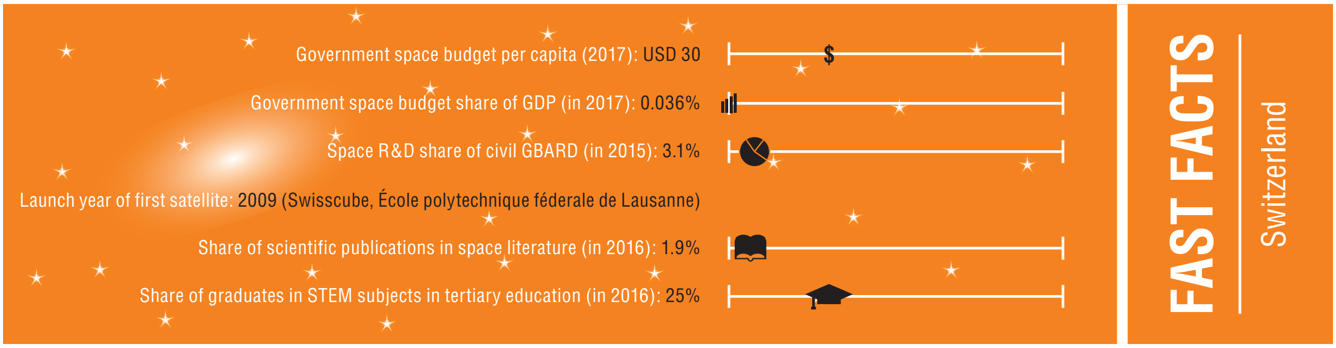
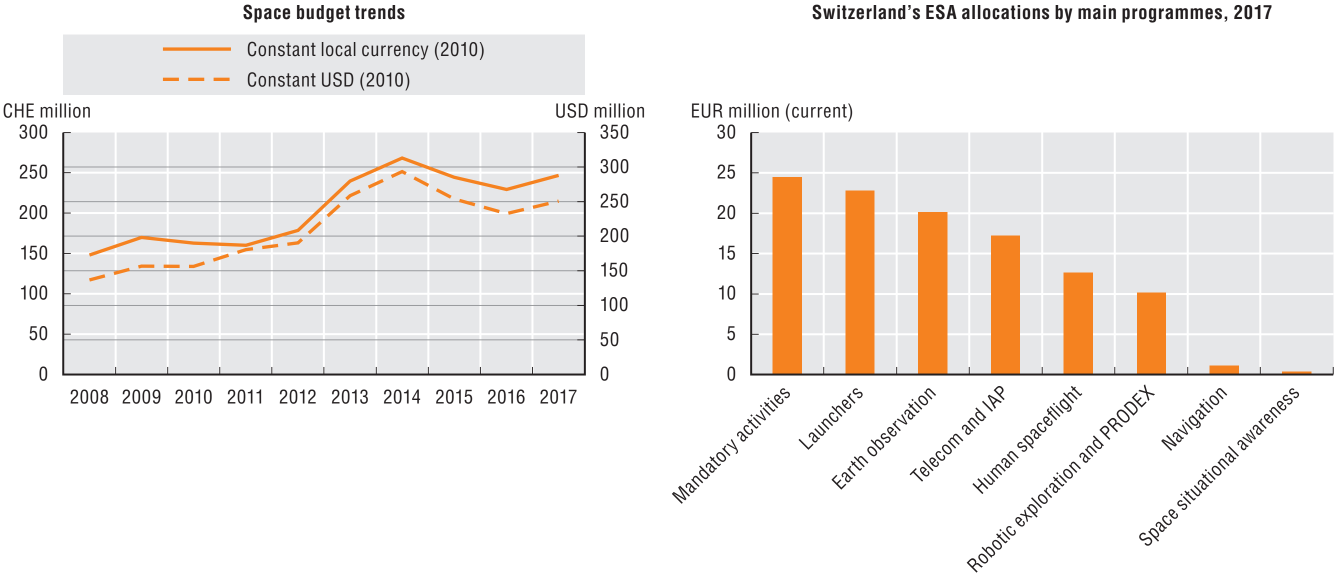


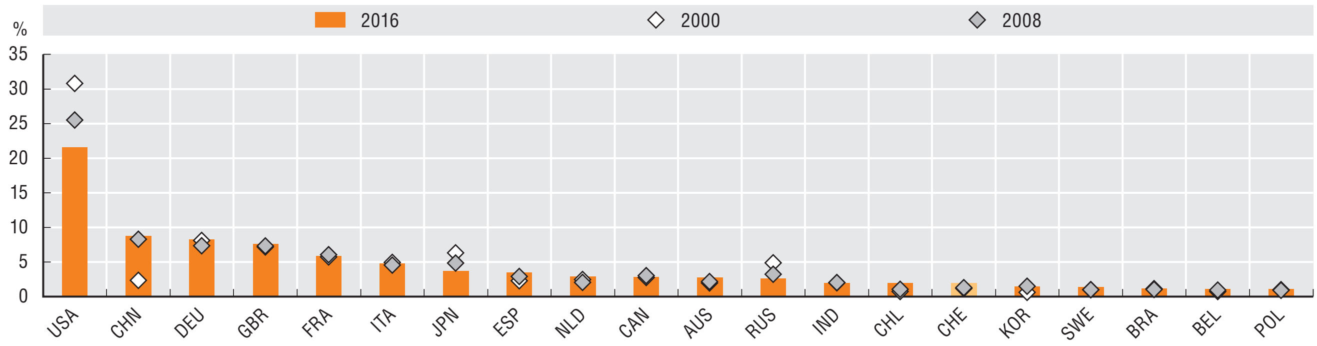
Figure 21.2. Space budget trends and main programmes



Source: OECD analysis based on institutional sources.

Figure 21.3. Scientific production in space literature, per country

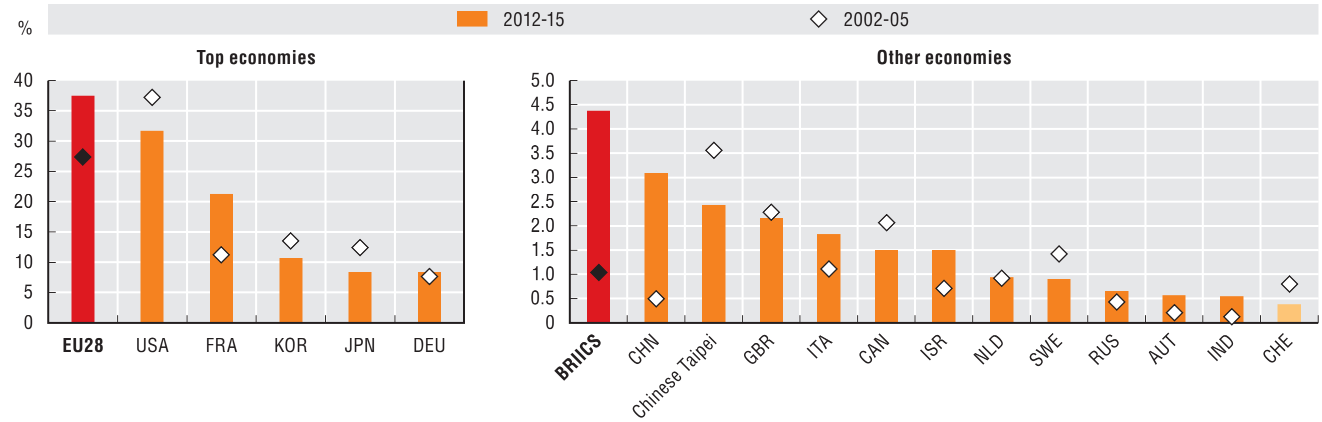
Share of total space publications, 2000, 2008 and 2016



Source: OECD analysis based on Scopus Custom Data, Elsevier, January 2018.

Figure 21.4. Top applicants of space-related patents

IP5 patent families, by priority date and applicant's location, using fractional counts, 2002-05 and 2012-15

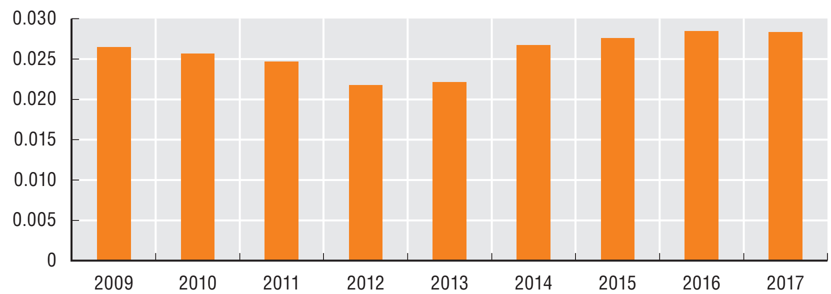


Note: Patent families are compiled using information on patent families within the five IP offices (IP5). Figures are based on incomplete data from year 2014.

Source: OECD STI Micro-data Lab: Intellectual Property Database, *http://oe.cd/ipstats*, March 2018.

Figure 21.5. Penetration of satellite telecommunication technologies in Switzerland

Satellite broadband subscriptions per 100 inhabitants, 2007-16



Source: OECD analysis based on OECD Broadband database, *https://www.oecd.org/sti/broadband/broadband-statistics/*, and ITU World Telecommunication/ICT Indicators database.

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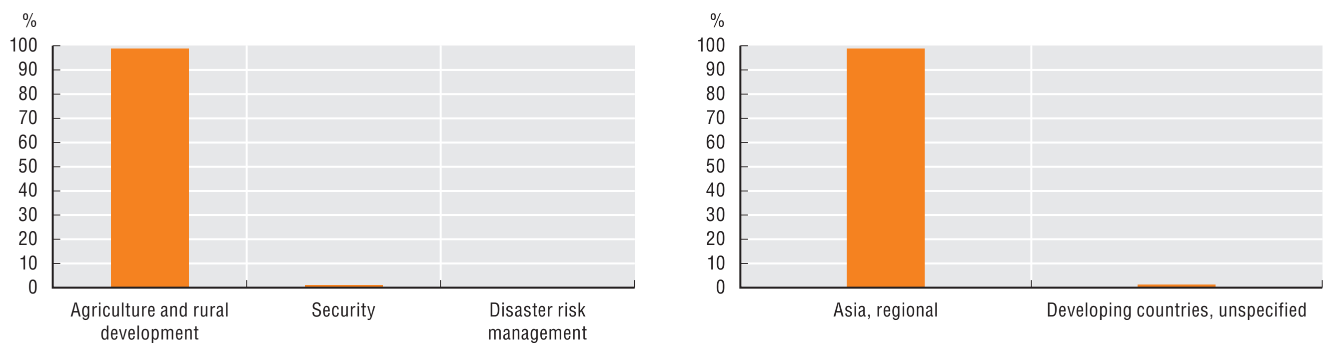
Share of total space-related commitments, 2000-16



Source: Analysis based on OECD DAC database (2018).

22. United Kingdom

The United Kingdom has been active in the space sector for more than 50 years and has a highly skilled and export-oriented industry. The UK Space Agency is an executive agency of the Department for Business, Energy and Industrial Strategy and the main government body responsible for civil space policy in the United Kingdom. The Agency represents the United Kingdom at the international level and co-ordinates and funds national research projects.

In the last ten years, the UK space sector has seen strong government support and increased national and international contributions, with the Innovation and Growth Strategy launched in 2010. One important initiative was the establishment of the Satellite Applications Catapult Centre in 2013 in Harwell. The Space Industry Act of March 2018 paves the way for suborbital activities and small satellite launches from UK territory (United Kingdom Houses of Parliament, 2018[1]).

In 2017, the UK government allocated an estimated GBP 430 million (USD 554 million) to national and international space activities, including EUMETSAT, a 48% increase in real terms compared to 2008. Almost 70% of funding went to the European Space Agency (ESA), but allocations to national activities have grown in the last years. ESA voluntary contributions in 2017 were equally distributed across programmes for science; human spaceflight, microgravity and exploration; and telecommunications and earth observation.

Important national and international research centres and installations include the RAL Space Laboratory at Harwell, the European Centre for Medium-Range Weather Forecasts and the European Centre for Space Applications and Telecommunications. Several UK universities play an active role in space-related R&D.

The UK space industry has commercial activities in almost all industry segments. Ancillary services are well represented, including financing, insurance and legal services. In the 2016-17 financial year, the industry generated some GBP 14.8 billion (USD 19 billion) in revenues, with downstream segments (operations, applications and ancillary services) accounting for almost 90% of the total (UK Space Agency, 2019[2]).

The UK space manufacturing industry has several domestic and international satellite producers, including small and very small satellites, which support an ecosystem of high-technology equipment and component suppliers (e.g. Airbus UK, Thales Alenia Space, Lockheed Martin and SSTL). A site in northern Scotland has been chosen as the location for the UK's first vertical spaceport. Funding has also been made available for boosting horizontal spaceport development (e.g. in Cornwall, Glasgow, Snowdonia).

In the downstream value chain, direct-to-home broadcasting dominates in terms of revenues (e.g. Sky UK), followed by satellite communications and positioning, navigation and timing, with Inmarsat as a major provider of mobile communications. There are also a growing number of providers of value-added products and services for different industries (e.g. maritime, extractive, finance, insurance).

The United Kingdom is one of the leading countries in terms of its share in scientific publications in the OECD "Space literature" dataset (see guide to the profiles), a position that has remained stable since 2000. In space-related patent activities, United Kingdom's share in applications has also remained stable and is comparable to that of Italy.

The penetration of satellite television increased between 2000 and 2010 but is now decreasing. Satellite broadband penetration is low and stable.

Over the 2000-16 period, space-related official development assistance projects have primarily focused on environmental management and education, training and research. Main recipient countries were China and Tanzania. The United Kingdom recently launched a developed aid programme that specifically relies on the use of satellite technologies. The International Partnership Programme (IPP) is managed by the UK Space Agency, with 2016-21 funding of GBP 152 million (USD 196 million). The primary objective is to use space expertise and knowledge to deliver socio-economic benefits to emerging and developing countries. The projects, in more than 30 countries, are implemented in partnership with local governments, aid organisations and private actors in the areas of land use and maritime monitoring, agriculture, disaster resilience, education and health. The projects qualify as official development assistance (ODA) (UK Space Agency, 2018[3]).

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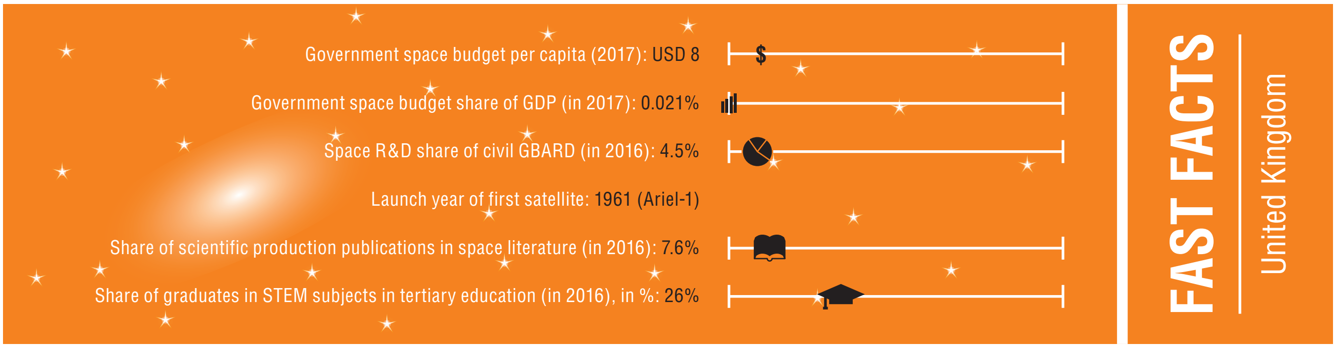

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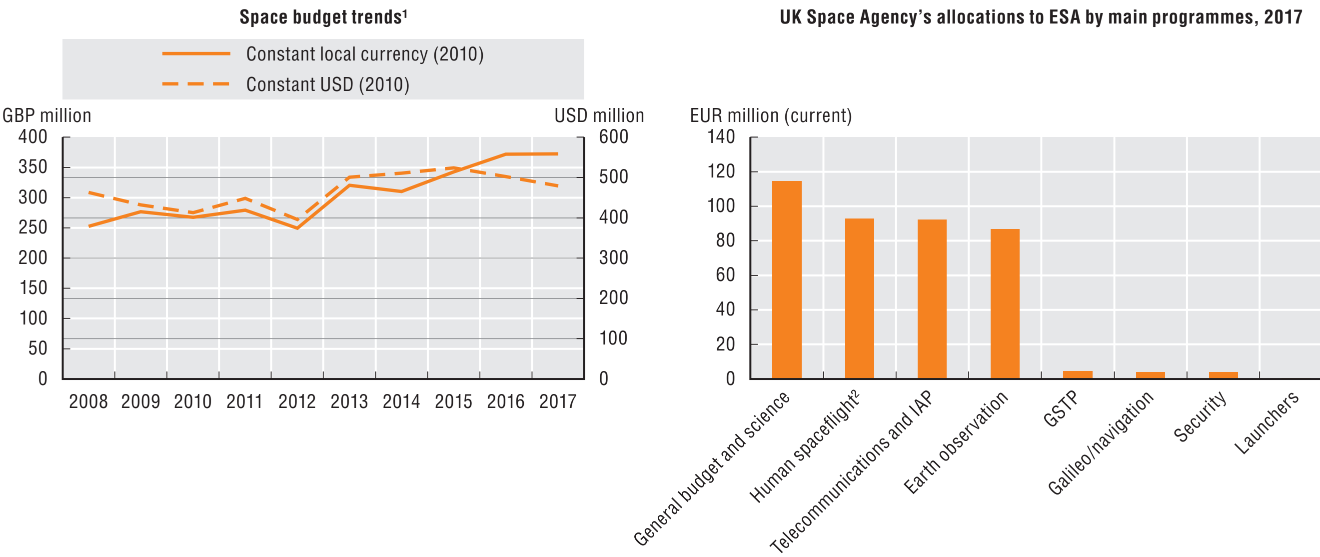
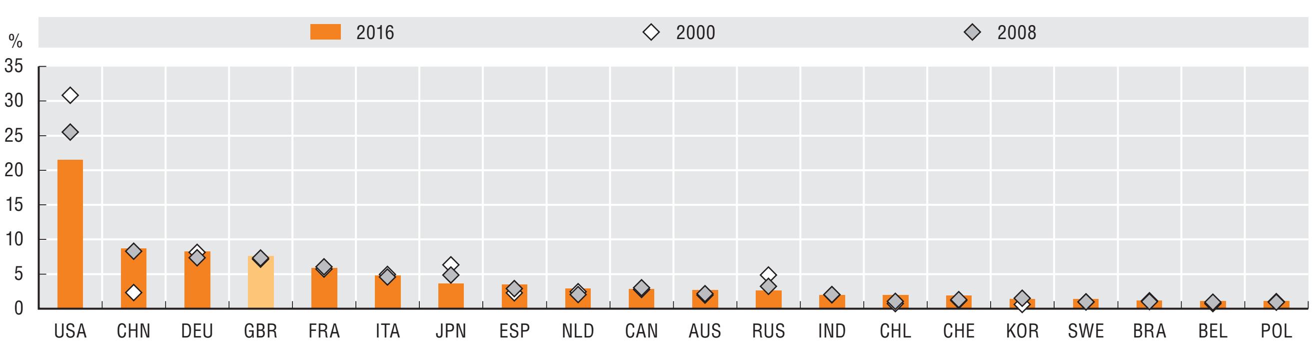


Notes: 1.The institutional space budget includes allocations to ESA, EUMETSAT and national/multilateral programmes. Data for EUMETSAT are estimates based on previous years. 2. Also includes microgravity and exploration.

Source: OECD analysis based on institutional sources.

Figure 22.3. Scientific production in space literature, per country

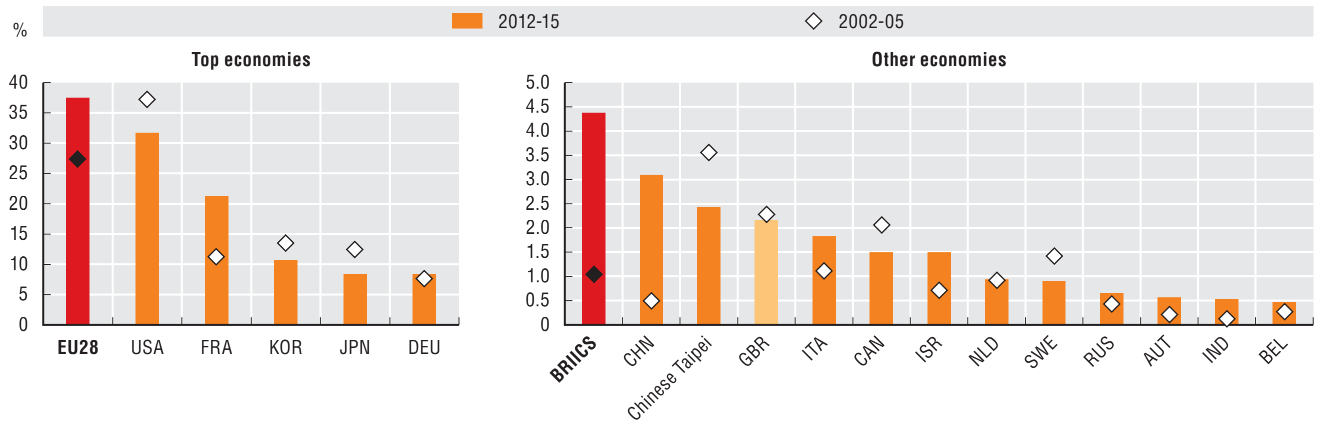
Share of total space publications, 2000, 2008 and 2016



Source: OECD analysis based on Scopus Custom Data, Elsevier, July 2018.

Figure 22.4. Top applications of space-related patents

IP5 patent families, by priority date and applicant's location, using fractional counts, 2002-05 and 2012-15

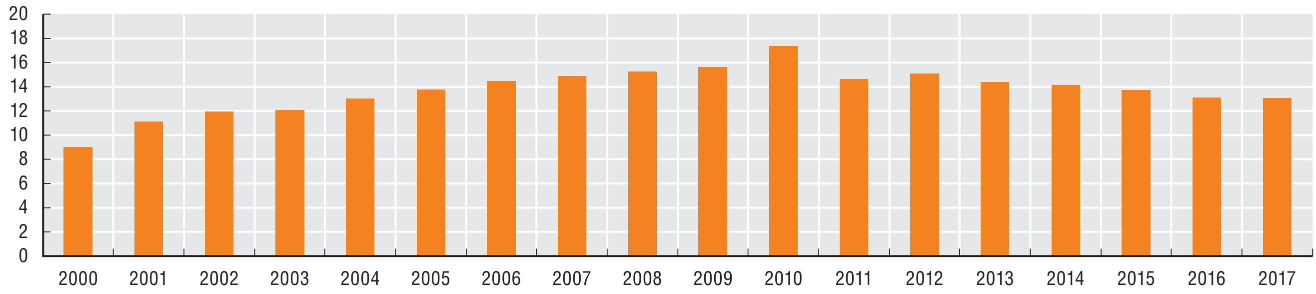


Note: Patent families are compiled using information on patent families within the Five IP offices (IP5). Figures are based on incomplete data from 2014.

Source: OECD STI Micro-data Lab: Intellectual Property Database, *http://oe.cd/ipstats*, March 2018.

Figure 22.5. Penetration of satellite telecommunication technologies in the United Kingdom

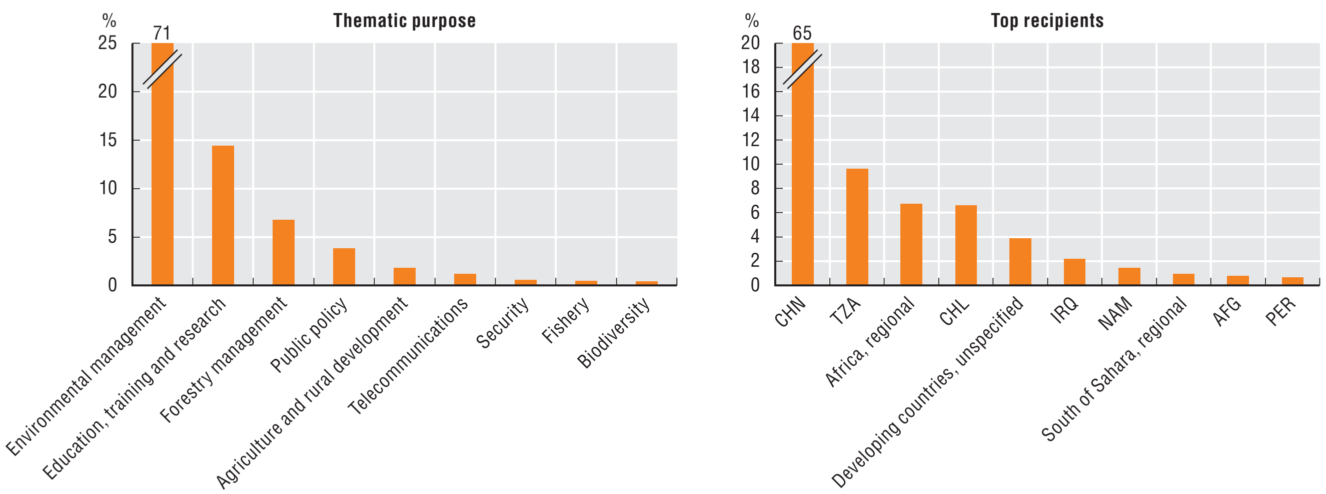
Satellite TV subscriptions per 100 inhabitants, 2000-16



Source: OECD analysis based on OECD Broadband database, *https://www.oecd.org/sti/broadband/broadband-statistics/*, and ITU World Telecommunication/ICT Indicators database.

Figure 22.6. UK space-related official development assistance commitments

Share of total UK space-related commitments, 2000-16



Source: Analysis based on OECD DAC database (2018).

23. United States

The United States has the world's largest government space programme and has been a leading global space actor since its first successful satellite launch 60 years ago.

The National Aeronautics and Space Administration (NASA) is the national space agency, but other federal agencies and administrations also have important space programmes, including the Departments of Defense, Commerce (National Oceanic and Atmospheric Administration) and the Interior (US Geological Survey). The National Space Council, set up in 2017 within the Executive Office of the President, provides strategic directives for the US Space programmes.

Several space policy directives have been enacted. There is a reinforced focus on exploration and commercialisation, with directives specifically addressing human space exploration, space traffic management and the creation of a US Space Force. In 2019, the Space Development Agency was established as a separate organisation within the Department of Defense, in an effort to streamline the development of military space capabilities and promote strategic relations with commercial and international partners.

In 2017, the United States allocated some USD 48 billion to space activities (a conservative estimate), financing civil and military space programmes and activities implemented by multiple government departments and agencies. The main priorities of NASA's USD 19.7 billion budget in 2017 included science (29% of funding), space operations (25%) and human exploration (22%) (US Congress, 2017[1]). Important programmes include the development of the Space Launch System (SLS), scheduled for launch in the early 2020s and the US deep exploration programme (e.g. human landing on the Moon and the deployment of the *Gateway*, a manned space station orbiting the Moon). While the United States currently depends on the Russian Federation to send astronauts to the International Space Station, Boeing and SpaceX are conducting advanced testing for commercial crew capsules. The first manned flights are expected late 2019 or early 2020.

Another important government space programme is the National Environmental Satellite, Data and Information Service (NESDIS) at the National Oceanic and Atmospheric Administration. In 2017, it received some USD 2.2 billion in funding (US Congress, 2017[1]), mainly for the operations and future development of satellite meteorological systems. NESDIS works closely with both commercial and international actors to improve forecasting strength. It is responsible for a range of data products for science and climate research.

Important research actors in space science, earth science and engineering include both government and non-government research organisations and multiple higher education institutions, such as the NASA-funded Jet Propulsion Laboratory located at the California Institute of Technology.

The United States has market-leading capabilities in all space industry segments: space manufacturing and launch, operations and downstream applications. In 2016, the US space industry generated some USD 110 billion in revenues (Satellite Industry Assocation, 2017[2]). The space manufacturing sector consists of several thousand companies (US Department of Commerce, 2014[3]). Start-up activity is high. The space manufacturing industry, which employed some 80 000 persons in 2017, is located throughout the United States, with a concentration near research centres, facilities and high-technology clusters in California, Texas, Florida, New Mexico, Colorado and Alabama. Several new manufacturing facilities (e.g. OneWeb, Blue Orbital) are being built in the Kennedy Space Center Exploration Park in Florida.

Important downstream activities include telecommunications and navigation-related equipment and services, which accounted for an estimated 90% of total US space industry revenues in 2016 (Satellite Industry Assocation, 2017[2]). Earth observation has seen considerable entrepreneurship in the last years, particularly in data analytics.

The United States has the highest share in scientific publications in the OECD "Space literature" dataset and space-related patent applications (see guide to the profiles). In both cases, the share has decreased since 2000, mainly due to increased activity of other countries. US satellite TV and satellite broadband penetration rates are some of the highest in the OECD area. The number of satellite TV subscriptions has remained stable since 2009, while the number of satellite broadband subscriptions doubled between 2007 and 2016.

US space-related official development assistance projects have mainly focussed on biodiversity (e.g. the monitoring of forest cover and land use change) and telecommunications over the 2000-16 period. Main recipient countries and regions (when excluding unspecified recipients) were located in sub-Saharan Africa and Far East Asia (East and Southeast Asia). NASA and the US Agency for International Development (USAID) run the SERVIR programme, which provides satellite-based earth observation data, models and applications to assist environmental decision-making in developing countries.

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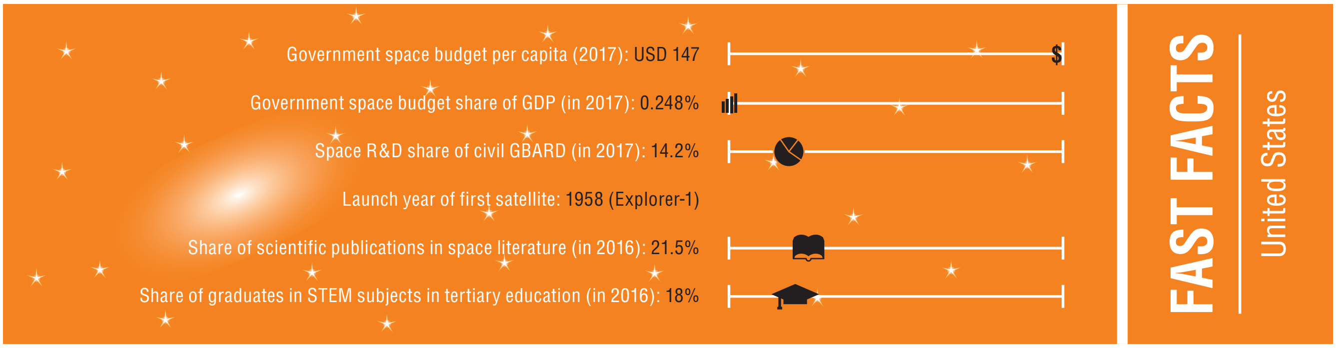

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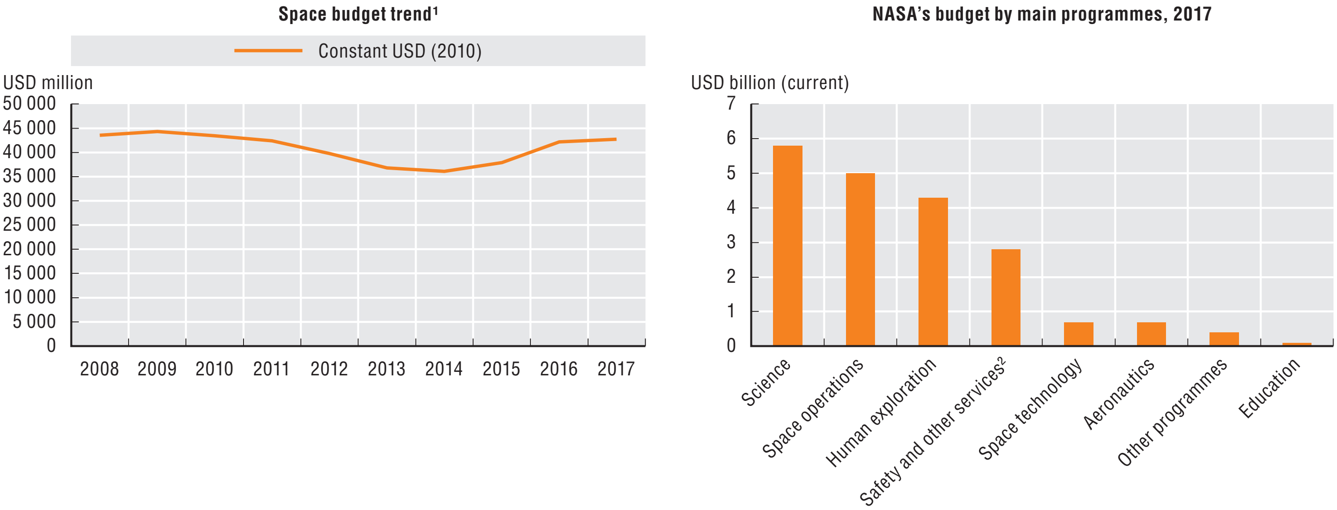
In constant USD million and USD billion (current), 2017

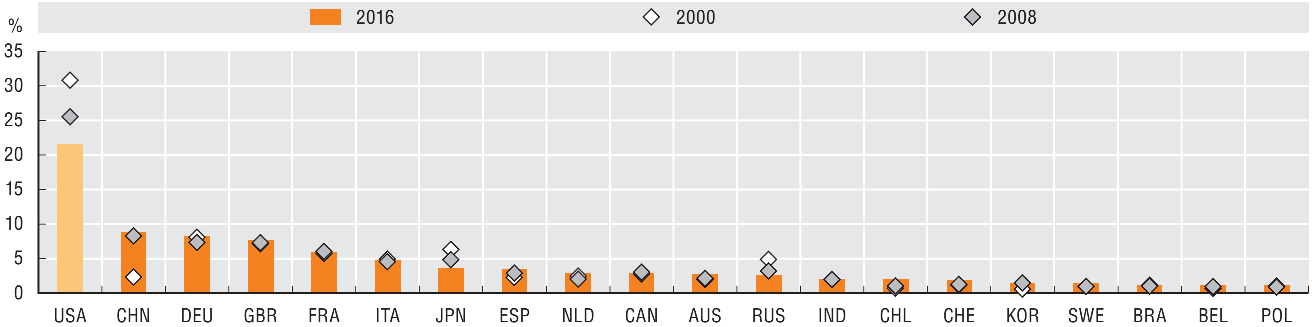


Notes: 1. Space budget trends are estimates. 2. This category also includes security and mission services.

Source: OECD analysis based on institutional sources.

Figure 23.3. Scientific production in space literature, per country

Share of total space publications, 2000, 2008 and 2016



Source: OECD analysis based on Scopus Custom Data, Elsevier, July 2018.

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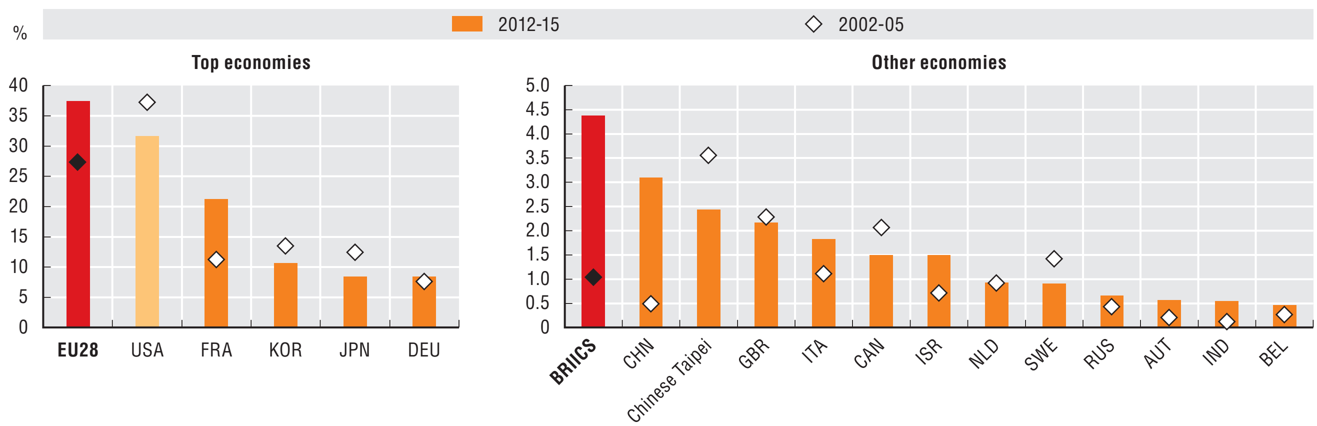

Note: Patent families are compiled using information on patent families within the Five IP offices (IP5). Figures are based on incomplete data from year 2014.

Source: OECD STI Micro-data Lab: Intellectual Property Database, *http://oe.cd/ipstats*, March 2018.

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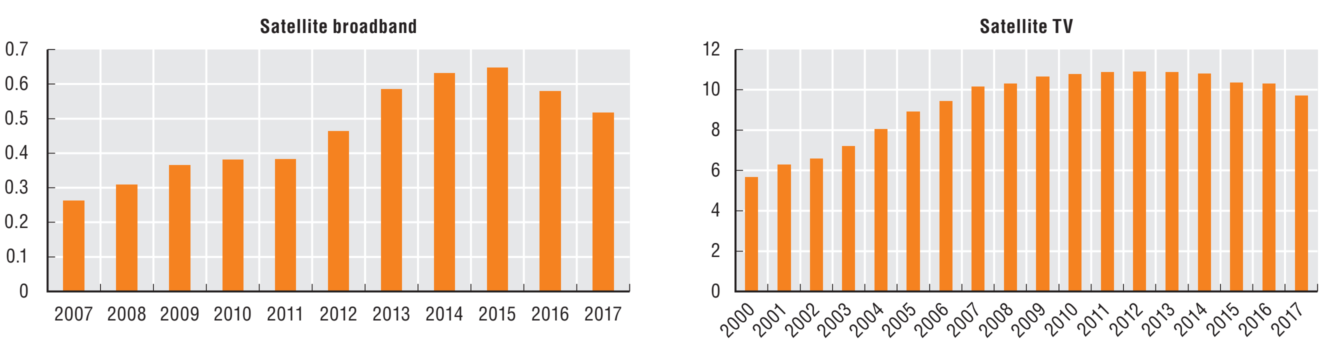

Source: OECD analysis based on OECD Broadband database, *https://www.oecd.org/sti/broadband/broadband-statistics/*, and ITU World Telecommunication/ICT Indicators database.

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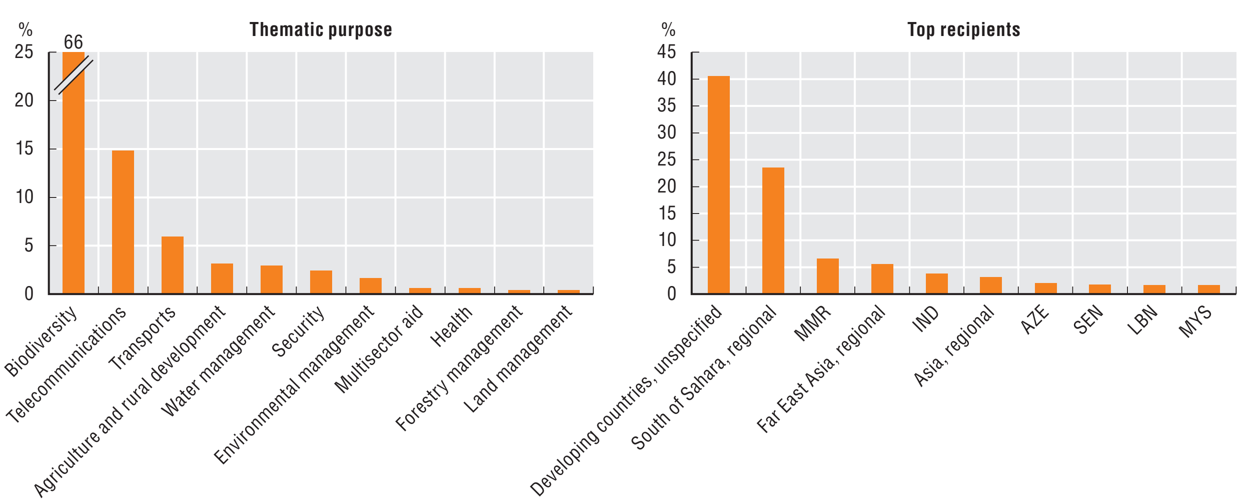

Source: Calculations based on OECD DAC database (2018).

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The Space Economy in Figures

HOW SPACE CONTRIBUTES TO THE GLOBAL ECONOMY

The space economy is expanding and becoming increasingly global, driven by the development of ever-more governmental space programmes around the world, the multiplication of commercial actors in value chains, durable digitalisation trends, and new space systems coming of age. This report describes these emerging trends using new and internationally comparable data and indicators. It highlights the growing importance of space activities for the economy, for developing country strategies (based on original official development assistance statistics), for the pursuit of knowledge and scientific discoveries, and for society in general. To get the most out of space investments and promote sustained socio-economic growth, this report provides some recommendations to countries in building up their statistical evidence on space actors and activities.

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