Space and Innovation

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Please cite this publication as:
OECD (2016), *Space and Innovation*, OECD Publishing, Paris.
http://dx.doi.org/10.1787/9789264264014-en

ISBN 978-92-64-26400-7 (print)
ISBN 978-92-64-26401-4 (PDF)

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Foreword

In our interconnected world, science and technology activities are a major source of innovation, productivity and economic growth. The space sector has been playing its part, having been for decades a driver of scientific exploration and knowledge, a sector with cutting-edge technologies, and a source of innovation diffused in other economic sectors. Many essential activities would be almost unthinkable today without satellite technology, like weather forecasting, or global communications and broadcasting. This new report highlights innovation dynamics that are transforming the space sector. New OECD analysis and indicators contribute to answering some of the following questions: Is the space sector still a driver for innovation in the 21st century? What are the determinants for an innovative space sector? And what are the policy responses to better harness and encourage space-related innovation?

This publication is based on research and analytical work conducted by the OECD Space Forum in the Science and Technology Policy Division in the Directorate for Science, Technology and Innovation (STI), under the management of Dominique Guellec. The publication was prepared under the guidance of Claire Jolly, with support in conducting research and analysis from Marit Undseth, Mattia Olivari, Eryi Xu and Anita Gibson. Editorial assistance was provided by Angela Gosmann, STI Publications, and Jennifer Allain, Editor. The report also benefited from contributions from other experts, particularly Hélène Dernis on patents and Brigitte Van Beuzekom on bibliometrics know-how, both from the Economic Analysis and Statistics (EAS) Division in STI.

The team particularly thanks the institutions that are members of the OECD Space Forum for providing instrumental information, data and comments on innovation processes in the space sector. 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 OECD Space Forum workshops. Two international workshops were organised, each gathering up to 100 invited experts: "Innovation and Low-Cost Access to Space" took place on 12-13 May 2016 in Paris and was co-hosted with the UK Space Agency; “Innovation and Downstream Space Activities” took place on 9-10 June 2016 at the European Centre for Space Applications and Telecommunications in Harwell (United Kingdom).

This activity on innovation is part of the OECD Space Forum’s programme of work. The Space Forum was established to assist governments, space-related administrations and the private sector to better identify the statistical contours of the space sector, while investigating the space infrastructure’s economic significance, innovation role and potential impacts for the larger economy. In spring 2016, the Space Forum’s Steering Group included ten members, i.e. space agencies or official bodies in charge of space activities from OECD countries: Agencia Espacial Mexicana (AEM), Agenzia Spaziale Italiana (ASI), Centre National d’Études Spatiales (CNES), Canadian Space Agency (CSA), Deutsches Zentrum für Luft- und Raumfahrt (DLR), European Space Agency (ESA), Korea Aerospace Research Institute (KARI), National Aeronautics and Space Administration (NASA), Norwegian Space Centre (NSC), and the United Kingdom Space Agency (UKSA).

To learn more about the Space Forum’s activities, please visit: https://www.innovationpolicyplatform.org/oecd-space-forum.

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Known for its high technology dimensions, the space sector is currently experiencing an innovation-driven paradigm shift, both from within and outside of the space domain. “New space”, “small satellites for all”, “broadband everywhere”, “space tourism” represent some of these most recent evolutions. But one particular dynamic and transformative factor is the (r)evolution in downstream space applications, attracting new governmental and commercial entrants at both ends of the space sector’s value chains (from satellite and rocket manufacturing to satellite services). The availability of satellite positioning, navigation and timing signals, telecommunications connections in isolated locations and on mobile platforms (smartphones, ships at sea, aircrafts) and the growing access to satellite imagery combined with advances in miniaturisation, computer processing power and analytics are leading to new products and services, as entrepreneurs begin to seize satellite signals and data to create new businesses (e.g. the Pokemon Go application uses satellite positioning).

And while the space sector has also continually contributed to major scientific advances (e.g. discovery of the ozone hole, global monitoring of sea-level rise), developed revolutionary technologies (e.g. accessing space, rovers on Mars, living in space), and even diffused innovations in different sectors via technology transfers and spin-offs (e.g. satellite radar instruments used in medical radiology), it remains risk adverse in some respects, since space systems need to be reliable and durable, stifling sometimes further innovations in the space sector itself. This paradox makes long-term fundamental research and development phases still critical as sources of breakthroughs for future space activities and their many applications.

Against this backdrop, this publication provides an overview of the space sector today and the many policy instruments that support the development of innovative space activities.

Drivers of space innovation

Three overarching thrusts are driving innovation in the space sector and will probably continue to do so over the next decade: the persistence of national security and science objectives with ever-more countries investing in space programmes, the expansion of downstream space applications, and the pursuit of human space exploration. Under these broad overarching objectives, recent innovations in the space sector are driven by evolutions in industrial processes (advanced manufacturing, new processes), often hard-pressed by new commercial entrants, and new technological developments.

A preliminary mapping of space innovation can be drawn by examining the scientific space literature and patents. Key sources of innovation can be identified like small and very small satellites (including cubesat and nanosatellite), electric satellite propulsion, reusable technologies for launchers and satellite navigation applications to name a few. The increasing importance in scientific publications of satellite navigation systems and their many derived location-based and timing services can also be traced to recent patenting activities by commercial actors, demonstrating again that much innovation occurs today in downstream space activities.

When exploring technological trends and the potential of space innovation for the next decades, the space sector seems to be on the verge of starting a new cycle in its development. This cycle could be characterised by the ever-growing uses of satellite infrastructure outputs (signals, data) to meet societal challenges, like helping bridge the digital divide and contributing to mitigate climate change with global satellite monitoring. But in parallel, innovative mass-market products could be on the horizon, a more extensive mapping of our solar system and beyond is already anticipated thanks to new telescopes and robotic missions, new generations of smart-satellites and orbital space stations are envisaged, while a number of commercial space activities could be coming of age (e.g. new human-rated space launchers, in-orbit servicing).

The enablers of space innovation

A variety of actors are involved in the creation and diffusion of knowledge in the space sector. Although business enterprises play a significant role in space programmes in many countries, public research institutions and universities still lead space innovation in a majority of economies, with start-ups particularly active in downstream space applications. Governments are the main funders of science and long term R&D, as well as the main customers for many space-related products and services, via a diversity of policy instruments such as grants, procurement, loans, and tax incentives.

Private sources of investment (seed funding, venture capital, private equity) for some innovative space ventures have been growing, although the amounts still pale as compared to public funding. Crowdfunding, only recently used in the space sector by students raising funds online to develop their very small satellite projects, is a promising financing mechanism, as are challenges and prizes. Some of the prizes' objectives, such as the challenge of landing a commercial rover on the moon by the end of 2017, are attracting entrepreneurs and media attention, but also motivating the established industry.

The uses of public testing services and facilities by diverse governmental, academic and commercial actors are often key enablers of technology prototype development and flight-qualification. These and other clusters, incubators and platforms of co-operation are playing an important role in fostering interactions between very diverse actors, and accelerating the growth and success of entrepreneurial companies.

Policy responses to stimulate space innovation

Policy-makers will have an important role to play in determining what the space sector will look like in the coming decade. Some concrete steps forward are provided below.

- *Review national policy instruments that support space innovation*: the policy instruments that support the development of innovative space activities are often those used for supporting innovation in different high-tech domains (e.g. grants, loans, export credits), but some are more specific to space (e.g. procurement mechanisms, prizes). As national situations differ widely, governments looking to support space innovation trends should review and evaluate existing instruments to determine those most promising with respect to their space programme's objectives. Particular attention should be paid to examining the networks of knowledge diffusion, such as clusters and incubators, to ensure complementarity at regional and national levels.

- *Participate in downstream space activities*: all countries and firms have the opportunity to participate and benefit from the space sector's global value chains, but this situation puts new competitive pressures on governments to adopt reforms that enable start-ups and innovative firms to find or to retain niches in which they may make the most of their capabilities. In this context, 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.

- *Capture spin-offs and technology transfer*s: significant outcomes from government-funded space research have consisted of space technology transfers leading to the development of new commercial products and services in various economic sectors (e.g. transport, health, environment), and the creation of spin-off companies. Agencies should systematically examine and track the spin-offs and technology transfers to other sectors that are derived from space investments. Although their importance as outputs of space missions or programmes should not be exaggerated, they constitute useful pointers. The Space Agencies Technology Transfer Officers group, recently established to exchange best practices, is a positive step in that direction.

Chapter 1.

New trends in space innovation

Known for its high technology dimensions, the space sector can be at times a conservative sector. But it is also currently experiencing a profound transformation driven by innovation both from within and from outside the space domain. This chapter reviews the main innovation characteristics of the space sector, the main drivers for space innovation, then provides policy responses to better monitor and encourage space innovation.

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Innovation characteristics of the space sector

As stated in the OECD Innovation Strategy, “innovation underpins the growth and dynamism of all economies” (OECD, 2015a). The space sector has, over the years, contributed to major scientific advances (e.g. discovery of the ozone hole, global monitoring of sea-level rise), developed revolutionary technologies (e.g. accessing space, rovers on Mars, living in space stations), and even diffused innovations into different sectors via technology transfers. At the same time, the sector has been conservative in some respects, as it has to ensure reliability, durability and cost, sometimes stifling further innovation in the space sector itself. It is currently experiencing a profound transformation driven by innovations both from within and outside the space domain.

Box 1.1. **Defining innovation**

The notion of what innovation is and what role policies can play to encourage innovation has evolved over the past decades. Innovation is a broad phenomenon, with many different features.

The third edition of the *Oslo Manual*, which serves as in international guide for innovation measurement purposes, focuses mainly on business enterprise innovation and defines innovation as the “implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations” (OECD/Eurostat, 2005: para. 146).

But innovation activities are much broader in scope, since innovation activities are “all scientific, technological, organisational, financial and commercial steps which actually, or are intended to, lead to the implementation of innovations. Some innovation activities are themselves innovative; others are not novel activities but are necessary for the implementation of innovations. Innovation activities also include R&D that is not directly related to the development of a specific innovation” (OECD/Eurostat, 2005: paras. 40-42).

The *Oslo Manual* is currently under revision, and its forthcoming edition should go beyond business enterprise innovation and provide guidelines to measure some of these broader innovation activities. In parallel, the newly revised *Frascati Manual* provides already useful definitions and guidelines for specifically measuring research and experimental development (R&D) (OECD, 2015b). It provides guidance and examples on differentiating R&D activities from broader innovation processes, when the objective is to only measure R&D activities (OECD, 2015b: 60-67).

Sources: Adapted from OECD/Eurostat (2005), *Oslo Manual: Guidelines for Collecting and Interpreting Innovation Data*, http://dx.doi.org/10.1787/9789264013100-en; OECD (2015b), *Frascati Manual 2015, Guidelines for Collecting and Reporting Data on Research and Experimental Development*, http://dx.doi.org/10.1787/9789264239012-en.

From research to operations

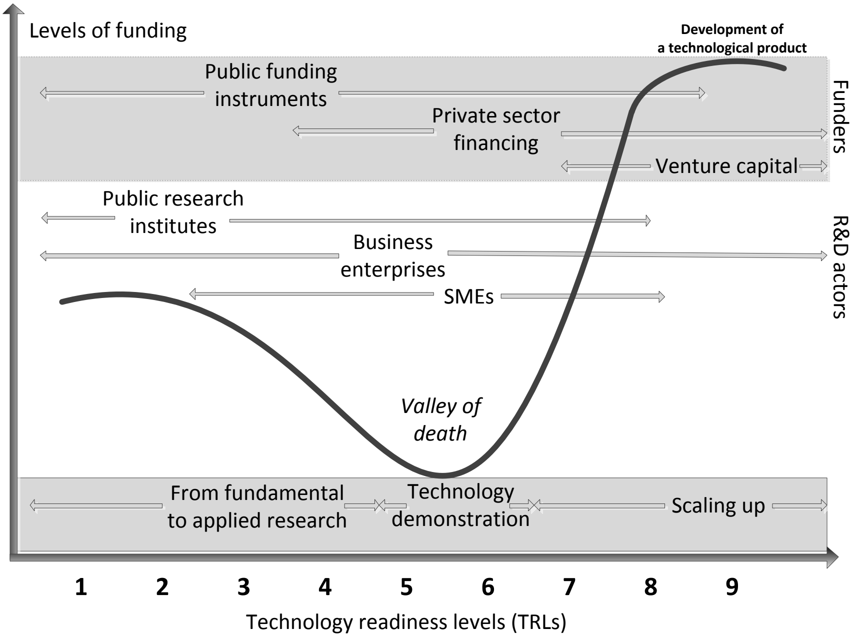
Since the beginning of the space age, space systems have been paradoxical technological beasts: they lead to the emergence of revolutionary technologies during their exploratory and development phases, but once they are operational, the focus often turns to reliability, durability and cost, stifling further innovations by risk adverseness. Situations differ somewhat depending on the systems and the applications, but this paradox makes fundamental research and development phases critical as sources of breakthroughs for space activities and their many applications.

From an engineering point of view, space systems pose tremendous challenges. Space vehicles and instruments are exposed to extreme temperatures, noise, radiation and vibration, both during the launch and in the space environment. A metric called the technology readiness level (TRL) was introduced by the United States' National Aeronautics and Space Administration (NASA) in the early 1980s to assess the risks associated with technology development. Since then, it has become widely used by research organisations and companies around the world to assess the maturity of a particular technology and to allow consistent comparison between different types of technologies. There are variations in the uses of TRL in different organisations and sectors (e.g. oil and gas, nuclear energy), but the same concept of trying to assess technology maturity prevails.

The TRL system comprises nine levels, ranging from 1 (lowest) to 9 (highest, mature technology) (Figure 1.1). Readiness levels 1-4 cover the fundamental and applied research stages. TRLs 5 and 6 involve different degrees of testing, and at the end of TRL 6 the technology or the application is deemed to have a fully functional prototype or run a demonstration phase. In the case of a prototype aimed for a space mission, it is then tested in a space environment in TRL 7, making it a "space flight-qualified" technology in TRL 8 and integrated into an already existing technology or broader system. Once a technology has flown on a successful mission and is "flight-proven", it reaches the final TRL 9.

In the space sector, advancing technologies beyond TRL 6 (i.e. from building a functional prototype to flying it in space, or from developing a functioning space application and expanding its uses after a demonstration phase) is a major maturation step, which also comes at a very high cost. Although it may not be representative of all space projects, the cost of advancing a space technology from TRL 5 to TRL 6 was found to represent nearly four times more than the cost of all the previous TRL advancements combined (Mankins, 2009). This key passage is often referred to as the technology "valley of death". In the private sector, the commercial dimension is added in parallel, whereas each level still characterises the progress in the development of a technology, from the concept to the full deployment of a new product in the marketplace. When a space product or service has been demonstrated, it requires more funding to be fully launched operationally to overcome the valley of death, either via crucial governmental and/or private support.

Figure 1.1. **Simplified overview of technology readiness levels with funding and R&D actors**



Source: Adapted from Mankins (2009), "Technology readiness assessments: A retrospective", http://dx.doi.org/10.1016/j.actaastro.2009.03.058.

In this context, advanced technological developments in the space sector, which may lead to new applications or considerably improve existing ones, still rely on some level of governmental support (Box 1.2). Although there are some exceptions, without the availability of some critical technologies funded by governments and sustained institutional support to cross the TRL valley of death, many applications would not have been possible. This is the case for civil and commercial remote sensing in the 1980s and 1990s. With the Landsat programme in the United States and the Spot programme in Europe, satellites were at the edge of the technical performances of digital sensors that are now used in many different sectors (e.g. medical radiology). This was also the case for the early Global Positioning System (GPS) satellites, which demonstrated for the first time the possibility to use miniaturised atomic clocks in space (with now crucial timing applications used in banking and stock markets). This is not a situation unique to the space sector; the role of governmental support has been demonstrated for many other high-tech sectors, leading later on to mass-marketed products and services (Rose, 1986; Mazzucato, 2013).

Box 1.2. **Justification for government intervention**

Market failure occurs where there are no mechanisms for diversifying or hedging risk and if uncertainty prevails for private investors. In that situation, government intervention in the space sector can be justified by:

1. The inability of private capital markets to finance the development of new technologies. This is typically the manifestation of a market failure based on risk aversion, it is a source of the technology "valley of death" argument (see above), and without funding support, it might remain challenging to scale up space systems or applications to full use.
2. The non-appropriability of the benefits of R&D or innovations by private actors. In many cases, the investment in innovative space activity may not necessarily yield goods, services or industrial processes which can be reserved for the exclusive use of the innovator, even if it is a private entity. This is particularly true for space missions that may include many diverse actors, all benefiting in some ways. But the activity may nevertheless still be valuable enough to attract some private investment, depending in part on the degree to which new products and processes are protectable under the existing intellectual property regime.
3. The distortions caused by existing government policies or regulations that interfere with development of new space technology. This obviously requires adjustment in government intervention, although it is sometimes difficult to pinpoint which policies or instruments work best or are detrimental.

Source: Adapted from Rose (1986), "The government's role in the commercialization of new technologies: Lessons for space policy", http://economics.mit.edu/files/10556.

Balancing reliability issues and breakthroughs

Most space systems and applications are designed from the start with a view to reliability and durability, with as little technical uncertainty as possible. This is true for scientific and space exploration missions, as well as for commercial satellites (e.g. typically commercial telecommunications satellites costing several hundred million dollars apiece) (Box 1.3).

Box 1.3. **An illustration of a conservative space sector approach**

Since the very early years of spaceflight, the space manufacturing sector has been a highly specialised industry, with a particular emphasis on precision and verification procedures, and an extremely low tolerance of risk and error. Based on the decades-long investments needed, only a few countries in the world have the technology and facilities to carry out an orbital space launch, or to maintain a fleet of operational launchers (United States, Russian Federation, People's Republic of China [hereafter "China"], Japan, India, Israel, Islamic Republic of Iran and Korea) and the European Space Agency (ESA). Production volumes have traditionally been low, with an average of 70-100 space launches per year. Within this specific context, satellites and expendable launchers have, in practice, been treated like prototypes. Space launchers, for example, have been historically very much technology-driven during development phases. This led to breakthroughs in specific technologies, such as propulsion systems (e.g. new rocket engines) and structures that determine the performance of the launching systems (e.g. uses of composite materials). Other evolutions include the development of fully reusable space launch systems, which would allow the reuse of rockets, following the model of aeronautics. Still, until very recently, relatively few technological breakthroughs have occurred in civilian and commercial access to space. Competition has hardened with more companies entering the relatively small market for commercial launches (around USD 2.5-3 billion a year). Overall, rockets have not evolved dramatically since the 1980s and their robustness has contributed to ensure the successful launch of hundreds of satellites. Once a launcher is operational, after one or two decades of R&D, any major change in subsystems that could create the risk of failure is typically avoided. As a result, after a few years of operation, electronic systems may seem outdated compared to new state-of-the-art electronic technologies. Until recently, despite much R&D in specific fields (propulsion, reusability), only incremental advances were included in most of the operational launchers, without many impacts on costs. In 2014, India joined the handful of countries mastering cryogenic rocket technology for example. This advanced type of rocket engine uses liquid hydrogen and liquid oxygen, and is more efficient than more conventional liquid and solid fuels, allowing it to deliver heavier satellites into orbit. Only the United States, the Russian Federation, France, Japan and China, the ESA and now India have the capabilities to perform similar launches so far. So although sustained R&D has been continuing around the world to eventually lower the costs of access to space, the situation has radically changed only very recently with the first successful commercial flight of the then-newcomer SpaceX in December 2013.

The space sector fosters major advances, improving existing space systems (see drivers for R&D in Table 1.1) and diffusing innovations in different sectors (see Chapter 2). At the same time, it needs paradoxically to be conservative in some respects and risk adverse, since it relies on proven and sometimes quasi-outdated systems to ensure constancy for some space missions. As the space sector becomes an essential provider of public and private infrastructures, with growing public, commercial and citizens' reliance on satellites' signals and data, a difficult balance needs to be found between fostering innovation and ensuring stable and durable systems.

Table 1.1. **Selected space programmes and their R&D drivers**

Selected programmes	Main features	Drivers for R&D
Public good infrastructure		
Weather Climate monitoring Navigation Disaster management	– Long-term and guaranteed service needed (> 20 years) – Often public infrastructure financing with delegated exploitation	– Improved scientific instruments – Advanced ground computation – Often, available services have to be tied together by appropriate merging technologies
Commercial services		
Broadcasting (television via satellite) Broadband Mobile telecommunications Location-based services and traffic management Commercial remote sensing	– Global financial and insurance arrangements dictate schedule for early return on investment – Typically 3-4 years from kick-off to launch – Constellation build-up over several years, from a few to several dozens of satellites	– End-to-end turn-key approach for customers – Commercial services are "fully digital" (digitalisation) – Interface with diverse terrestrial devices, platforms (standards) – Powerful on-board satellite digital signal processors for simpler user-end – Use of higher frequencies – Ground stations for constellation control
Science and exploration		
Astrophysics Moon/Mars exploration Human spaceflight	– 8-10 year cycle typical for large space agency missions – Public funding from R&D budgets – Often international programme setup	– Usually technology demonstrators on major scientific missions – Very demanding developments in all technical fields – Technology-push approach – Mission success oriented – High human/machine interactivity
Space transportation		
Expendable launchers Future reusable systems	– 10-20 years of development – Operational flexibility – Guaranteed availability	– Improved propulsion – Reusability of subsystems and entire launchers – New materials
Human spaceflight		
Space-based infrastructure Passenger transportation Logistics, payload support	– Traditional reliance on public funding for R&D – Long development time – Indefinite system lifetime	– Safety (very high reliability) – Maintenance and reconfiguration of elements – Design update during lifetime – Habitability

The drivers of space innovation

Systems of innovation are dynamic by nature according to Schumpeter, one of the major theorists of innovation (Schumpeter, 1947), and the space sector is currently facing a paradigm shift, like many other economic sectors. Innovations are currently taking place throughout the space sector's value chain, from fundamental research to distanced applications, like groundbreaking mass-market uses of satellite signals in smartphones. A combination of factors is leading these evolutions. This section first reviews the major overarching thrusts for space innovation; then the new state of affairs in industrial processes and technologies, with the involvement of non-space actors; and finally the key role of downstream space applications in pushing for ever-more innovation.

Major overarching thrusts

The space sector is facing a new cycle in its development (Table 1.2). Three overarching thrusts are driving innovations in the space sector and will probably continue to do so over the next decade (as Chapter 4 demonstrates by exploring future trends in the space sector): the persistence of national security and science objectives, the expansion of downstream space applications, and the pursuit of human space exploration. One undetermined factor will be the role of commercial actors in leading efforts in human space exploration.

More governmental research for national security and science. Since the beginning of the space age, geopolitical considerations have played a dominant role in shaping space programmes. This is likely to continue into the future. As is the case in other high-tech sectors, the role of governmental research for national security reasons will remain a major source of future innovations that will eventually trickle down into the civilian and commercial domains (Chapter 3 details the performers of innovation). Many of the known (unclassified) programmes in OECD countries all point to potential breakthroughs over the next decade in terms of ever-improved satellite data analytics and space access, as space technologies converge with other advances in information technologies, materials, robotic, and artificial intelligence, to name a few. Science and space exploration supported by governments should also remain key drivers for much of the fundamental space research and R&D. Space missions bring also national prestige and technological know-how (e.g. spin-offs, discussed in Chapter 2). Space telescopes and robotic exploration have already considerably increased our understanding of the universe and of the Earth itself.

Table 1.2. **Cycles of space development**

Cycles	Dates	Description
Pre-space age "-1"	1926-42	First rockets (from Goddard to the V2)
Pre-space age "0"	1943-57	Military race for intercontinental ballistic missiles, first satellite on orbit (i.e. Sputnik)
Cycle 1	1958-72	Space race (from Sputnik to the end of the Apollo era), beginning of military applications (e.g. spy satellites), humans in space, robotic space exploration
Cycle 2	1973-86	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, China [People's Republic of], Japan)
Cycle 3	1987-2002	Second generation of space stations (Mir, ISS), stronger role of space applications in militaries, strong development of civilian and commercial applications
Cycle 4	2003-18	Ubiquitous use of space applications in various fields thanks to digitalisation (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	2018-33	Growing uses of satellite infrastructure outputs (signals, data) in mass-market products and for treaties' global monitoring, 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 (2004), *Space 2030: Exploring the Future of Space Applications*, http://dx.doi.org/10.1787/9789264020344-en.

The expansion of downstream space applications. Further development of space applications will be pursued to solve problems on Earth and/or to make a profit. Civil and commercial space systems have seen an exponential expansion all over the world, with sophisticated and diverse applications, as many space technologies have been gradually transferred from scientific and military applications to civil and commercial ones. Recent innovations, like small satellites development and enhanced uses, are only starting to impact the value chains in space manufacturing, contributing to develop cheaper access to space solutions, and possible new mass-market downstream applications (e.g. live video feeds from space). Although competing terrestrial technologies may affect the uptake of some applications (e.g. fibre rollout in selected large cities), the advances in digitalisation and further technology convergence could contribute to bring about new applications (e.g. building on the expected user-centric 5G mobile telecommunications standards). A section later in this chapter is devoted to this (r)evolution in downstream space applications.

Humans in space. Although criticised at times for its high costs, many regard the exploration of space by humans as another foremost thrust of future space programmes and innovations. One major change, as compared to only a decade ago, is that such a vision is not only articulated by scientists in space agencies with more or less support from policy makers, but it is also an objective of some entrepreneurs and large commercial firms. NASA's concept of the low Earth orbit economy (i.e. the "LEO economy") envisages a possible strong role of the private sector in developing future human spaceflight activities in orbit, with a major role for space agencies in building the technological blocks for human exploration beyond the Earth's orbit (NASA, 2016). As part of this vision, NASA's Space Launch System (SLS), a heavy-lift launcher (the largest rocket ever built), and its Orion capsule are under development, with the aim to launch humans by the mid-2020s on missions to an asteroid and eventually to Mars. In parallel, several long-term space exploration proposals call for setting up permanent scientific and commercial outposts on the Moon (e.g. the ESA's suggestion for a Moon village by 2040) and landing eventually humans on Mars. As Earth's orbit, and potentially the Moon, continue to serve as test-beds for human spaceflight programmes in the next decade (e.g. space stations, new human-rated launchers), with strong necessary institutional involvement, some commercial ventures may also make their mark, before future attempts to reach asteroids and Mars.

Industrial processes and technologies

The sources of innovation in the space sector can be traced to recent evolutions in industrial processes (advanced manufacturing, new processes) and technologies. A brief summary of these trends is provided below.

Advanced manufacturing. Technological advances in materials and advanced manufacturing techniques are gaining ground in the space sector. One example is the increased interest in additive manufacturing technologies, such as 3D printing and direct-write processes. Different manufacturing techniques are already in use in the space sector, mainly to fabricate models and prototypes, but increasingly also to produce space-related components on active missions. Preliminary experiences indicate significant cost and time savings. This is also an interesting technology for future space exploration, where one could imagine 3D printing of spare parts and other equipment directly in space. Experiments with plastic 3D printing have already taken place on the International Space Station to test the technology in a micro-gravity environment. Constructing 3D-printed habitats with materials that can be found on Mars was one recent NASA Centennial Challenge, where monetary prizes are offered to teams that come up with the best ideas. Another additive manufacturing technology is direct-write processes with conductive materials, which makes it possible to deposit sensors or antennas directly on the surface of the equipment, including hard-to-reach places, which would again lead to reduced weight and improved functionalities.

Box 1.4. The rise of small satellites

The last five years have witnessed the start of what could be a revolution in the design, manufacture and deployment of satellites. Small satellites, weighing less than 500 kilogrammes (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.

Small satellites are finding use across a wide range of applications – from Earth observation and communications to scientific research, technology demonstration and education, as well as defence. 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). Since the first CubeSat launch in 2002, the number of very small satellites sent into orbit has increased at a remarkable rate. Recent advances in miniaturisation and in satellite integration technologies may significantly increase the functionalities of nano- and microsatellites and greatly extend their possible field of application (NASA, 2014). Constellations of small and very small satellites appear to be on the verge of scaling up very significantly, although business plans may still need some elaboration.

Whereas small satellites may in some regards be seen as a low-cost alternative to bigger, traditional satellites (although increasingly performant), the very small satellites have a completely different business model. The plan for current developers is to fly them in big constellations in low-Earth orbit, where frequent revisit times allow almost real-time monitoring and communications (e.g. real-time video from space). The technology can be upgraded and replaced quite often, because of short development and production times, as well as the short mission life. Launch and mission failure risks can be mitigated by using multiple launch vehicles, from multiple vendors, and placing more satellites than necessary in orbit. The value lies in the terrestrial processing and distribution of the data. Currently, most commercial constellations have optical sensors for Earth observation, but an increasing number carry an automatic identification system receiver, which allows for tracking of localisation data of ships carrying a transmitter worldwide. Planned satellites have infrared and hyper-spectral sensors. GPS-occultation technologies may soon be used for commercial weather forecasting (e.g. Spire).

New industrial processes. Although often deemed conservative, most organisations involved in space programmes regularly update their industrial processes to take advantage of processing efficiencies to reduce production costs. Several successful high-tech simulation systems or computer aided design (CAD) software were developed in the aerospace industry in the 1990s and then were transferred to other sectors (Young and Hirst, 2012). But the main game-changer in recent years is the influence of new entrants, hard-pressing new processes for space manufacturing throughout the industry. To lower the costs of production, adaptation of new industrial qualification procedures are being pursued, using existing experience and data from high-volume industries, typically from the automobile and aeronautics industries, to mass produce spacecraft and launchers. This process has been promoted by SpaceX, a California-based US company founded by the billionaire Elon Musk (also founder of the PayPal and Tesla companies). This relatively new entrant in the space manufacturing industry was at first not taken seriously by incumbents, before imposing a model followed by many of them. The production is based on vertical industrial processes (i.e. more than 70% of each Falcon launch vehicle is manufactured at the SpaceX production facility), and mass production inspired by the automobile sector, not used before in the space industry. It has also benefited from supportive US institutional grants and then procurement to develop the activity. The company's fabrication volumes keep increasing, with production to grow more than five times year over year, with two Falcon rocket cores produced in 2012, and 17 produced in 2015. The resulting rocket systems have been tested and are now regularly launching satellites for commercial and governmental customers. The company's factory is configured to achieve a production rate of up to 40 cores annually (OECD, 2014). As a comparison, two to eight rockets are produced per year in other organisations (e.g. six launches of Ariane 5 in 2015), which has been until recently more than enough to cover institutional and commercial demand for access to space. The exceptions are China and India, where the number of satellite launches with indigenous rockets have accelerated in recent years.

This success has shaken the industry and other actors are adapting to this new competition. The US manufacturer Blue Origin plans, for example, to produce its entire space vehicle at its new production facility in Florida, with the exception of the engine, which is produced at a different location. The joint venture of Airbus and Safran, which will be producing the future European Ariane 6 and light launcher Vega-C with Arianespace, will also be consolidating its production supply chain, which is currently spread across 25 different European industrial sites. Other manufacturers, in contrast, are spreading out their supply chain, using cheaper international suppliers to cut costs, despite higher risks of delay (US Department of Commerce, 2014).

New industrial processes are also affecting the design and manufacture of satellites. Small satellites in particular benefit from advances in miniaturisation technologies (Box 1.4). Larger satellites still have a major role to play, as they carry more instruments and have longer lifetimes, which allows important commercial and governmental missions to be carried out. However, recent advances in miniaturisation and satellite integration technologies have dramatically reduced the scale of the trade-off (NASA, 2014).

Space technologies. Many specific developments in space technologies seem to have accelerated in the past three years and more breakthroughs may be on the horizon:

- Reusability of space systems: Space systems reusability may be on the verge of becoming a reality. Several companies are in the testing or planning phase to recover and reuse the most valuable parts of their launch vehicles. For example: the vertical landing of first stage engine and reuse of entire launcher stages (SpaceX, Blue Origin); the horizontal landing of first stage (Arianespace's Ariane 6); or incremental and partial first-stage recovery and reuse of the first-stage engine power plants (United Launch Alliance). Ongoing efforts are also taking place in governmental programmes, with India's winged reusable launch vehicle technology demonstrator, which realised its first supersonic flight; the US Air Force's X-37B spaceplane programme, with already more than a year in orbit; or DARPA's reusable spaceplane XS-1 programme with a planned 24-hour turnaround time, with a flight potentially in 2020.
- Electric propulsion: Another trend is the increased use of electrical satellite propulsion on commercial satellites. In-space electric propulsion for satellites and space exploration probes has been the focus of targeted R&D efforts for decades, and the technology is now becoming economically viable on commercial telecommunication satellites. Electric propulsion considerably lowers mass formerly occupied by chemical fuel and frees space for more transponder capacity or other instruments, in addition to allowing the use of a smaller and cheaper launch vehicle. Different electric propulsion technologies have been used for decades, either in combination with chemical propulsion or as main propulsion on explorative probes. This was first used on NASA's Deep Space 1 launched in 1998. The downside is that its thrust is less powerful, so that orbit-raising with electric propulsion lasts months instead of weeks, which had, until recently, disqualified it for commercial operations. The biggest satellite manufacturers in the United States and Europe now all propose partial or all-electric propulsion solutions, with both Boeing and Airbus being contracted for five satellites each as of spring 2016. In addition, the 648 planned satellites in the forthcoming OneWeb constellation, which Airbus will be producing, will be all electric.

- In-orbit servicing: Several governmental agencies and commercial companies have developed, or are in the process of acquiring, some capabilities for in-orbit servicing. 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, the Russian Federation and the United States. 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 International Space Station (ISS) in 2016. In terms of in-orbit refuelling, some long-term R&D programmes are underway, supported increasingly by satellite communication operators as final customers. They have 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, 2016). 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. Advances in this area are promising for future commercial in-orbit servicing ventures and orbital space debris cleaning initiatives, but they also cause some security concerns.

The (r)evolution of downstream space activities

Advances in computer processing power and analytics are contributing to a string of innovations at the end of the space sector's value chain: a real (r)evolution in downstream space applications. Innovative and sometimes baffling uses of satellite signals and data by entrepreneurs are contributing to create new businesses (e.g. the successful Pokemon Go smartphone application uses satellite positioning). The availability of satellite positioning, navigation and timing signals, telecommunications connections in very isolated places and on mobile platforms (ships at sea, aircrafts), and the growing access to satellite imagery is leading to new innovations in products and services, like never before. None of these downstream products and services would function without satellite signals or data (Box 1.5).

Some 14 years ago, GPS devices were expensive, often costing several hundred US dollars for the most advanced ones (OECD, 2004). Today, location information derived from satellite data has become more of a feature than a stand-alone product. Services and technology are constantly evolving and becoming integrated in smartphone applications and other mobile devices. In the case of satellite imagery, it has become possible in only a few years to develop thousands of new applications, thanks to faster computer processing, cloud computing, allowing the handling of very heavy datasets and machine learning techniques. In terms of satellite telecommunications, operators are competing to make their networks ever more accessible and to tailor connectivity for their customers' needs. Some are providing tools, like application programming interfaces, to help developers create new applications using satellites capacities (Soumagne, 2016). Although expertise is still essential to make sense of the diversity of existing data, the digitalisation tools that have become available to even small companies are game changers.

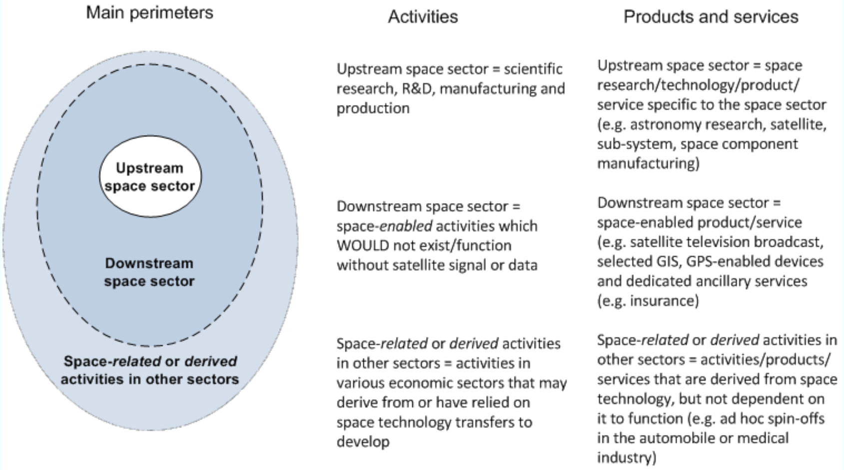
The innovators that make use of satellite capacity in the downstream community are increasingly thriving on mobility needs and new digitalisation tools. Based on a very preliminary mapping of downstream space activities (OECD, 2016), some of the most active companies using satellite data for their business do not own large infrastructure. They rely on analytics, quasi real-time big data, including satellite data, and visualisation tools for their businesses. They invest time and money in developing and sustaining entire communities of users, and creating new business models.

The successful commercialisation of their products and services depends indeed on inventing constantly new products or improving existing ones, but also on other complementary capabilities in design, marketing, production and distribution. As an illustration, the company Democrata Maritime was founded in 2014, and supported by one of the European Space Agency's business incubation centres (BIC). It relies on constant streams of satellite data and it developed original algorithmic models to provide customers in the shipping and insurance industry with information to help them measure and insure against collision risks and other risks at sea (Marine Traffic, 2016). Although registered as a data processing company under the standard industrial classification codes, and not at all as a space firm, the company would not function without satellite capacity.

Box 1.5. **Defining the space economy**

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 research 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 the economy and society. Following a large international consultation in 2015-16, three main space economy perimeters were identified. The approach received broad international support from administrations and space industry players in helping classify activities and allowing better international comparisons, even with existing data available. There are three main perimeters that irrigate each other (Figure 1.2).

Figure 1.2. **Defining the perimeters of the space sector and its derived activities**



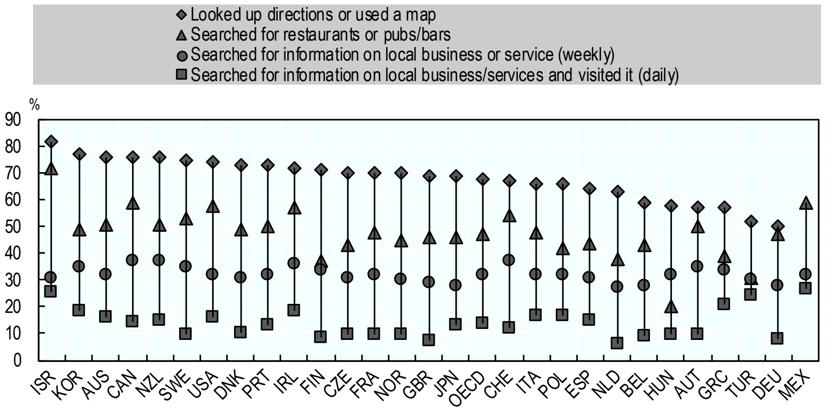
Activities	Products and services
Upstream space sector = scientific research, R&D, manufacturing and production	Upstream space sector = space research/technology/product/ service specific to the space sector (e.g. astronomy research, satellite, sub-system, space component manufacturing)
Downstream space sector = space-*enabled* activities which WOULD not exist/function without satellite signal or data	Downstream space sector = space-enabled product/service (e.g. satellite television broadcast, selected GIS, GPS-enabled devices and dedicated ancillary services (e.g. insurance)
Space-*related* or *derived* activities in other sectors = activities in various economic sectors that may derive from or have relied on space technology transfers to develop	Space-*related* or *derived* activities in other sectors = activities/products/ services that are derived from space technology, but not dependent on it to function (e.g. ad hoc spin-offs in the automobile or medical industry)

As another example, an increasing number of start-ups and established consulting firms in North America are now regularly producing early predictions of yield across a range of crops, using satellite imaging, weather and climate data, and powerful machine learning algorithms. They sell their forecasts to hedge fund managers, livestock feeders or to businesses linked to individual farmers.

Box 1.6. **Successful location-based services**

A majority of economic sectors are now impacted by the development of satellite navigation technologies, with location-based services. Receivers are found in all kinds of electronic devices for everyday use such as mobile phones, personal digital assistants, cameras, portable PCs or wristwatches. As applications are accessed over mobile networks and used together with other services in a single interface, standards and potential for integration are major success factors. For applications developers, the ability to interface with a variety of devices allows access to new markets and business segments. The growing uses of open sources are also contributing to the development of location-based services and lowering costs for the users, who create additional functionality at little cost to the original developers and provide feedback for improvement.

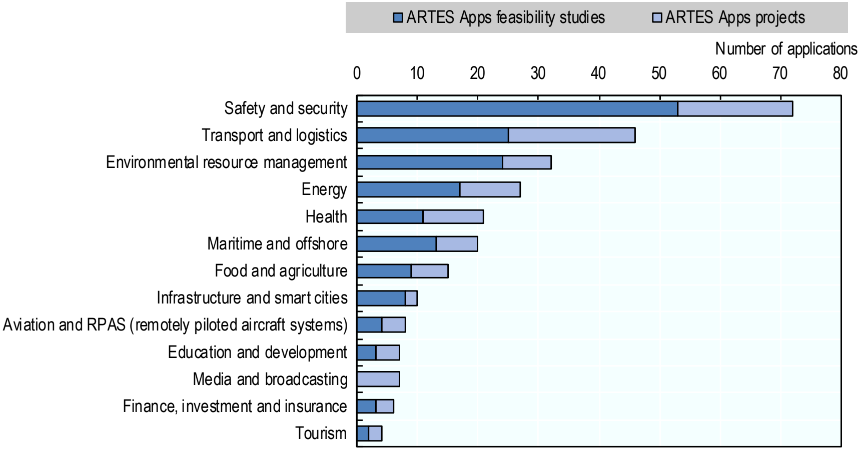
Figure 1.3. **Use of location-based services on smartphones, 2013**



Source: OECD (2015c), *OECD Digital Economy Outlook 2015*, http://dx.doi.org/10.1787/9789264232440-en.

In terms of satellite telecommunications, many important developments are ongoing in the space sector (see also Chapter 4), including in the diffusion of innovations to other sectors. At the European Space Agency, the Advanced Research in Telecommunications Systems (ARTES) programme, based on co-funding of projects by public and private actors, has led to many innovative applications (ARTES Apps) in a wide diversity of economic sectors (Figure 1.4). Out of the 192 downstream projects developed so far under ARTES, 40% reached successful commercial exploitation, 18% became operational but were not commercialised, and almost a quarter did not have any follow up. The rest is still at the seed stage (Vaissière, 2016).

Figure 1.4. **Sectors impacted by innovations in satellite communications**



Source: Vaissière (2016), "Promoting space applications: ESA lessons learned".

But in addition to new businesses, one very important trend in new downstream space activities is the increasing uses of satellite-based information. Access to satellite-based information opens the door for new unexpected uses. In 2015, reporters investigated the links between illegal fishing in Asia and the supply of seafood to American supermarkets and restaurants. They found that slave labour was extensively used for fishing operations (McDowell, Mason and Mendoza, 2015). In order to identify and actively track the ships and the locations where slaves were kept, they combined precise high-resolution satellite images to detect small fishing vessels (i.e. analysing images of 31-centimeter resolution) with their ground-based investigation. In the end, their reporting contributed to freeing more than 2 000 slaves and to bringing perpetrators to justice in Indonesia. For this original reporting, the journalists earned the Pulitzer Prize in 2016 (Werner, 2016).

One business opportunity, as well as a challenge for all these downstream firms, will be to harness future data management challenges. Big data refers to the amount, complexity and variety of digital data generated from an ever-growing number of sensors and devices, as well as the technologies used to manage and generate value from this data, e.g. for processing, storage, distribution, analytics, etc. (OECD, 2015d). The volume and variety of data generated from increasingly performant satellite instruments (i.e. Earth observation and navigation satellites), and a growing number of sensors and devices, pose the same challenges as in other sectors in terms of processing and storage, most concretely, but also in distribution and analysis. Furthermore, with the growing importance of timely, and in some cases real-time data flows, the rapid down- or uplink of information, as well as processing and distribution, will be equally important, and essential for commercial sustainability. The ever-improved machine-to-machine communications with fixed or mobile devices (e.g. boats, pipelines, oil wells) should provide new business opportunities.

Policy actions to support space innovation

Despite decades of breakthroughs, continued innovation in the space sector is not a guaranteed phenomenon, it needs support. This calls for policy actions, so that developments in the space sector may bring more benefits to society at large. This section reviews space's relevance in different science, technology and innovation policy objectives. It then summarises trends that are expected to drive further innovations, and finally provides a set of recommendations to improve the monitoring of space activities and policies.

Space in innovation policies

Space policies are part of a much larger framework of science, technology and innovation policies. Although space programmes have developed following their own specific national preconditions (e.g. strategic priorities, availability of funding and human resources), the inclusion of the space sector in innovation and industrial policies has been progressive and stimulated by successive trends in science and technology policy objectives, which still coexist today. The resulting "policy mix" reflects governments' efforts to respond to national and international challenges over time (OECD, 2015a). As governments seek to develop key enabling technologies, a strong innovation system encompassing different sectors and able to respond to societal challenges through science and technologies, space will continue to provide relevant input to different complementary national policies.

Mission-oriented policy. Mission-oriented policies have been the starting point of most space programmes around the world. After the Second World War, most research and technology policy in OECD countries focused on large-scale technologies requiring major technical infrastructures, long project timelines and significant budgets, like nuclear energy or space programmes to respond to specific missions. Still today, national security missions inspire much space innovation, because of strong requirements from defence actors (see Chapter 3 for the role of public research institutes). The dual use concept and the transfer of military technology to civilian fields of application arose much later. For example, the satellite Global Positioning System (GPS) was developed originally for the US military and has now become indispensable for many different economic sectors (e.g. transport, banking).

Key enabling technologies development policy. Funding the development of key enabling technologies became a fundamental pillar of research and technology policy in OECD countries from the 1960s. And space technologies became an increasing part of the portfolio of attractive technologies for an increasing number of countries. Key enabling technologies are often linked to industrial policies, as they are thought to bring significant impacts on productivity and competitiveness.

Innovation system policy. This approach, developed in the 1980s-1990s, takes a more holistic view, linking innovation with economic growth, international trade, and with a focus on the networks and growing linkages between very different actors. Freeman and Lundvall at the OECD coined the term National System of Innovation (Freeman, 1995). The importance of framework conditions favourable to innovation, set by the state (including policies related to employment, tax, product-specific regulations) became more evident (Meissner, Polt and Vonortas 2016). For the space sector, this came at a time of major changes with the end of the Cold War, facilitating technology transfers amongst countries and firms, the privatisation of large satellite telecommunication public operators in the United States and Europe, and the expansion of profitable commercial space applications, like satellite television. Although not a business like any other, space started to find its place in broader innovation policies.

Responding to societal challenges. Finally, in the past decade, research and innovation policies in OECD countries have added another layer, with the objective of responding to major societal challenges. Most of these challenges are common to countries around the world (e.g. climate change mitigation and adaptation, mobility, demography, migration, health and well-being), even if they may be considered with different levels of priority. Science and technologies then have a role to play in solving societal problems, and, as a consequence, science and research programmes are under pressure to provide solutions. Applications derived from past space investments are, in many cases, well placed to respond to many of today’s challenges (OECD, 2005). Satellites contribute valuable data and communication links around the world (e.g. more than half of the essential climate variables are derived from satellite data). As part of the changes seen in many countries, potential users of the technology, particularly stakeholders from very diverse policy areas (environmental policy, social or health policy, etc.) are ever more included in the selection processes concerning some specific space R&D programmes. The aim is to accelerate as much as possible the broad diffusion of the “space solutions” to very wide communities, even if the solution is only incremental and brings only at first small improvements.

In alignment with national innovation and industrial policy frameworks, many countries have revised or established national space policies over the years. The scope and approaches of space policies varies considerably across countries, with some countries applying a more top-down approach, building on active government participation, while others choose a more piecemeal, bottom-up approach focusing on business capabilities and needs. These space strategies are generally closely related to objectives of national security and depend to a large extent on domestic science and technology capabilities and geography (e.g. Canadian Space Policy Framework, 2014; Norway's white paper "Between heaven and Earth: Norwegian space policy for business and public benefit", 2013). Hence, maintaining independent access to space remains a priority for several countries (e.g. China, France, India, Korea, the United States), while others focus on specific geographical reasons for exploiting space technologies for government use (e.g. monitoring of large landmass or marine resources using space assets in Canada and Norway) and for creating business opportunities (e.g. favourable location for launch or satellite tracking in Australia and Brazil, entering global value chains for Mexico).

A growing focus concerns the development of downstream applications with specific policy actions (e.g. China, France, Germany, Italy, the United Kingdom). In Italy, the newly created Cabina di Regia Spazio, a co-ordination body set up by the Presidency of Council of Ministers, in collaboration with the Conference of Regions and Autonomous Provinces and the Italian Space Agency, launched in spring 2016 a Space Economy Strategic Plan (Bartoloni, 2016). The objectives are to develop the adoption and use of space systems, products and services by Italian authorities and in new markets. Under this national strategy, Italian regions have the tasks to launch regional support policies, with co-funding from the national development and cohesion policy funds. Public demand for commercial products in Italy is to be supported through pre-commercial procurement mechanisms and new public-private partnerships. In China, the State Council released in March 2016 its 13th Five-year Plan (2016-20), which is the country's top-level social and economic development plan (China's State Council, 2016a). Specific references to space activities and space applications are mentioned throughout the different underlying layers of different national strategies (e.g. China's Innovation-Driven Development Strategy; Made in China 2025 Policy; China's Strategic Emerging Industry Development Plan; Military-Civilian Deeper Integration Development Strategy), with the aim to encourage further Chinese space developments (e.g. more fundamental research to lead to space innovation, increased R&D intensity of state-owned enterprises, more patents by public research institutes, set-up of new incubators within diverse high-tech clusters). A strong focus is put on facilitating technology transfers of defence-funded space programmes for civilian use, and space technology transfers to non-space sectors to create new Chinese commercial products (e.g. speed the integration of Chinese satellite navigation signals in new mass market applications) (China's State Council, 2016b).

Box 1.7. **The multiplication of national space agencies**

The establishment of a national space strategy often brings with it a need for a specific governmental body to ensure policy implementation. In the last ten years, there has been a growth in the number of government agencies or offices entirely dedicated to space activities, such as the UK Space Agency (UKSA), the Mexican Space Agency (AEM) or the South African National Space Agency (SANSA), all established in 2010. The United Arab Emirates established the UAE Space Agency in 2014 and the Mohammed Bin Rashid Space Centre in 2016 (UAE Space Agency, 2016), with the aim to develop Earth observation satellites, cubesat demonstration missions and the first space exploration mission to Mars to be carried out by a middle-eastern country (i.e. scientific probe to Mars by 2021). Denmark established a space office within its agency for science, technology and innovation in 2016. Turkey may establish a space agency by late 2016. A number of eastern European countries are also setting up frameworks for their space activities within their national strategies and space offices, often in combination with increasing co-operation with or adherence to the European Space Agency (Czech Republic, Estonia, Poland). Some countries have introduced bodies to improve transversal co-ordination across government ministries (Australia, Canada, Italy, Japan), while France, Italy and the United Kingdom have created co-ordination structures incorporating public actors and industry.

Recommendations for improving the monitoring of space activities and policies

Policy makers will have an important role to play in determining what the space sector will look like in the coming decades, as they can use a number of policy levers to shape the sector's development (see Chapter 3 for an analysis of policy instruments). The space sector can benefit from supply-side innovation policies (i.e. aimed to provide incentives to firms undertaking R&D and innovation), as well as increasingly from demand-side innovation policies (i.e. established to stimulate innovation in areas where societal needs are pressing). In today's context, some concrete steps forward are provided below, to help accompany and support developments in the space sector that may benefit the most actors:

- **Reviewing national policy instruments that support space innovation:** This publication provides an overview of many of the policy instruments that support the development of innovative space activities (see Chapter 3). These instruments are often generic, and are used for supporting innovation in different high-tech domains, but some are more specific to space (e.g. procurement mechanisms). Policy instruments require regular evaluation to ensure that the expected outcomes are reached, and this is also true for instruments targeted at developing innovation in the space sector. Since national situations differ widely, governments willing to take advantage of space innovation trends should not only map and review existing instruments, but also evaluate the ones that are the most promising depending on their space programme's objectives (e.g. level of space investments, role of public administrations and businesses in value chains). Particular attention should be given to examining the networks of knowledge diffusion, such as clusters and incubators, to make sure the right tools to support innovation are complementary at regional and national levels.

- **Capturing downstream space activities:** All countries and firms have the opportunity to participate and benefit from global value chains and innovation in the space sector, particularly in downstream space activities. However, this situation puts new competitive pressures on governments to adopt reforms that enable start-ups and innovative firms to find or to retain niches in which they may make the most of their capabilities. In this context, governments which fund space programmes should better track and measure who is doing what in the space industry and beyond, via regular industry surveys and analysing existing administrative data. This includes mapping the many actors along the value chains in their national space economy.

- **Spin-offs and technology transfers:** The diffusion of space innovation in different sectors is difficult to quantify, although it has been captured by different indicators over the years (see Chapter 2). Significant outcomes from government-funded space research have consisted of space technology transfers leading to the development of new commercial products and services in non-space sectors, and the creation of spin-off companies. Agencies should systematically examine and track the spin-offs and technology transfers to other sectors that are derived from space investments. Although their importance as outputs of space missions or programmes should not be exaggerated, they constitute useful pointers. The Space Agencies Technology Transfer Officers (SATTO) group, established in 2015 to exchange best practices, is a positive step in that direction.

The OECD is already working in co-operation with the space community and beyond on these important topics and will continue to do so.

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Chapter 2.

Mapping space innovation

Innovation activities are diverse, complex and challenging to measure in a quantitative way. This chapter maps knowledge flows and innovation in the space sector in an original way. The analysis builds on new OECD indicators using bibliometrics and patents, examining scientific production in space literature (what are the hot topics in the literature?), looking at the globalisation of space innovation (who publishes and co-operates with whom?), and exploring the diffusion of space innovation in different sectors.

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

Innovation activities are diverse, complex and challenging to measure in a quantitative way. Still, this chapter provides original OECD indicators on space innovation using bibliometrics and patents. The analysis of scientific literature production and patents are two useful, although imperfect, ways of measuring innovation activity outputs in the space sector (see Box 2.1 for methodologies).

Box 2.1. Tracking space innovation with bibliometrics and patents

Bibliometrics indicators provide useful information on knowledge production and innovation diffusion in specific fields, including space technologies. The analysis is based on data related to scientific publications contained in the Elsevier's Scopus Custom Data (Scopus Custom Data, Version 4.2015). The Scopus database is a global database of peer-reviewed scientific articles, with bibliographic 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). The dataset established for this analysis includes papers from all journals in the space and planetary science classification (ASJC code 1912). It further includes a selection of relevant journals belonging to the aerospace engineering field (ASJC code 2202) and journals dedicated to specific space applications (e.g. GPS, GNSS, satellite remote sensing and navigation). In total, a selection of 124 journals over the period 1999-2014 forms a space journals database (the "space literature") to include only publications relevant to space activities (e.g. space sciences, technologies, satellite communications). One limitation is the non-inclusion for this analysis of many journals which may still feature space applications (e.g. satellite earth observation for environmental monitoring, agriculture, transport). This will be an area for further OECD research. 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 data include scientific publications in English (the majority) as well as other languages.

Space-related patents are identified using a combination of codes from the International Patent Classification (IPC) and key word searches in the patent title. IP5 patent families are families of patents filed in at least two intellectual property (IP) offices. In addition to being filed nationally, they must also be filed in one of the top patenting offices worldwide: the European Patents Office (EPO), the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), the United States Patent and Trademark Office (USPTO), or the State Intellectual Property Office of the People's Republic of China (SIPO). Relying on patent families allows controlling for patent protection sought for the same invention in several countries, and to reduce possible geographical biases. Additionally, the condition imposed on the family size (at least two members) ensures the selection of more valuable inventions. USPTO patents and IP5 patent family counts before 2001 are to be considered somewhat underestimated. Furthermore, owing to patent pendency at the USPTO, statistics on USPTO patent applications are timelier than those of USPTO granted patents.

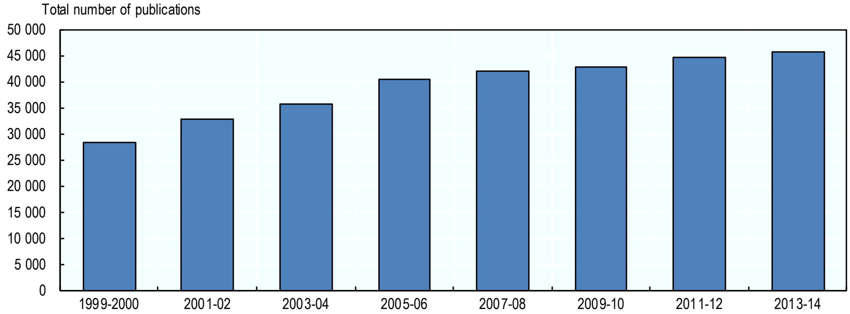
Scientific production in the space sector

Peer-reviewed scientific publications convey the research findings of scientists worldwide and give useful hints of future innovation trends. An original analysis of the literature on space activities is conducted in this section to 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 (OECD, 2014).

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 and 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, the People's Republic of China [hereafter "China"] and South Africa). The volume of scientific publications in space literature doubled in size between 1999 and 2014 (Figure 2.1). The amount of publications rose from around 28 000 in the first biennium (1999-2000) to almost 46 000 in the last one (2013-14). This increase is driven by several factors: not only do researchers in countries with long-standing space programmes publish more than they used to, but there are also many more actors from various countries. It should be noted that scientific production activities increased for all areas, not only space, during the same time period.

Figure 2.1. **Scientific production in space literature**

Number of scientific articles



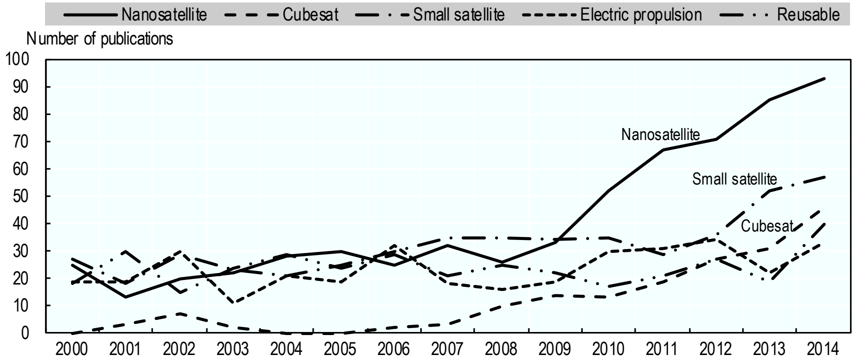
Note: See Box 2.1 for methodologies.

Sources: OECD analysis based on Scopus Custom Data, Elsevier, Version 4.2015 and SCImago Journal Rank (SJR) list of journals by subject, April 2016.

Certain subject areas represent key areas of the innovation in current space developments. They include, in particular, small and very small satellites (including cubesat and nanosatellite), electric satellite propulsion, and satellite navigation applications (such as GPS, for the US Global Positioning System and GNSS, for Global Navigation Satellite Systems).

There is a growing body of scientific publications dedicated to these "hot topics" in the space literature. Figure 2.2 shows the evolution in the number of publications with the keywords "nanosatellite", "cubesat", "electric propulsion", "reusable" technologies and "small satellite" in the title or abstract. Titles and abstracts related to small and very small satellites show a strong upward trend, although the absolute number of publications remains low at less than 100 publications per year. Publications with the topics "GPS" and "GNSS" do not appear in the figure as the volume of publications dedicated to them is much higher and would have outsized the other time series. Publications dealing with "GPS" count more than 500 per year, while those dealing with "GNSS" quickly grew from less than ten publications before 2003 to more than 300 per year from 2004 onwards.

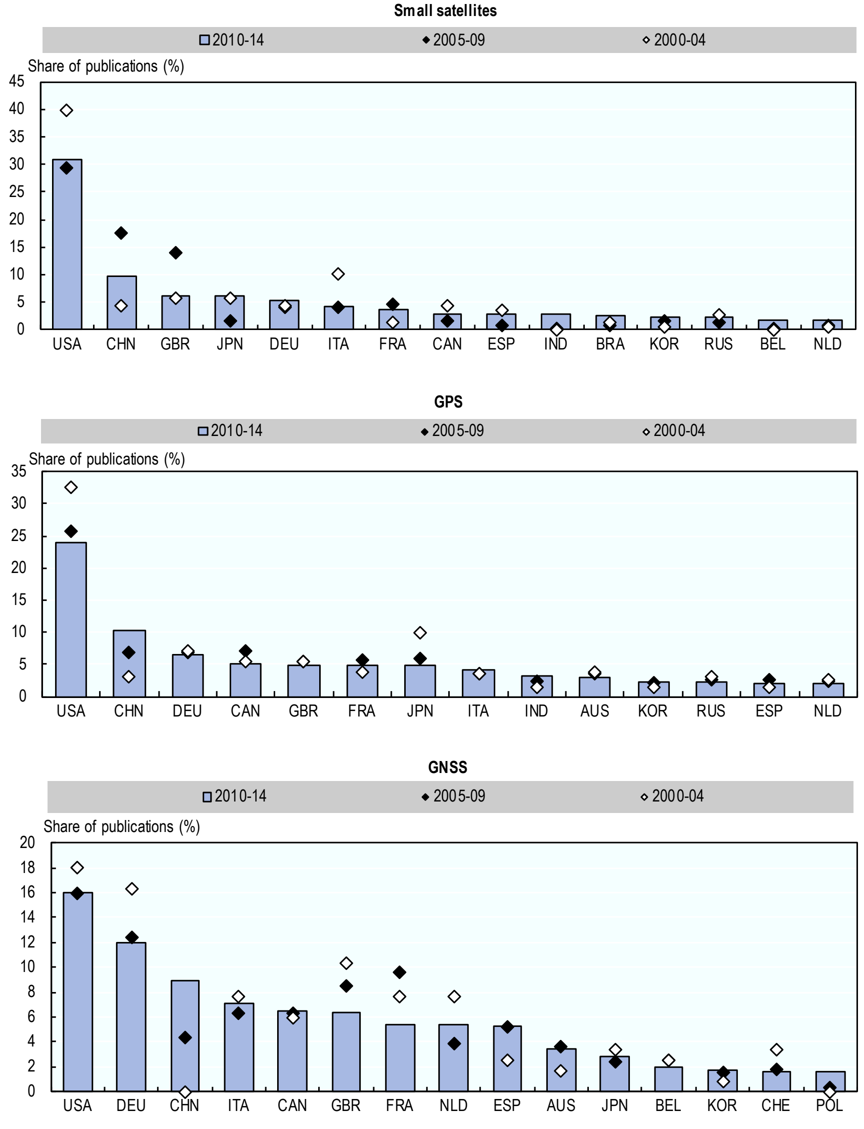
Figure 2.2. **Selected hot topics in space literature**



Sources: OECD analysis based on Scopus Custom Data, Elsevier, Version 4.2015 and SCImago Journal Rank (SJR) list of journals by subject, April 2016.

In terms of scientific publications per country, the United States has the largest share of publications on small satellites, accounting for more than 30% of publications, followed by China and the United Kingdom in the period 2010-14 (Figure 2.3). A growing number of national R&D programmes around the world are dedicated to the development of small satellites. Many countries are also taking a larger share in the GNSS literature, reflecting the development of the Chinese satellite navigation system Beidou and the European Galileo system over the last ten years.

Figure 2.3. **Selected hot topics in space literature per country**



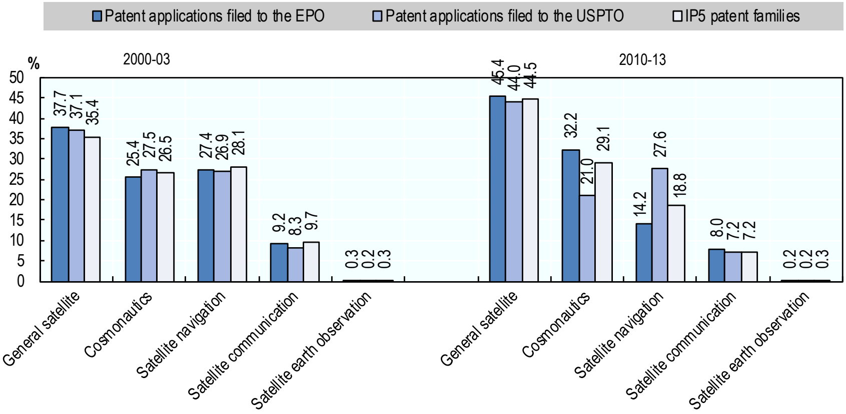
Note: GPS: Global Positioning System; GNSS: Global Navigation Satellite System.

Sources: OECD analysis based on Scopus Custom Data, Elsevier, Version 4.2015 and SCImago Journal Rank (SJR) list of journals by subject, April 2016.

The increasing importance of satellite navigation systems and their many derived location-based and timing services in scientific publications can also be traced to recent patenting activities (Figure 2.4). 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 satellite-related patents has almost quadrupled in 20 years, particularly in the space application areas (i.e. satellite navigation, earth observation, telecommunications).

Figure 2.4. **Space-related patents by main domains**

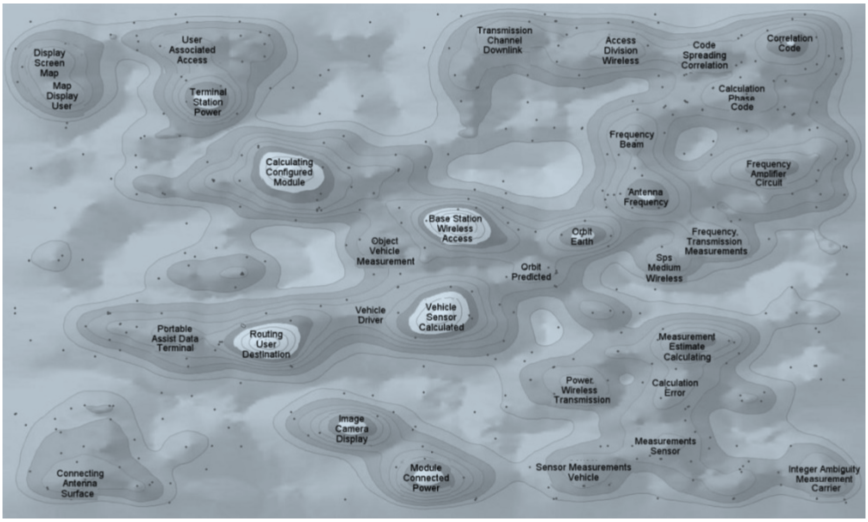
% of patents, by patent offices and priority date



Source: OECD (2016), *STI Micro-data lab: Intellectual Property Database*, http://oe.cd/ipstats.

Figure 2.5 shows a visual representation of the main topics of space-related patents by the UK Patent Office over the 2009-13 period (UK Intellectual Property Office, 2014). Published patents are grouped according to the occurrence of keywords in patents' title and abstract. The largest snow-capped peaks in the centre of the map illustrate the highest concentration of patents, based on prevalent keywords. The most prolific areas of patenting (e.g. base station wireless access, vehicle sensor calculated, routing use destination) suggest that the content and potential use of these technologies mainly concern ground-based applications of satellite data, with commercial applications in GPS-based applications and telecommunications (e.g. patents on satellite antennas, satellite data amplifiers and wireless transmission of data). The industrial actors that are patenting these technologies include the US corporations Qualcomm, Boeing, Honeywell and Trimble; the Japanese firms Mitsubishi, Sony and Seiko Epson; the European Airbus Group (with many companies); the French firms Thales and Alcatel-Lucent; the Korean firms Samsung and ETRI; and top UK companies including Inmarsat, BAE Systems, CSR and QinetiQ. This tends to support that argument that much space innovation occurs today in downstream space activities.

Figure 2.5. **Patent landscape map of all patents relating to satellites, 2009-13**



Source: UK Intellectual Property Office (2014), "Eight great technologies: Satellites, a patent overview", https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/360986/Eight_Great_Technologies.pdf.

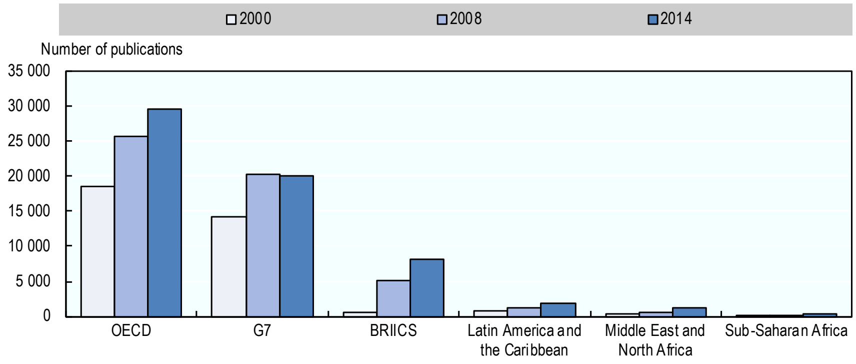
Globalisation of space innovation

Research and development (R&D) and innovation activities are increasingly global, as there is more cross-border collaboration between research institutions (OECD, 2015). This is also the case for space activities. The increasing complexity of innovation and pervasiveness of new technologies generate a drive towards much wider partnerships extending over national borders. This is illustrated, for example, by the international co-operation in space exploration between space agencies and by the shifting international organisation of functions within multinational enterprises, which are internationalising their R&D at a faster pace and on a larger scale than before (OECD, 2013a). Scientific publications and patents data can also be used as proxies to track this globalisation and growing linkages.

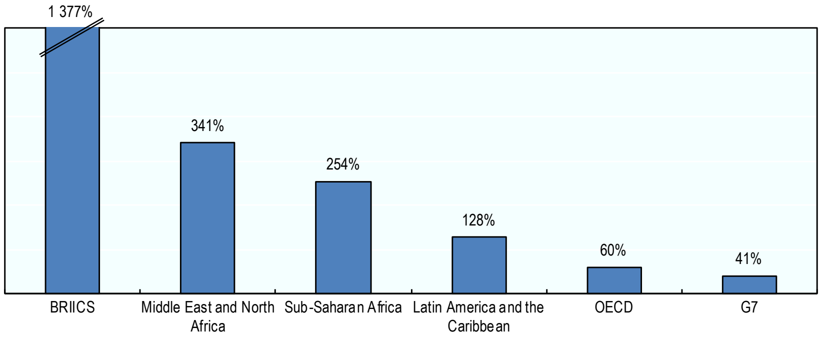
In the period 1999-2014, the number of contributors to international scientific journals and conference proceedings grew, allowing the inclusion of more researchers in different knowledge networks. When examining scientific production in the period (Figure 2.6), the biggest increase in space literature took place outside OECD countries. This is also the case in most scientific fields and high-technology sectors. The number of space-related publications increased overall in the OECD area between 2000 and 2014, but the BRIICS economies saw a dramatic increase in their production. When looking at scientific production per country (Figure 2.7), Japan and the United States saw a reduction in the absolute number of publications in the 2008-14 period.

Figure 2.6. **Scientific production in space literature, per region**

Number of publications



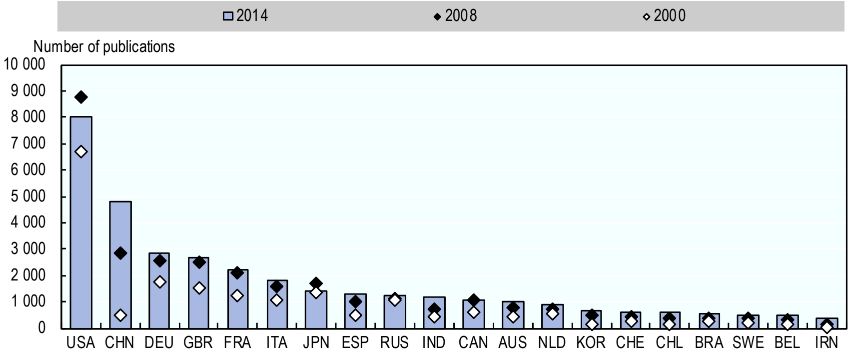
Relative growth rates in the number of publications by region (2000-14)



Sources: OECD analysis based on Scopus Custom Data, Elsevier, Version 4.2015 and SCImago Journal Rank (SJR) list of journals by subject, April 2016.

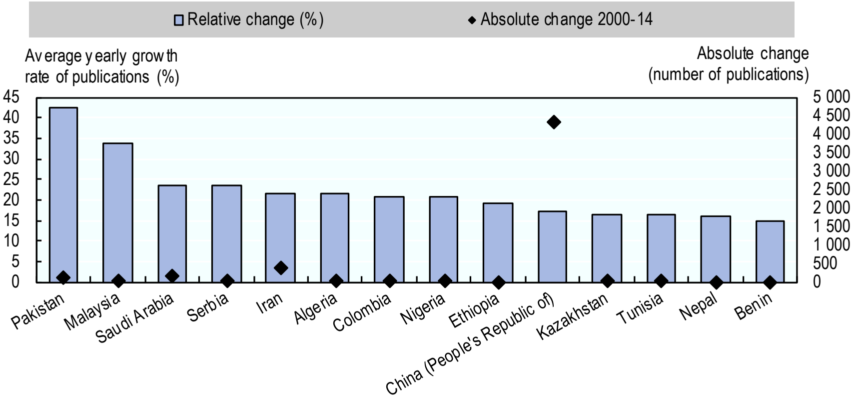
Meanwhile, partner economies, such as China and India, saw significant increases in the same period. China's scientific production increased ten-fold between 2000 and 2014 (from 500 to almost 5 000), making it one of the leading contributors worldwide, which reflects the growing interest in the space sector in China. In India, the number of publications more than doubled between 2000 and 2014. Other emerging economies saw very high growth rates (Figure 2.8), but started from very low levels (e.g. Malaysia and Pakistan).

Figure 2.7. **Scientific production in space literature, per country**



Sources: OECD analysis based on Scopus Custom Data, Elsevier, Version 4.2015 and SCImago Journal Rank (SJR) list of journals by subject, April 2016.

Figure 2.8. **The dynamics of scientific production: Growth rates for selected countries between 2000 and 2014**

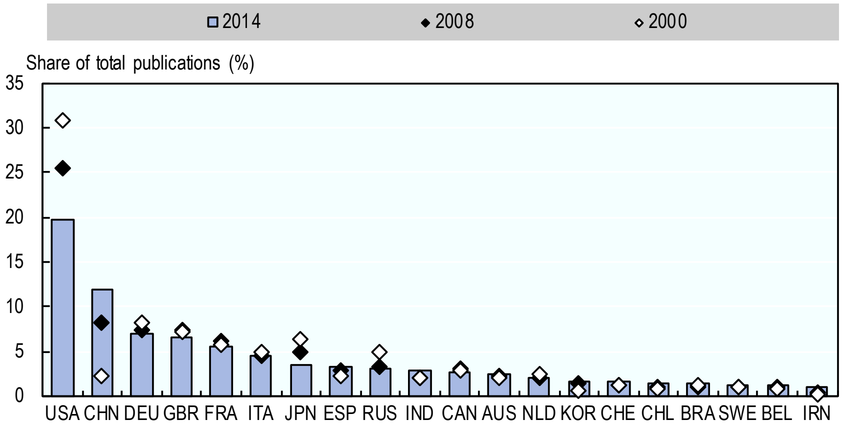


Sources: OECD analysis based on Scopus Custom Data, Elsevier, Version 4.2015 and SCImago Journal Rank (SJR) list of journals by subject, April 2016.

In terms of the international distribution of scientific production (Figure 2.9), the United States accounted for about 20% of the total number of publications in space literature in 2014, followed by China (12%), Germany and the United Kingdom (7%), and France (5%).

Figure 2.9. **Top producers in space literature**

% as share of total publications in space literature



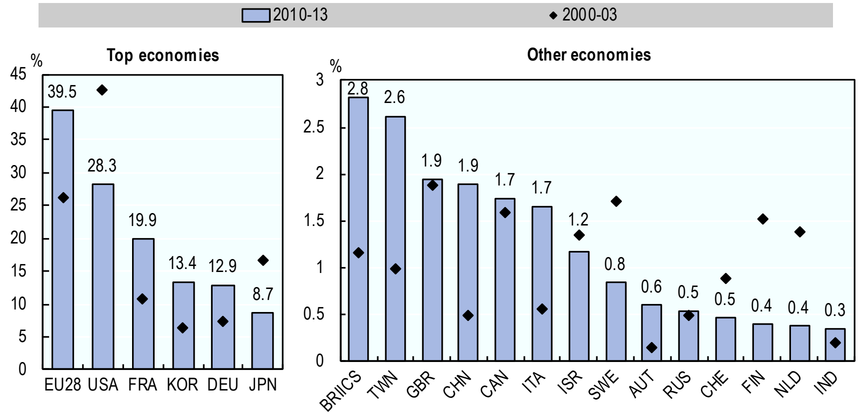
Sources: OECD analysis based on Scopus Custom Data, Elsevier, Version 4.2015 and SCImago Journal Rank (SJR) list of journals by subject, April 2016.

When comparing national patent applications for space-related technologies in 2001-03 and 2010-13, the United States still leads but its share has shrunk; while the European Union (EU28) grouping's share has increased (Figure 2.10). Several economies have seen their shares of worldwide patents grow in relative terms, noticeably France, Korea, Germany, China and Italy.

The revealed technological advantage (RTA) is an index which provides an indication of the relative specialisation of a given economy in selected technological domains. The RTA index in space technologies is calculated as the share of patents of an economy in space-related technologies relative to the economy's share of total patents. Based on the analysis, eight economies demonstrate a level of specialisation in space technologies (Figure 2.11). France, the Russian Federation, Israel and the United States show a relatively large amount of patenting in space activities, compared to other economic sectors.

Figure 2.10. **Top applicants of space-related patents per economy**

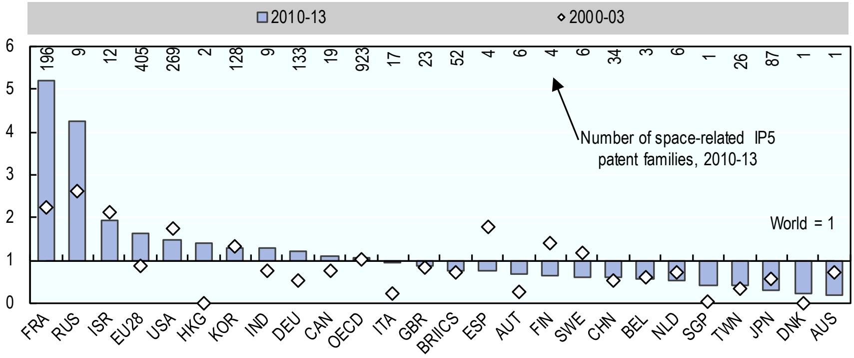
IP5 patent families, by priority date and applicant's location, using fractional counts



Source: OECD (2016), *STI Micro-data lab: Intellectual Property Database*, http://oe.cd/ipstats.

Figure 2.11. **Revealed technological advantage in space technologies**

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



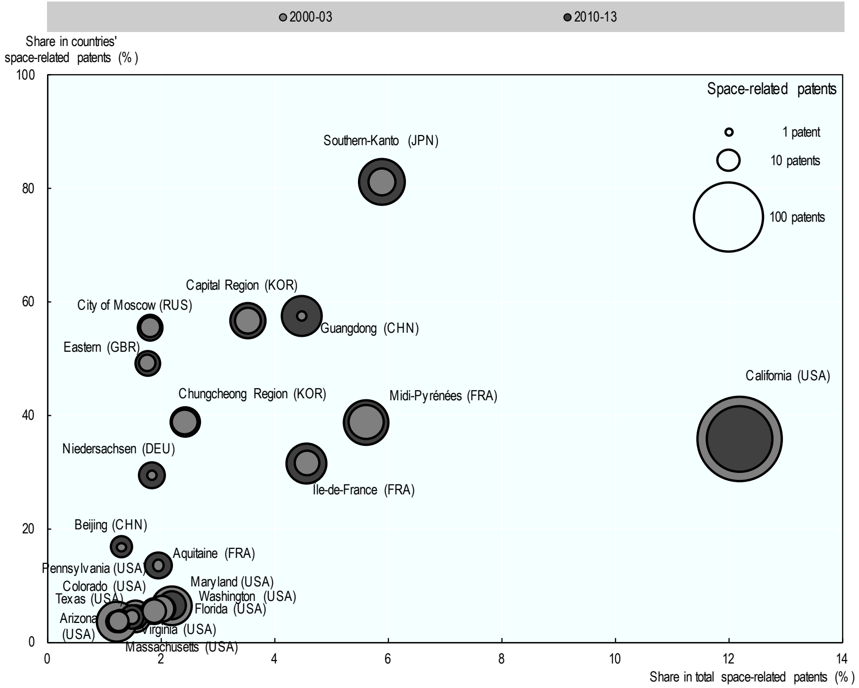
Source: OECD (2016), *STI Micro-data lab: Intellectual Property Database*, http://oe.cd/ipstats.

When examining space-related patenting on a regional scale (Figure 2.12), the highest shares of patents can be found in a few selected regions, homes to significant space industry clusters. Around 12% of worldwide space patenting occurs in California (United States), 6% in the Midi-Pyrénées (France) and in Southern Kanto (Japan). Other regions with relative high rates of space-related patenting include Île-de-France (France), Guangdong (China) and the Capital Region (Korea). 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. Between 2000-03 and 2010-13, 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 (Île-de-France, Guangdong, Niedersachsen, Hamburg, Aquitaine, Ontario).

Figure 2.12. **Top 20 regions in space-related patents**

Patent applications filed under the Patent Co-operation Treaty by inventor's residence and priority date



Source: OECD (2016), *STI Micro-data lab: Intellectual Property Database*, http://oe.cd/ipstats.

These clusters tend to interact more and more, especially when institutional grants and procurement mechanisms require cross-border collaboration. While analysing European-funded satellite navigation programmes, Balland, Suire and Vicente (2013) identified, for example, seven main clusters active in Global Navigation Satellite System (GNSS) in Europe. Based on the number of organisations in each region involved in GNSS projects (including large prime contractors) and the number of relations within each cluster, the

Community of Madrid was found to be the largest GNSS cluster (with GMV in Madrid), followed by the Lazio region (Telespazio in Rome), and the Midi-Pyrénées region (Thales Alenia Space in Toulouse).

Another globalisation trend in space-related scientific production is the increased scientific cross-border collaboration. Joint space exploration and scientific missions have historically been an important source of international co-operation, contributing to increased linkages between national space agencies and industries around the world (Box 2.2). Space sciences and planetary missions have developed markedly over the years, with new actors joining in.

Box 2.2. **Space exploration as a driver of international co-operation**

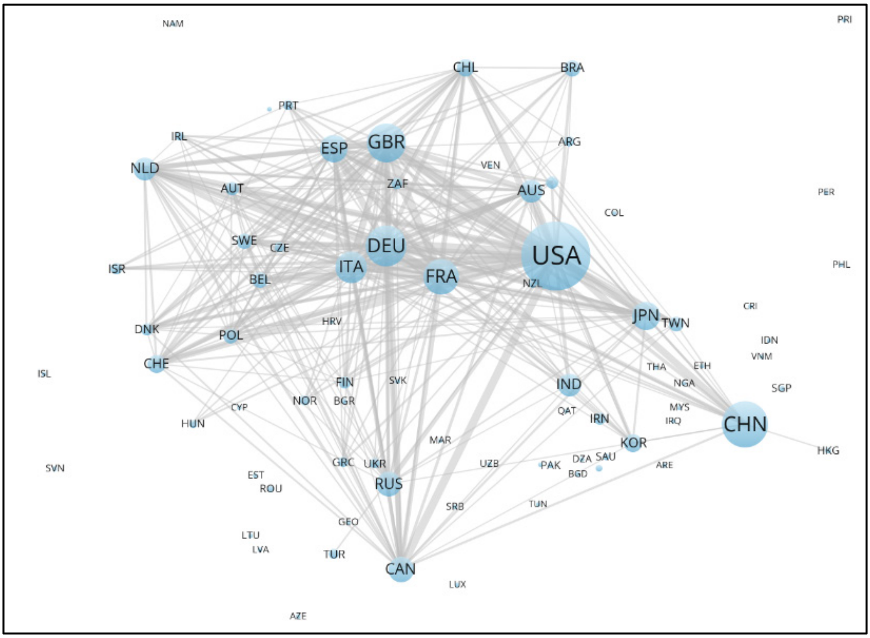
During the Cold War, major scientific and engineering breakthroughs took place in different parts of the world, often in isolation, as military research and development and industrial secrecy forced economies to preserve their own technological advances. As international conferences of scientists have prospered since 1991, allowing researchers to collaborate on and disseminate scientific advances, knowledge flows and dual-use technological transfers have also increased from OECD countries and the Russian Federation to other parts of the world. This has sometimes caused tensions concerning the transfer of sensitive technologies (i.e. rockets carrying satellites are based on missile technologies), and a tightening of technology export controls. One of the first emblematic joint space missions took place in 1975, when an American Apollo spacecraft, carrying a crew of three, docked in orbit for the first time with a Russian Soyuz spacecraft with its crew of two. Russian cosmonauts and American astronauts met for the first time in orbit. In addition to the political significance of the event, it was a major engineering accomplishment as, at the time, both the US and the Russian industrial chains relied entirely on domestic hardware and national standards. Bilateral working groups were set up for the first time to develop compatible rendezvous and docking systems in orbit, which are still in use today.

Source: OECD (2014), *The Space Economy at a Glance 2014*, http://dx.doi.org/10.1787/9789264217294-en.

Figure 2.13 maps the co-authorship network in space literature over the 2011-14 period. The size of the nodes for each economy is proportional to the amount of publications produced, and the thickness of the lines between economies is proportional to the number of co-authorships.

The figure underlines the prominent role of the United States in this area, which has already been illustrated in the previous figures. It shows that it is also firmly embedded in the international research network through a high number of co-authorships. It is also interesting to note the close interaction between several European economies. China, India and Korea have relatively high levels of production, but lower levels of co-authorships.

Figure 2.13. **Co-authorship networks in space literature, 2011-14**



Sources: OECD analysis based on Scopus Custom Data, Elsevier, Version 4.2015 and SCImago Journal Rank (SJR) list of journals by subject, April 2016.

Space innovation diffusion to other sectors

Diffusion is the way in which innovations spread, through market or non-market channels, from their first implementation to different consumers, countries, regions, sectors, markets and firms (Box 2.3). There is much literature on the emergence and diffusion of technology, with a focus either on discontinuities (like disruptive technologies) or on generational evolutions of technological fields. Different metrics also exist in trying to forecast technological changes, with some recent significant inputs from new data-mining techniques applied to patent and publication data (see Dernis, Squicciarini and de Pinho, 2015).

The diffusion of space innovation in different sectors is difficult to quantify, although it has been captured by different indicators over the years. As mentioned in previous sections, much innovation is taking place in downstream space activities, with new ways of using satellite signals and data in various products and services (see Chapter 1). The mapping of these original downstream activities is a large ongoing endeavour, providing insights on how space technologies permeate entire sectors. In addition to this aspect, significant outcomes from government-funded space research have been documented over the years on space technology transfers to non-space sectors.

Box 2.3. **The diffusion of innovation**

Actors develop different interactions and relationships in the innovation system (e.g. policy makers, public research organisations, suppliers, collaborating firms, etc.) and act both as channels for the inflow and outflow of knowledge, and the inbound and outbound diffusion of innovation. Organisations can obtain knowledge in different ways, via:

- open information sources (openly available information that does not require the purchase of technology or intellectual property rights, or interaction with the source)
- the acquisition of knowledge and technology (purchases of external knowledge and/or knowledge and technology embodied in capital goods [machinery, equipment, software] and services, which do not involve interaction with the source)
- innovation co-operation (active co-operation with other enterprises or public research institutions for innovation activities, which may include purchases of knowledge and technology).

Outbound diffusion can take place via the sale of a new good or service to consumers or the sale of a new product or process to another firm, or the sharing of information via the same channels as for inbound diffusion. For the private sector, outbound diffusion is linked to the protection of intellectual property and subject to close control. Conversely, for the public sector, widespread outbound diffusion increases the economic impact of the innovation.

Source: Adapted from OECD/Eurostat (2005), *Oslo Manual: Guidelines for Collecting and Interpreting Innovation Data*, http://dx.doi.org/10.1787/9789264013100-en.

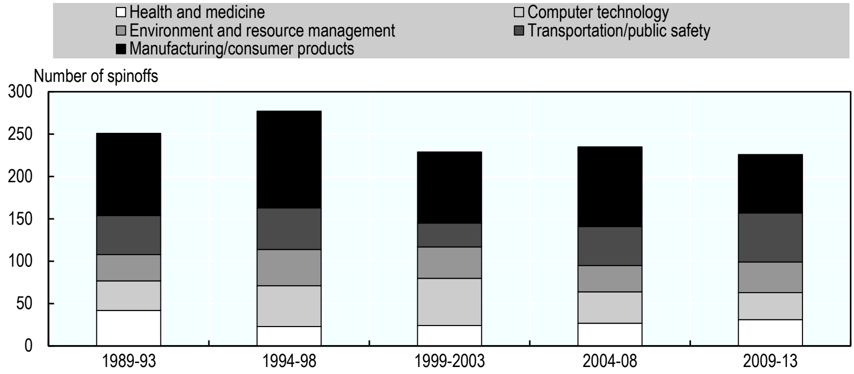
Definitions differ when examining transfers of space technologies. Research-based spin-offs are generally understood to be small, technology-based firms whose intellectual capital originated in universities or other public research organisations, like space agencies. Large businesses can also encourage the creation of small spin-off companies, with the mission to develop specific corporate intellectual property (OECD, 2013b).

For the US National Aeronautics and Space Administration (NASA), a spin-off is a commercial product or service that incorporates NASA technology or expertise. These new products or services are developed through various NASA instruments (e.g. licensing, funding agreements, assistance from NASA experts, the use of NASA facilities) with private industry, other government agencies and academia. The European Space Agency (ESA) and other national agencies in Europe (e.g. CNES, DLR) use the expression “technology transfer” to share the benefits of European research and development, making space sector technologies available to the larger industry. The ESA’s Technology Transfer Programme Office identifies industrial needs and maps them to suitable space technologies as a way of enabling new applications and business opportunities. In Germany, the DLR has set up a proactive Technology Marketing Office to turn research findings from its different institutes into commercial products, using for instance the Science2Business innovation partnership with enterprises to facilitate licensing and the creation of spin-off companies (DLR, 2016). As the international knowledge base grows, several public research institutions have recently set up a Space Agencies Technology Transfer Officers (SATTO) group to exchange best practices.

NASA has documented nearly 2 000 commercial products and services successfully developed, with the majority recorded in the sectors of computer technology, environment and resource management, and health and medicine (NASA, 2016). Since 2000, the number of new products and services has remained fairly stable, averaging 25-35 per year (Figure 2.14). As an illustration, a cardiac imaging system was 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, a 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, 2016).

In Europe, documented 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 sporting products from racing yachts to running shoes (ESA, 2016). An analysis of spin-offs 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). The sectors developing the highest number of commercial products based on space technologies were then software solutions, the environment, lifestyle and medical applications. 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). Recently, the DLR 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).

Figure 2.14. **NASA spin-offs in different sectors**



Source: OECD (2014), *The Space Economy at a Glance 2014*, http://dx.doi.org/10.1787/9789264217294-en based on *NASA Spin-off Database*.

It remains that, for some technologies, the target market is so specialised or the product is so advanced that it takes a long time to be commercialised (NASA, 2016). For example, rotating cellular bioreactors have taken nearly 20 years to reach commercial maturity, as their application in cellular-level biological research is more advanced than current state-of-the-art technology. Some medical technologies also require regulatory certification or clearance nationally and in different countries before they are used publicly, thus taking even longer to reach the market. At the other end of the spectrum, some technologies have been rapidly commercialised. One US company, for example, licensed in a few months an electrolyte-based rehydration beverage developed at the NASA Ames Research Center (OECD, 2014).

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Chapter 3.

Institutions and policies conducive to space innovation

Setting up the right environment for innovation is a constant challenge for policy makers. For the space sector, the determinants for innovation include the availability of a skilled workforce within the organisations that perform innovation and adequate access to financing. Another increasingly important factor concerns "linkages", which are taking the shape of clusters and networks, facilitating technology transfer and broader innovation diffusion.

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

Setting up the right environment for innovation is a constant challenge for policy makers (Box 3.1). As explored in detail on the OECD-World Bank Innovation Policy Platform, the determinants of innovation activities are quite varied. For the space sector, they include the availability of a skilled workforce within the organisations that perform innovation and adequate access to finance. Another increasingly important factor concerns "linkages", which are taking the shape of clusters and networks, facilitating technology transfer and broader innovation diffusion. These factors are presented in the next sections.

Box 3.1. **Environment conducive to innovation**

OECD analysis, detailed in the OECD Innovation Strategy 2015, suggests that innovation thrives in an environment characterised by the following features:

- A strong and efficient system for knowledge creation and diffusion that invests in the systematic pursuit of fundamental knowledge, and that diffuses this knowledge throughout society through a range of mechanisms, including human resources, technology transfer and the establishment of knowledge markets.

- A sound business environment that encourages investment in technology and in knowledge-based capital; that enables innovative firms to experiment with new ideas, technologies and business models; and that helps them to grow, increase their market share and reach scale.

- Policies that encourage innovation and entrepreneurial activity. More specific innovation policies are often needed to tackle a range of barriers to innovation. Many of these actions include policies at the regional or local level. Moreover, well-informed, engaged and skilled consumers are increasingly important for innovation.

- A skilled workforce that can generate new ideas and technologies, bring them to the market and implement them in the workplace, and that is able to adapt to technological and structural changes across society.

- A strong focus on governance and implementation. The impact of policies for innovation depends heavily on their governance and implementation, including trust in government action and the commitment to learn from experience. Evaluation of policies needs to be embedded into the process, and should not be an afterthought.

Source: OECD (2015a), "OECD Innovation Strategy 2015: An agenda for policy action", www.oecd.org/sti/OECD-Innovation-Strategy-2015-CMIN2015-7.pdf.

Performers of space innovation

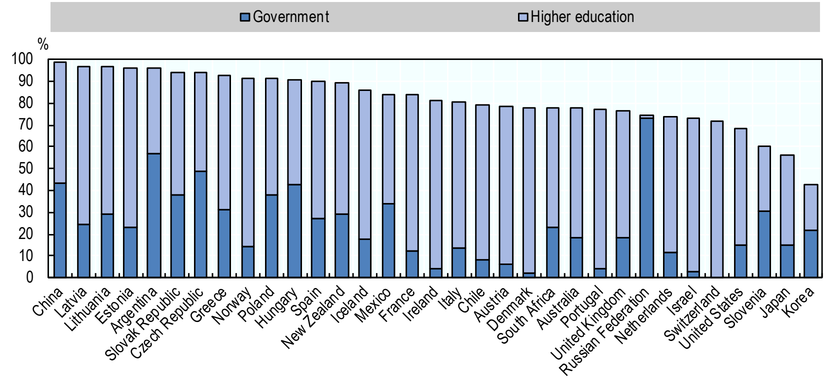
A variety of actors are involved in the creation and diffusion of knowledge in the space sector. Many of them are performers of research and development, but they also intervene at different levels of innovation. Although business enterprises play a significant role in space programmes in many countries, public research institutions and universities tend to lead innovation in a majority of economies (Box 3.2).

Box 3.2. **Importance of basic research performed by the public sector**

While the relationship between science and innovation is complex, public investment in scientific research is widely recognised as an essential feature of effective national innovation systems. Public research plays a key role in innovation systems by providing new knowledge and pushing the knowledge frontier. Public research institutions and universities often undertake longer term, higher risk research and complement the research activities of the private sector. Although the volume of public R&D is less than 30% of total OECD R&D, universities and public research institutions perform more than three-quarters of total basic research.

Figure 3.1. **Basic research performed by the public sector, 2012**

As a percentage of total basic research



Source: OECD (2014), *OECD Science, Technology and Industry Outlook 2014*, http://dx.doi.org/10.1787/sti_outlook-2014-en.

Government plays a critical part in providing the foundations for innovation, particularly in the space sector, as public research institutions play many roles in the creation and transmission of knowledge. 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. These research capacities under governmental control have important impacts on employment and public innovation capabilities for the space sector. In most OECD countries, these public research institutions are typically funded by ministries of research or the economy, and receive additional project funding and contracts from national and international agencies. They may also receive private financing via contracts, licensing arrangements, etc. (e.g. the French space agency participates in commercial joint ventures). Parts of the activities may also be defence-related, and in all the countries with major space programmes, military organisations fund space-related R&D, either supporting entire research institutes or test facilities, or through project funding. Depending on the country, the national space administration can be one of the core space research centres (e.g. the aeronautics and space research centre DLR in Germany), with in some cases an important role in space systems manufacturing (e.g. the Korean Aerospace Research Institute in Korea, the Indian Space Research Organisation in India). Other countries have several public research institutes involved in parallel in space research (e.g. France's space agency the CNES, the aerospace and defence research centre ONERA and the French Armaments Procurement Agency [DGA]).

Some of these research organisations specialise in space activities, but more often they also include aeronautics and/or defence-related research activities. This brings both challenges in terms of national security issues and opportunities in terms of intersectoral technology transfers as well. Recent government investments in space situational awareness for example (i.e. monitoring what happens in orbit, in terms of space weather conditions, radiation, space debris evolutions, activities of foreign satellites and launchers, and most importantly tracking foreign military missiles) is affecting research in future commercial satellites' resilience and autonomy. This type of government-led research both drives and is fuelled by innovation in the areas of robotics and artificial intelligence.

Public research institutions often host ground test facilities and laboratories, and they may be linked to high-technology hubs, academic as well as private actors, and play an important role in local industry development. The US National Aeronautics and Space Administration (NASA) has many centres spread across the United States, mainly located on the east and west coasts, the majority of which are involved in R&D or testing activities. The US space programme also benefits from the US Air Force's and the Department of Defense's Defense Advanced Research Projects Agency's (DARPA) facilities, among others (Box 3.3). The Indian Space Research Organisation (ISRO) has almost 20 centres spread across the country, with a concentration in the southern part of the country, including the ISRO headquarters in

Bangalore and the space launch centre in Sriharikota. The French space agency the CNES has facilities in Paris, Toulouse and French Guyana, while ONERA has eight different locations, including state-of-art wind tunnels for aerodynamics testing. In addition, the military aeronautic testing facilities under the auspices of the French DGA provide also locations for testing some space systems. The DLR has 15 different locations in Germany, with important testing facilities. The European Space Agency (ESA) also has different locations throughout Europe, in addition to its Paris headquarters.

Box 3.3. **Space innovation and DARPA**

The Defense Advanced Research Projects Agency (DARPA) in the United States plays a crucial role in space innovation. It was established in 1958, right after the first satellite Sputnik was flown by the Soviet Union. DARPA is the agency responsible for the development of science and emerging technologies that could be of use for American national security (DARPA, 2016a). As compared to other governmental agencies in most countries, DARPA has a very flexible approach and can fund in parallel dozens of fundamental research and R&D projects with relatively high risks of failure. The objective is to pursue breakthrough technologies. The agency has had, over the years, strong impacts on funding game-changing technologies that were then transferred to civilian and commercial uses, particularly in information technologies, like computer networking and graphical visualisation tools, or, more recently, unmanned aerial vehicles. The agency's portfolio covers many technological fields (e.g. cybersecurity, next-generation microsystems), and it plays a key role in the long-term R&D of space technologies. It provided, for example, seed funding with NASA in 2011 for the 100-Year Starship Project. This project's objective was to encourage the private sector to study technologies useful for long-term interstellar travel (DARPA, 2016b). Closer to Earth, DARPA's commitment in demonstrating "aircraft-like access to space" includes research in reusable spaceplanes and an Experimental Spaceplane (XS-1) programme. This could lead, in parallel to simultaneous efforts in classified defence programmes and the private sector, to future breakthroughs in the US space sector.

Sources: DARPA (2016a), Defense Advanced Research Projects Agency website, www.darpa.mil; DARPA (2016b), 100-Year Starship Project website, http://100yss.org.

The testing facilities that some of these research organisations provide are necessary for technology prototype development and flight qualification. The extreme strain caused by launching a satellite to orbit and the harsh space environment itself (e.g. radiation and temperature) necessitate extensive ground testing before launch. Laboratories and test facilities for space vehicles include wind tunnels, propulsion test cells, vacuum chambers, cryogenic chambers, microgravity, acoustic and vibration testing facilities, as well as computer simulation facilities and services. Many of these facilities are very costly to maintain and operate, and when it comes to wind tunnels, for instance, there is growing pressure to reduce the number of centres due to the maturing and increased use of computational simulations.

In some countries, the role of governmental agencies involved in space activities is undergoing profound change. New circumstances are changing the initial missions of some public administrations from conducting fundamental research and R&D and channelling financial support for R&D to third parties, to, in addition, co-ordinating and enabling broad knowledge diffusion and business development of start-ups. These new crucial and challenging missions need to be taken into account when reviewing the performance of these administrations.

Although public sector research is usually smaller than business research and development in the majority of OECD countries (see Box 3.2), these R&D capacities under governmental control have an important impact on future public and private innovation capabilities for the space sector that should not be underestimated. There is, for instance, growing literature on the positive link between basic research and long-term productivity growth, as well on the significant spillovers coming from public-funded research, such as crowding-in effects on private sector innovation and patenting activity (OECD, 2015b). In OECD countries, business firms are also important performers of space-related R&D. Although R&D is often carried out in government agencies and academic institutions, it is the business-driven research that is mostly associated with the creation of new products and business practices and innovation.

In 2013 and 2014, more than half of available NASA R&D procurement dollars were awarded to business firms (NASA, 2013; 2014a). A similar level of participation is estimated in Europe and in Canada. Business firms are active participants in national and international research programmes, often in large consortiums or in public-private partnerships. In countries with a less mature space industry, business firms still participate in R&D activities, but these tend to be led by public research organisations.

Funding of space innovation

Access to financing remains fundamental for innovation, whether for public research institutions or private actors involved in the space sector. Space activities have historically required large upfront investments and a long-term funding commitment. This is still very much the case for many space programmes, particularly for public good-related programmes, such as satellite environmental monitoring, weather and major scientific missions. Although there is an increasing role for business enterprises in developing new space products and services, with the increasing involvement of new private investors, market and system failures still justify public intervention in funding space innovation.

Portfolio of public instruments

Governments set stable framework conditions for investment in R&D and innovation. In many countries, governments finance the public and private actors involved in space programmes, but they also increasingly promote access to third-party financing for these actors. Governments may use a diversity of generic policy instruments to fund space innovation, such as grants, procurement, loans and tax incentives (Table 3.1). Each instrument has specific features and applications to the space sector, as in the case of other high-tech domains. Public support through both direct financing instruments (especially competitive grants) and indirect tax instruments have increased over the past decade (OECD, 2014).

Institutional budgets remain therefore critical in starting-up and developing innovative activities in capital-intensive and high-technology sectors such as space. As an indicator of public investment, government budget allocations for R&D (GBARD) data are assembled by national authorities and classified by "socio-economic objective" (OECD, 2015c). These diverse objectives represent the intention of the government at the time of funding commitment, and a special category "exploration and exploitation of space" exists. Although the data provide only a partial picture of space R&D investments, the long-term time series provide useful trends on policy orientations (Figure 3.2). Civil space R&D programmes (i.e. the exploration and exploitation of space) accounted for about 8% of total OECD government R&D budgets (excluding defence) in 2014. In comparison, health and environment R&D (i.e. programmes funded for the purpose of the protection and improvement of human health; control and care of the environment; and for the exploration and exploitation of the Earth) accounted for 24% and "non-oriented research programmes", which mainly include basic research performed in public research organisations, for 18%.

In the United States, civil space R&D accounted for 17% of civil GBARD, the biggest share in the OECD, followed by France (11%), Italy (9%), Germany (5%), Canada and the United Kingdom (4%), Korea (3%), and Norway (2%). There have only been minor changes since 2005. These estimates do not include defence R&D nor space-related R&D budgets of the European Union. Some space-related funding can probably also be found in the health and environment R&D category (i.e. control and care of the environment; exploration and exploitation of the Earth). On the other hand, "the exploration and exploitation of space" category may comprise a non-negligible share of operational activities which are not R&D, strictly speaking.

Table 3.1. **Selected financing instruments to promote entrepreneurial financing**

	Financing instruments	Key features	Instruments used in the space sector
Direct financing	Grants, subsidies	Used as seed and early-stage funding for innovative start-ups and small and medium enterprises (SMEs) in most countries, filling the financing gap between innovators and investors. Relatively small amounts of money for feasibility study, proof of concept and prototype development. Awards are generally granted on an open and competitive basis.	EXIST (Germany); START (Russian Federation); Industry Innovation Partnerships (South Africa); SBRI (Small Business Research Initiative) (United Kingdom); SBIR (Small Business Innovation Research) (United States)
	Procurement	Public procurement stimulates innovation by creating a demand for innovative products or services and often helps bridge the pre-commercialisation gap by awarding contracts for pre-commercial innovations (i.e. first sales of technology).	Innovation-oriented public procurement schemes are used in all countries with space programmes
	Public and private venture capital	Public venture capital provides strategic funds designed to accelerate entrepreneurial activities at the seed and early stages. In contrast, private venture capital provides equity finance for later, less risky stages. Public venture capital funds are often managed by private fund managers. Exits can be made through mergers and acquisitions or initial public offerings. Corporate venture is another exit channel.	Seed Fund Vera (Finland); Business Angels Netzwerk Deutschland e.V. (Germany); BPI (France); Development and Growth Fund (Chile).
	Loan/loan guarantee	One of the most common tools for access to finance for entrepreneurial companies during the entire technology life cycle. Loans are paid back (principal and interest). Governments can offer reduced interest rate loans (soft loans) or make loans repayable only if the project succeeds. Governments often provide loan guarantees for start-ups and SMEs because they lack collateral or a track record.	BPI (France); Enterprise, Finance Guarantee (United Kingdom); Canada Small Business Financing programme (CSBF) (Canada)
Indirect financing	Tax incentives	An instrument that is combined with direct government finance in most countries. It includes exemption from personal or corporate income tax or capital gains tax to stimulate private investment in R&D and innovative entrepreneurial activities.	In 2015, 28 OECD countries provided tax incentives for R&D

Source: Adapted from OECD (2014), *OECD Science, Technology and Industry Outlook 2014*, http://dx.doi.org/10.1787/sti_outlook-2014-en.

Figure 3.2. **Shares of public R&D budgets for space and other selected socio-economic objectives**

% of civil GBARD

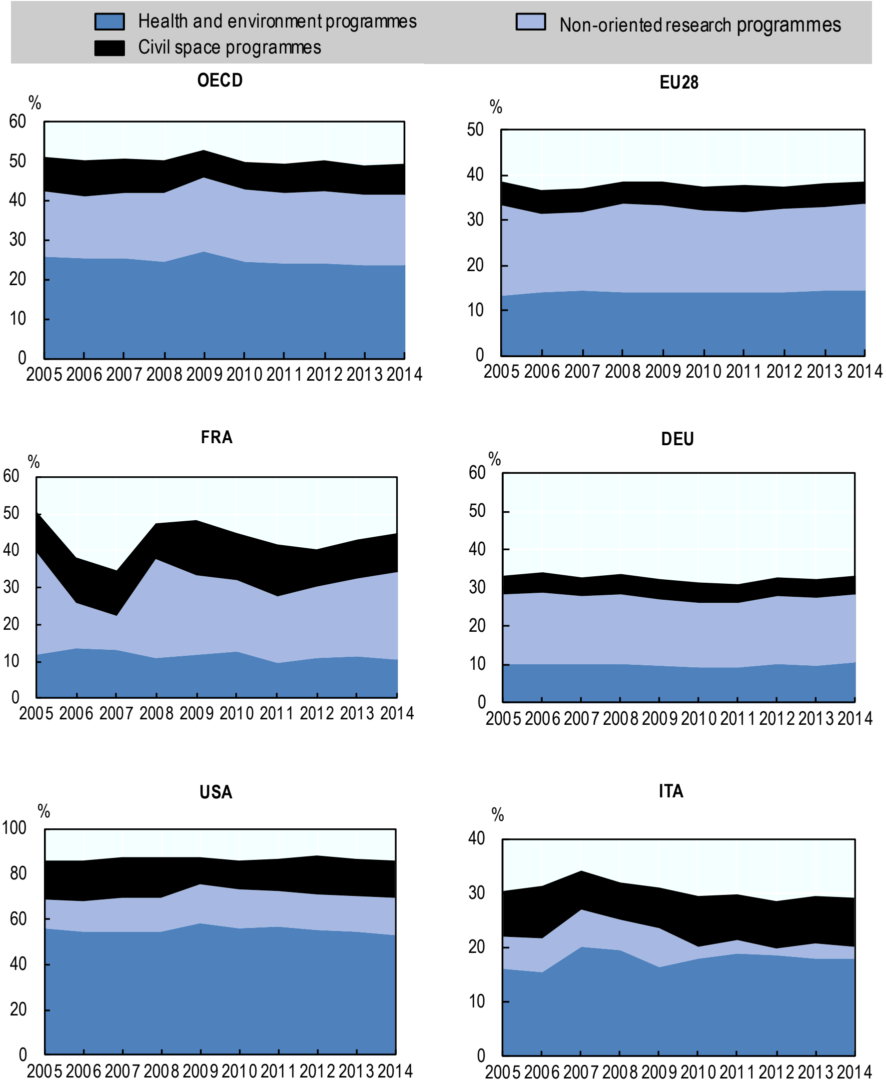
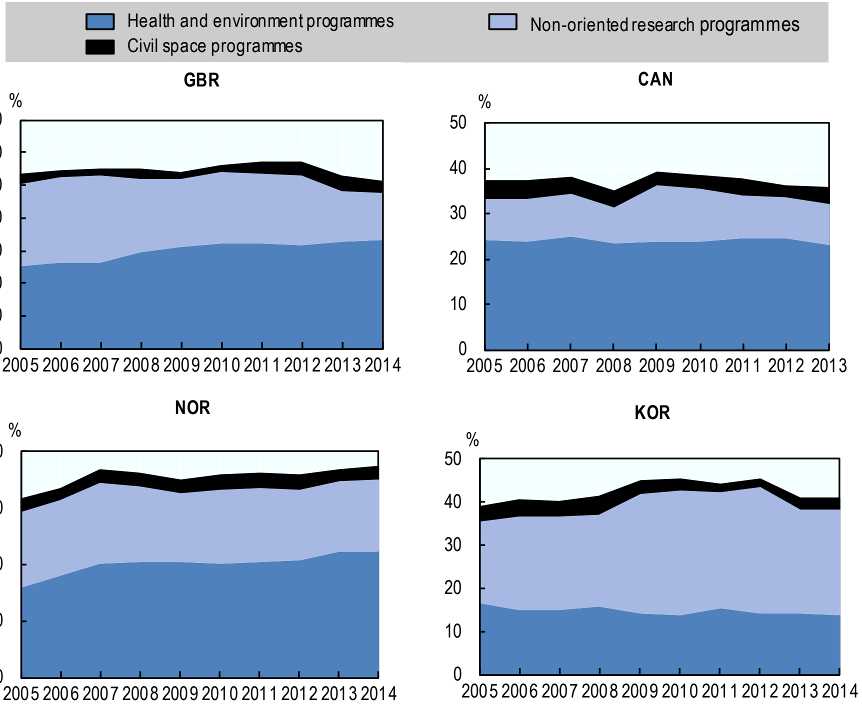


Figure 3.2. **Shares of public R&D budgets for space and other selected socio-economic objectives** (*continued*)

% of civil GBARD



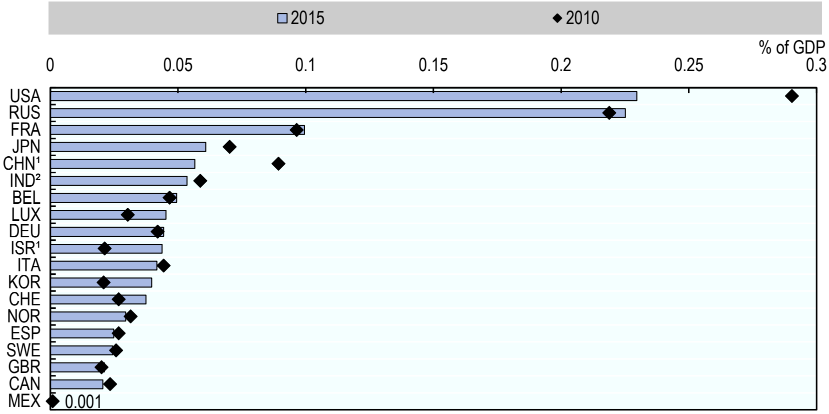
Note: GBARD: government budget allocations for R&D.

Source: OECD (2016a), "Main Science and Technology Indicators", *OECD Science, Technology and R&D Statistics* (database), http://dx.doi.org/10.1787/data-00182-en.

In terms of institutional budgets for space activities (not only R&D), the amounts in most economies are still modest in view of other much wider governmental programmes (e.g. defence, health, social security). The budgets of the Russian Federation and the United States accounted, as a percentage of gross domestic product (GDP), for slightly more than 0.2% of their GDP in 2015, followed by France at 0.1% and Japan at 0.06% (Figure 3.3). Still, the majority of OECD countries' space budgets constituted less than 0.05% of GDP in 2015 (including civil and military space activities). Variations 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. Illustrating this, People's Republic of China (hereafter "China") and India have relatively low space budget/GDP ratios because their budget allocations have not kept pace with high GDP growth.

Figure 3.3. **Selected space government budget estimates**

As a share of GDP, based on national currencies (current)



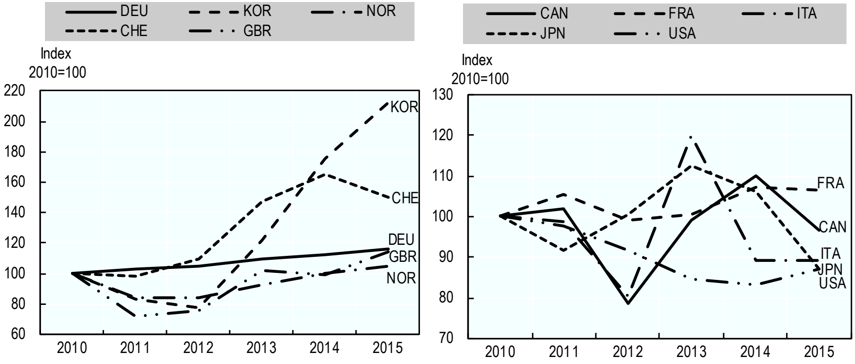
1. Estimates.

2. Based on preliminary budget estimates for the fiscal year 2015-16.

Source: OECD calculations based on government sources and OECD (2015d), "OECD Economic Outlook No. 98", *OECD Economic Outlook Statistics and Projections* (database), http://dx.doi.org/10.1787/eo-data-en.

Figure 3.4. **Evolution of space budgets in constant prices**

Index 2010 = 100



Source: OECD calculations based on government sources and OECD (2015d), "OECD Economic Outlook No. 98", *OECD Economic Outlook Statistics and Projections* (database), http://dx.doi.org/10.1787/eo-data-en.

In most economies, institutional space programmes have avoided major budget cuts since the 2008 crisis, keeping in pace with inflation (the budgets presented here cover civil and defence activities; see Box 3.4). These trends are reinforced when taking a closer look at funding in individual countries (Figures 3.4 and 3.5). For most countries, there have only been small changes during the last six years, but some economies have seen notable increases or relative decreases since 2010. The United States, which has the largest space programme, first saw an overall budget decrease with the dismantling of the space shuttle, but the budget has started to return to previous levels with increases in 2016-17. The NASA budget amounts to around USD 19 billion in 2016, while the European Space Agency budget amounts to around USD 6 billion (EUR 5.25 billion). Korea, Switzerland and the United Kingdom have also accorded increasing importance to the space sector and have scaled up funding in the past six years.

Box 3.4. **International comparisons of space budgets**

International comparisons of budgets can be affected by many factors, in particular exchange rate issues. The past three years have seen a lot of fluctuations, limiting comparisons of national budgets in US dollars.

Overall the total volume of global institutional funding increased in 2015 in real terms as compared to 2013, and individual budgets for selected economies are expected to grow further in 2016-17. Comparing budgets using indices and the ratio budget/GDP based on national currencies provide a reliable snapshot of the situation (Figure 3.4) and provides a good illustration of the major differences in budget trends when comparing budgets in constant national currency and constant USD. Indeed, when converting national budgets in a given currency, typically the US dollar, the total volume of global institutional funding in 2015 seems undervalued (USD 62 billion current for 34 countries), since several countries appear to have shrunk budgets in USD, when in reality they have larger budgets in real terms (even taking into account inflation). Converting 2015 national budgets using purchasing power parity (PPP) significantly increases the total global volume of global institutional funding (USD PPP 77 billion in 2015), but there are also methodological limitations.

Different techniques usually rely either on real market exchanges rates (e.g. USD current) or USD PPP. Market exchange rates have limitations when comparing complex institutional programmes: high volatility can create fluctuations in aggregate measures of growth even when growth rates in individual countries are stable. Furthermore, they do not take into account domestic non-tradable goods and services, and tend to underrate the purchasing power of low-income countries. To remedy this, different purchasing power parity statistical techniques can be used, but they also bring specific comparability issues. The institutional budgets presented here are based on estimates for 2015 and 2016 (for selected economies), and actual expenditure for previous years, subject to availability. They include both civil and military space programmes. Budgets of European countries also include national contributions to the European Space Agency and Eumetsat, when applicable.

A substantial share of global space activities is taking place outside the OECD area. Since 2010, most of the global growth in space budgets has taken place in emerging economies. Countries such as China, India and the Russian Federation devote significant resources to space activities. However, several economies are struggling to maintain the level of funding since the recent fall in commodity prices. The ten-year budget for the Russian Federal Space Programme 2016-2025 is facing a downturn as compared to the initial proposal of RUB 2.5 trillion, down to the current estimate of RUB 1.4 trillion. High inflation is another issue as well as productivity; both the Indian and Russian programmes are having some difficulty reaching annual targets.

Figure 3.5. **Evolution of space budgets for selected countries**

Constant national currency and constant USD

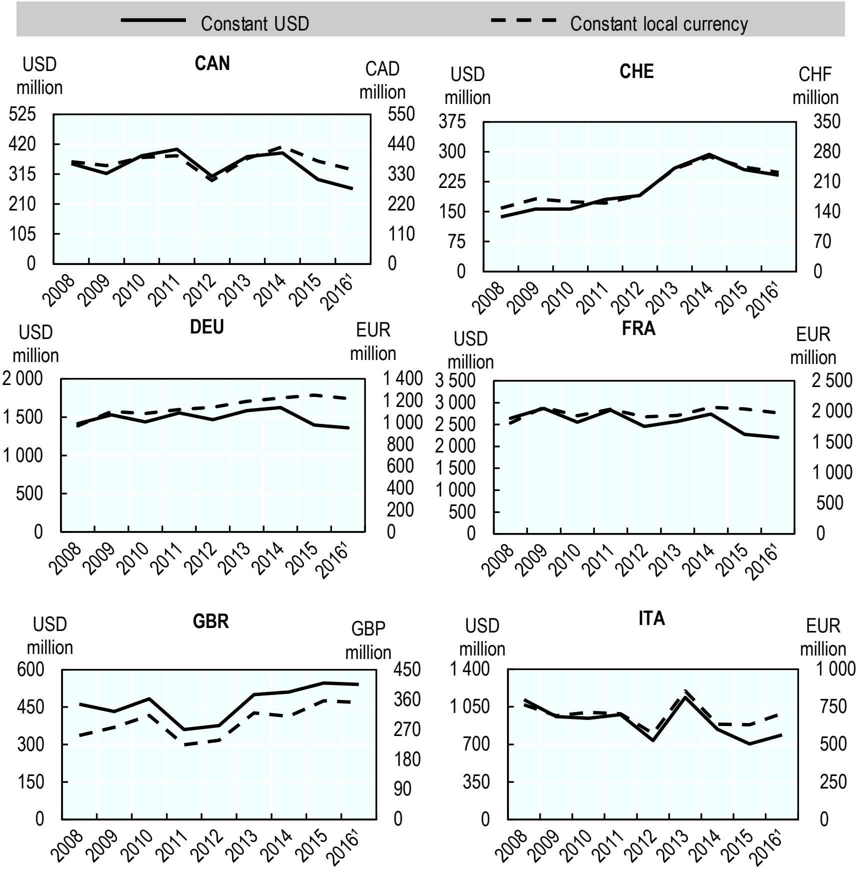
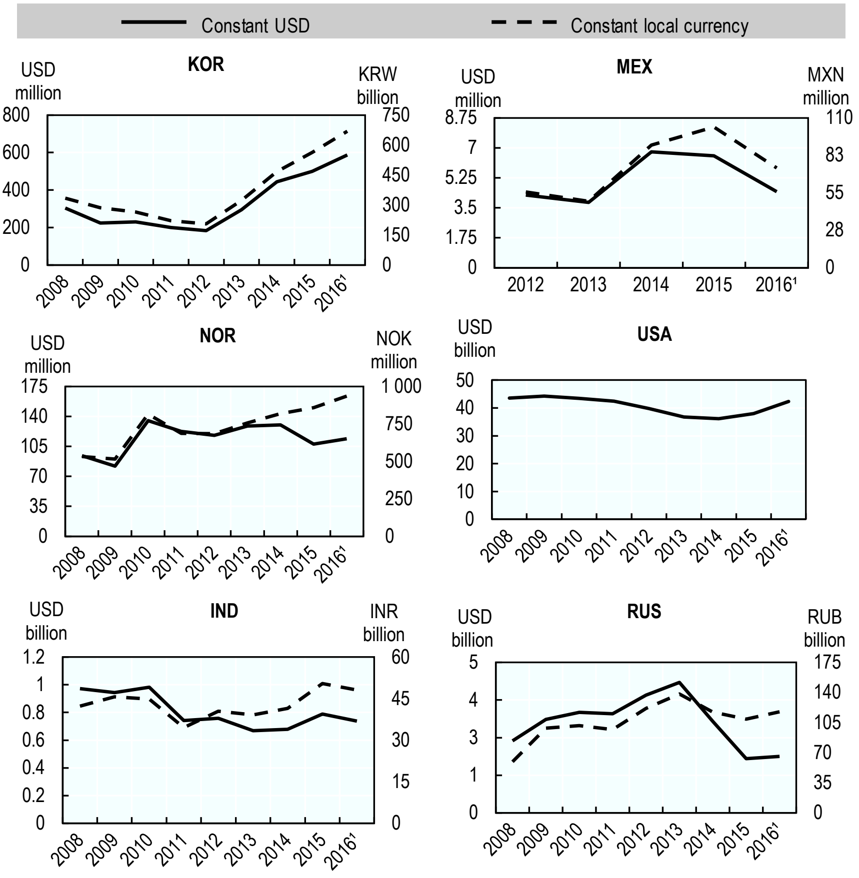


Figure 3.5. **Evolution of space budgets for selected countries** (*continued*)

Constant national currency and constant USD



1. Estimates.

Source: OECD calculations based on government sources and OECD (2015d), "OECD Economic Outlook No. 98", *OECD Economic Outlook Statistics and Projections* (database), http://dx.doi.org/10.1787/eo-data-en.

Grants

Grants for research and development are one of the most common support mechanisms in the space sector. Institutional grants are usually allocated by ministries or space agencies through regular tenders and peer review-based selections. National research agencies or innovation promotion agencies are also sometimes responsible for the allocation of space-related fundamental research funding (e.g. Norway). If grants are allocated to the private sector, different levels of co-funding are normally required, as one of the main objectives of direct funding programmes is to induce an additionality effect in firms, with the result that they end up investing more of their own resources in R&D than originally planned. Also, as in other sectors, R&D grants in the space sector are increasingly designed to contribute to other policy goals, such as promoting innovation in small and medium enterprises (SMEs), collaboration among firms, entrepreneurship, or university-industry collaboration (Pisani-Ferry and Lallement, 2016).

Space strategies and national technology development plans determine where and how R&D grants should be used (e.g. Canadian Space Technology Development Programme, German National Programme for Space and Innovation). As an illustration, in addition to supporting robotics, Canada has launched several R&D programmes with grants to support the development of new Earth observation applications. This includes the Earth observation applications and utilisation programme (i.e. business use of Earth observation data) and the government-related initiatives programme (i.e. developing government use of space-based land, ocean, and atmospheric observation systems and services). In Germany, a recent R&D programme is the Component Initiative, aimed to make German off-the-shelf components competitive for the small satellite manufacturing market. In France, the Future Investments Programme (PIA) has allocated grants to launcher and small satellite development. In Mexico, the development of the planned Mexican next generation of Earth observation and communications constellation and high throughput satellite communications satellite is seen as an opportunity to transfer knowledge and R&D capabilities to the private sector (Gutierrez, 2015).

Grants can furthermore support specific business sector demographics, such as small businesses. In the United States, NASA and other US federal agencies with extramural R&D budgets exceeding USD 100 million are required to allocate 2.8% of their R&D budget to Small Business Innovation Research programmes (SBIR), and to reserve another 0.3% to Small Business Technology Transfer programmes if their R&D budgets exceed USD 1 billion. In other countries there are now dedicated project calls for SMEs, with lower co-financing requirements (e.g. Italy). Finally, R&D grants may target technology transfer activities, for example by requiring different actors to collaborate (SMEs and prime contractors, academia and the private sector) on projects. In the United Kingdom, the International Partnership Space Programme awards grants to British companies which develop satellite technology with international partners to tackle societal problems (e.g. flooding, deforestation) in emerging economies.

Procurement programmes

Procurement programmes directly support national and international space programmes (e.g. science, exploration, launchers). They play not only an important role in maintaining or developing a domestic industrial base, but they also stimulate innovation by creating a demand for innovative products or services. They also help innovators bridge the pre-commercialisation gap for their innovative products and services by awarding contracts for pre-commercial innovations (i.e. first sales of technology or services).

For countries with extensive space programmes, domestic procurement via military and civil space programmes often constitutes the main market for their industry (e.g. China, India, Japan, the Russian Federation, the United States), and are extensively used by industry to develop new space products and services. By comparison, the European space industry faces an important level of exposure to international markets, with a reliance on commercial and export sales for almost half of the space industry's manufacturing revenues.

In the United States, several dedicated procurement programmes support business sector manufacturers and service providers. These programmes focus on the competitive provision of space services with different types of contract arrangements to cap costs (e.g. capped contracts, indefinite delivery – indefinite quantity contracts). The most extensive programme is the NASA Commercial Crew & Cargo Program to develop private space transportation services (NASA, 2014b). The initial Commercial Orbital Transportation Services (COTS) programme which operated between 2006 and 2011 awarded USD 788 million in funding to develop new solutions for cargo delivery to the International Space Station, with the new phase awarding some USD 17 billion in resupply contracts for the 2009-24 period. This constituted less than half of the total development costs, the rest of which was covered by the first contracted companies, SpaceX and Orbital. A third company, Sierra Nevada, has been awarded in the same way resupply contracts to the International Space Station for the period 2016-24.

NASA also uses procurement programmes to support innovation in the development of suborbital and very small satellite launchers. Six commercial launch providers have been accorded indefinite delivery – indefinite quantity (IDIQ) contracts for the NASA Flight Opportunities programme for suborbital research missions. The companies under contract will compete for task orders to deliver payload integration and flight services. All task orders must be initiated within the contract's three-year performance period, with a maximum value of contracts not exceeding USD 45 million. Another initiative is the Venture Class Launch Services programme for very small satellite launchers (cube, micro and nanosatellites). It is designed to provide additional launch opportunities within the existing NASA Cubesat Launch Initiative programme, which currently offers ride-share opportunities for research payloads on government launches. Some USD 17 million have been awarded in fixed-cost contracts to three cubesat launch providers (Firefly, RocketLab and Virgin Galactic) with a demonstration launch scheduled in 2018.

For countries with a smaller domestic market, international co-operation within international organisations or bilateral agreements constitute an important means of obtaining contracts and flight opportunities for domestic industry. In Europe, the European Space Agency (ESA) has created a regional market, pooling and redistributing contracts among its members according to the principle of geographical return (in accordance with a member country's financial contributions).

Other illustrations of government procurement programmes include:

- In Korea, a series of recent space missions have been planned to encourage business sector investments. According to its Middle and Long-Term Space Development Plan 2014-40, Korea would build and launch ten satellites with the domestic launch vehicle KSLV-II and prepare a lunar orbiter/lander by 2020. This will involve ever-more public procurement. Public research institutes and universities are still the most important developers in the Korean space sector, but the business sector will be prime contractor on the forthcoming satellite CAS-500-2 (Kim, 2015).
- The Department of Public Works and Government Services Canada uses the Build in Canada Innovation Program (BCIP), established in 2012, to procure and test late-stage innovative goods and services, including space technologies within the federal government.
- The UK Space for Smarter Government Programme (SSGP), established in 2014 by the UK Space Agency and the Space Applications Catapult Centre in Harwell, intends to support the UK governmental agencies in their procurement needs for commercial space products and services from the private sector. The aim is to boost the uptake of commercial solutions by governmental administrations if they can demonstrate value for money.
- The Norwegian Space Center also actively works with local industry and government agencies to develop adequate satellite data-dependent products for government use (and procurement), such as marine monitoring tools (e.g. oil spills, sea ice, ship traffic) and avalanche risk mapping and monitoring, involving satellite radar interferometry.

Other instruments (tax incentives, loans, export credit)

OECD analysis suggests that direct support measures – contracts, grants and awards for mission-oriented R&D – are generally effective in stimulating R&D and innovation in the space sector. But other instruments also contribute to spur innovation.

As a first family of instrument, tax incentives have the main objective to reduce businesses' marginal cost when engaging in R&D activities. A major characteristic of R&D tax credits, contrary to grants, is that they are generally technologically neutral, so firms get a level of support, whatever type of research they engage in. Tax credits are present in the majority of OECD countries, and are often used by large multinational groups which have diversified portfolios of R&D activities (e.g. aeronautics, space, defence). This specific type of support for business R&D through the national tax system is typically combined with a broader set of direct support mechanisms. In most sectors, there has been generally a slow shift away from direct financing support, and R&D tax incentives have become more generous (OECD, 2015e).

Seed grants, loans and guarantees are also used to enlarge and support the industrial base, directly targeting new activities or ailing enterprises. NASA's Experimental Program to Stimulate Competitive Research provides seed grants to develop academic research enterprises within higher education research institutions with modest research infrastructure.

Some space agencies have also entered into co-operation with venture capital firms to facilitate venture capital funding of space enterprises (e.g. United Kingdom, the ESA). In other countries, these financing instruments are provided by government actors at both the national and regional level (e.g. innovation agencies, research agencies, regional development banks).

Finally export credits or guarantees represent an important policy instrument for some countries, used to secure big international launch or satellite contracts for domestic industry and in this way facilitating the export of space products. This is a relatively new trend in the space sector. In the aeronautic sector, aircraft producers have received export-credit agency backing for decades, using this mechanism to help their customers secure funding to buy aircraft, in addition to using conventional debt and equity markets. A multinational agreement among developed countries fixes limits on export credit financing systems (OECD, 2016b). The support of national export credit agencies is widespread internationally, as the following illustrations demonstrate, even if the US Export-Import Bank (EXIM) has been, with France's Coface, one of the most active export-credit agencies in the satellite market in recent years. Between 2010 and 2014, EXIM has supported 16 satellite projects worth USD 4 billion (SIA, 2014). It is estimated that 60% of US satellite sales received some EXIM backing in that period. The French government-backed export credit agency Coface has also supported numerous projects, contributing to contracts for Thales Alenia Space and Airbus Space and Defence, while the UK Export Finance agency provided GBP 22 million in reinsurance for the Airbus Space and Defence satellite deal with the Malaysian satellite operator Measat (UK Export Finance, 2015). Export Development Canada provided credit financing to Ukraine in late 2009 to buy a satellite from the Canadian MacDonald, Dettwiler and Associates. And in late 2010, China Development Bank provided a commercial loan to Bolivia for its first communication satellite, built by Chinese companies, for 85% of its estimated USD 300 million value (OECD, 2011).

Increased use of challenges and prizes

Used in many sectors, challenges and prizes are a relatively recent set of tools to stimulate innovation and entrepreneurship in the space sector.

These prizes are multiplying around the world, and are funded by governmental agencies or private organisations, or jointly. They may include cash prizes for new concepts, technology development, incremental developments or technology implementation in new products and services. Competitions tend to bring in original ideas to governmental agencies and the established industry players, especially as some prizes aim to attract innovators from outside the space community, while helping entrepreneurs reach new audiences. In addition, prizes increasingly contribute to technology diffusion towards potential end-user communities (e.g. competition on satellite navigation signals for maritime applications), and can provide useful outreach opportunities to the general public for the space community.

In the United States, over the years, NASA has been organising ad hoc challenges open to students and commercial firms with prizes ranging from a few hundred thousand dollars to several million US dollars. NASA initiated, for example, the Centennial Challenges Program in 2005, which today includes four main competitions: the sample return robot challenge (i.e. demonstrating autonomous robotic capabilities to locate, retrieve and return specific sample types to a designated zone), the vascular tissue challenge (i.e. targeting ways to create human vascularized organ tissue in a controlled laboratory environment), the Mars ascent vehicle prize (i.e. technologies to return samples from Mars) and the CubeQuest challenge (i.e. developing small satellites capable of advanced operations near and beyond the Moon). NASA annually allocates some USD 4 million to these prizes (NASA, 2016). In 2010, the US National Space Policy encouraged further use of prizes and challenges to spur innovation (White House, 2010).

In Europe, students in information technologies are regularly sought out to participate to the ESA's annual Summer of Code in Space (SOCIS) competition to develop space-related open source software. In France, the ActInSpace hackathon has been organised in 2014 and 2016 by the French space agency CNES with the ESA and the Airbus Group. The competition is open to international teams for diverse space technologies' challenges, with teams from 24 cities in 12 countries for the 2016 edition (ActInSpace, 2016). In Germany, the DLR organised for the first time in 2016 the INNOSpace Masters competition aiming to demonstrate transfers of technologies and expertise from other industries to the space sector (or spin-ins), again with the ESA and Airbus. Some 50 start-ups, business enterprises, universities and research institutes from 8 European countries competed for the prizes in 2016, with topics ranging from flexible platform concepts, intelligent components and wireless technologies integrated in satellites to link subsystems instead of cables (INNOspace, 2016). Other prizes exist in Europe, like the European Satellite Navigation Competition, offering both money and in-kind prizes rewarding the best services, products and business cases that use satellite navigation (ESNC, 2016). In Mexico, the annual SpaceBootCamp is organised by the Mexican Space Agency (AEM) over three days, with competitions involving hundreds of students grouped in teams, and professionals from different sectors, spurring ideas for developing and improving space systems or applications. In 2015, the activity involved 400 students from 133 universities and research centres (CONACYT, 2015; Agencia Espacial Mexicana, 2016).

On the private sector side, several prizes have also attracted attention. The competition organised by the Ansari XPRIZE Foundation was an important source of inspiration in the late 1990s and early 2000s for commercial human spaceflight endeavours. Established aerospace companies and entrepreneurs (some supported financially by new and successful Internet companies), competed to develop a space vehicle capable of carrying three people at a 100 kilometre altitude, twice within two weeks. Although not reaching orbit, many planned space vehicles were based on past governmental programmes and/or off-the-shelf space technologies. Although few concepts reached the demonstrating stages, they contributed to test ideas and attracted a lot of interest from public bodies and the media. In 2004, the foundation awarded USD 10 million to SpaceShipOne, which was later bought by the newly formed Virgin Galactic company. In 2007, the Google Lunar XPRIZE was introduced, promising to award USD 20 million to the first privately funded team (no less than 90% of private funding) able to land a rover on the Moon, travel 500 metres on the surface and transmit back high-definition video and images before the end of 2017 (XPRIZE Foundation, 2016). The Lunar Prize was first intended to be funded by NASA, but the involvement of Google allowed for a bigger prize and the inclusion of non-US participants. As of summer 2016, the deadline is approaching and several companies are still in the process of developing their rovers and securing space launch opportunities. After submitting an application to receive the government's authorisation for the first-ever commercial lunar mission, the company Moon Express received a formal agreement from the US Federal Aviation Administration in April 2016 (Moon Express, 2016).

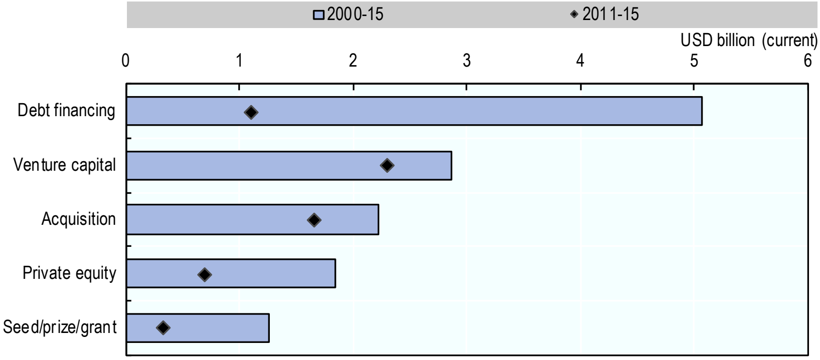
Private sources of funding

Although media coverage has grown concerning the new space entrepreneurs, private sources of investments for space projects are difficult to track. Current evidence sees these investments growing, although the amounts still pale as compared to public funding.

In the case of commercial satellite telecommunications, 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. Several operators have become publicly traded corporations. They 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, DigitalGlobe, a US satellite imaging company, launched initial public offerings of stocks in 2010, using the proceeds to build its next generation of satellites. But with hardened international competition, newcomers with new business models, and the necessary rollout of new technological solutions, access to finance is becoming more problematic for established players.

In terms of the more recent space companies, funding is particularly crucial for their creation and growth, in particular, in the early stages. The main sources of funding for start-ups are usually the founder's own funds, with money from the inner circles (friends and family), bank loans, equity capital (including from business angels and venture capitalists) and government support. The difficulties come from high-risk entrepreneurial activities and information asymmetries between investors and entrepreneurs. New businesses also have capital and human resource constraints, insufficient collateral and often lack of a roadmap. Seed and early-stage funding can help entrepreneurs gain access to finance and overcome the "valley of death", identified in Chapter 1, which can result from the difficulty of obtaining project or debt financing or venture capital for higher risk projects.

Figure 3.6. **Financing of space start-up ventures**



Note: Start-ups are defined in the report as companies that began as angel- and venture capital-backed start-ups.

Source: Tauri Group (2016), "Start-up space: Rising investment in commercial space ventures", https://space.taurigroup.com/reports/Start_Up_Space.pdf.

According to a recent report by the Tauri Group, equity and loan funding (including seed funding, venture capital, private equity, acquisitions, public offerings, loan financing and export credits) of space start-up companies amounted to USD 2.7 billion in 2015, with USD 13.3 billion in investment and debt financing raised in the period 2000-15 (Tauri Group, 2016). The report identified more than 250 different investors, including philanthropists, venture capital groups, private equity groups and banks, located in different parts of the world, with two-thirds located in the United States. In 2015 alone, Google and Fidelity invested around USD 1 billion in the SpaceX company.

Finally, crowdfunding is a new third-party financing mechanism that is growing rapidly. It is a collective Internet fundraising tool enabled by social networks. It allows financing access to even novice entrepreneurs, while engaging the general public with science and innovation (OECD, 2014). Used seldom in the space sector until recently, several examples are now cropping up, particularly in North America, of students raising funds online to develop their very small satellite projects.

Infrastructures and platforms enabling knowledge flows

Uses of public testing services and facilities

In countries with space programmes, space agencies and public research organisations have at their disposal highly sophisticated and expensive ground- and space-based infrastructure, often representing several decades of public investments. These resources are increasingly made available to external business and academic users at favourable terms to stimulate innovation and the development of private sector products and services, in particular those of start-ups and SMEs, through the provision of testing and demonstration services.

Public and private sector actors can benefit from extensive hardware and system testing in government laboratories and facilities, as well as suborbital flight opportunities (on balloons, sounding rockets, suborbital vehicles). The testing that some of these research organisations provide is essential for technology prototype development and flight qualification. Test facilities for space vehicles include wind tunnels, propulsion test cells, vacuum chambers, cryogenic chambers, microgravity, acoustic and vibration testing facilities, as well as computer simulation facilities and services. Space agencies also offer opportunities for flight demonstration on government space missions. OECD space agencies providing such services include Canada, France, Germany, Japan, Korea, the United Kingdom and the United States. The European Space Agency also provides testing services for its member countries.

Specific support programmes include the NASA Flight Opportunities programme (suborbital research flight programme), the Cubesat Launch Initiative (free launch opportunities for research cubesat missions) and the reimbursable or non-reimbursable Space Act Agreements. These provide external users access to available government space infrastructure and services (including astronaut time). Nanoracks is one of the companies benefiting from such an agreement by providing commercial launch and research services on the International Space Station. Examples in Europe include the UK Wind Tunnel Facility project (providing access to selected wind tunnels free of charge), and the German GATEs for German Galileo Test and Development Environments project, which provides an artificial test bed for Galileo satellite navigation applications and services. Furthermore, the ESA’s General Support Technology Programme (GSTP) gives companies, in particular SMEs and academic institutions, hosted payload flight opportunities on suborbital rockets, launchers, satellites and the International Space Station (ISS). The GSTP is an optional ESA programme, making the service only available to companies from subscriber countries. In Korea, the STAR-Exploration programme provides manufacturing facilities and equipment for start-ups so they may develop prototypes.

Clusters, incubators and platforms of co-operation

Clusters, incubators and platforms of co-operation play an important role in space innovation. Clusters are geographic concentrations of research institutions, higher education, business enterprises, and other public and private entities that facilitate collaboration on complementary economic activities

(OECD, 2016c). While some of the world's leading clusters specialise in high-technology industries (e.g. Silicon Valley, Bangalore), they are also found in many different economic sectors (e.g. agriculture). Incubators are often linked to clusters, but not only. They are organisations designed to accelerate the growth and success of entrepreneurial companies. They provide an array of business support resources and services to help start-ups (e.g. office space, seed capital, coaching, networking connection). Platforms of co-operation are government programmes set up to encourage public-private and universities interactions, with the aim to transfer technologies.

Many countries and regional authorities have supported the development of space-related clusters over the years, creating them from scratch with incentives for research centres and industry to relocate, or building on existing industry clusters. For instance, aerospace clusters have traditionally formed around research institutes or university centres. There are now a growing number of clusters nationally, such as the French Aerospace Valley near Toulouse, the Italian aerospace clusters of Lazio and Torino, the Korean high-technology clusters in Daejeon, the clusters in German Bavaria or Bremen. The most recent UK space industry cluster is located in Harwell. The European Centre for Space Applications and Telecommunications, the UK Satellite Applications Catapult, the Rutherford Appleton Laboratory (RAL) and the UK ESA business incubator centre are all within walking distance to one another. In the United States, many clusters are closely connected to NASA research centres, or large aerospace groups. There are also increasing international interactions between clusters, as already indicated in Chapter 2.

Since there is a growing recognition that start-ups and entrepreneurs play an important role in innovation and technology commercialisation, incubators for space start-ups are also being set up throughout OECD countries (Table 3.2).

For example, to cater to the needs of entrepreneurs, the European Space Agency, in co-operation with some of its member states, has created a network of ESA national business incubator centres or BICs (i.e. Belgium, Czech Republic, France, Germany, Italy, the Netherlands, Portugal, Spain, Sweden and the United Kingdom) with planned offices in another three countries (Austria, Ireland and Switzerland). The ESA BICs have so far supported some 400 start-up companies and the numbers are rising, with 120 new start-ups per year (ESA, 2016). For example, in the BIC Bavaria, 105 start-ups are currently active, representing 1 300 jobs created, and an 87% survival rate after five years (Salzgeber, 2016). There are also several start-up programmes backed by large corporations in North America and Europe in particular (e.g. Airbus, Boeing and Lockheed Martin).

Table 3.2. **Selected incubators in Europe for start-ups with space-related products and services**

Science Park Graz	Austria
iMinds	Belgium
ESA BIC Flanders	Belgium
ESA BIC Redu	Belgium
Aerospace Research and Test Establishment (VZLÚ)	Czech Republic
ESA BIC Prague	Czech Republic
Bordeaux Technowest	France
CEEI-Theogone Incubator	France
ESTIA Entreprendre	France
SATT Sud Est	France
SATT Midi-Pyrénées: Toulouse Tech Transfer	France
SATT Sud Est (Marseille)	France
Technologiepark Tübingen-Reutlingen (TTR)	Germany
ESA BIC Bavaria	Germany
ESA BIC Darmstadt	Germany
Ireland National Space Centre	Ireland
ESA BIC Lazio	Italy
ESA BIC Noordwijk	Netherlands
Oslotech StartupLab	Norway
Nordic Innovation House	Norway
ESA BIC Portugal	Portugal
Barcelona Activa	Spain
BIC Berrilan	Spain
Ciudad Politécnica de la Innovación – Universitat Politècnica de València	Spain
Parc Científic Tecnològic i Empresarial	Spain
Parc Científic – Universitat de València	Spain
Parque Científico de Alicante	Spain
Parque Científico-Empresarial	Spain
Vigo Free Trade Zone Consortium	Spain
ESA BIC Barcelona	Spain
ESA BIC Madrid	Spain
ESA BIC Sweden – Lulea	Sweden
ESA BIC Sweden – Trollhättan	Sweden
ESA BIC Sweden – Uppsala	Sweden
Surrey Research Park (Guildford)	United Kingdom
ESA BIC Harwell	United Kingdom

Source: Adapted from ESNC (2016), European Satellite Navigation Competition website, www.esnc.info.

Other platforms of co-operation are being set up throughout OECD countries to enable space technology transfers and the development of space applications.

- The Norwegian Centre for Integrated Remote Sensing and Forecasting for Arctic Operations (CIRFA) is a research network established in 2014 by the Norwegian Research Council, with 6 public research partners and 12 industry partners. The objective is to conduct research on methods and technologies that can reliably detect, monitor, integrate and interpret multi-sensor data describing the physical environment of the Arctic, and assimilate information into models to perform predictions of sea ice state, meteorological and oceanographic conditions on both short and long timescales.
- The French Booster programme supported by the public-private co-ordination group CoSpace with the CNES also aims to support the development of space applications in different areas. Four boosters have been established in conjunction with existing technology clusters: the Booster Morespace in Bretagne, focusing on ocean-related applications, and Boosters Nova near Toulouse, PACA in Provence and Seine Espace near Paris, the latter three targeting several sectors such as "smart cities", the environment and energy (Niedercorn, 2016).
- Finally, the US Center for the Advancement of Science in Space (CASIS) is providing a range of different services. In 2011, it was designated as the sole manager of the International Space Station's US National Laboratory (the American portion of the space station). Its main roles are to facilitate and accelerate space-based research, as well as raising awareness about scientific activities in space. CASIS can provide seed grants, advice on payload development, organise the space launch to academia and start-ups in particular (CASIS, 2015).

Regulations

The legal and regulatory framework determines the rules according to which space actors operate and can innovate. During the 1960s and 1970s, a set of international treaties and principles was enacted establishing the peaceful uses and non-appropriation of outer space. Based on this regime, governments are liable under international space law whenever a space object is launched from their territory, even if it is by a private entity. This international regime is complemented by national space laws, to mitigate the risks for governments involved in space activities with an appropriate national licensing structure that regulates institutional and private space activities taking place on their soil. Since the 1980s, the rapid progression of commercial space activities that followed the privatisation of international telecommunications organisations, such as Intelsat and Eutelsat, has spurred the swift development of national laws and regulations worldwide.

Recent initiatives include the US Commercial Space Launch Competitiveness Act, which provides long-term extensions of the "learning period" that limits the Federal Aviation Administration's ability to enact regulations regarding the safety of spaceflight participants, as well as for government indemnification of third-party damages for commercial launches beyond a level that the launching company must insure against (US Congress, 2015). The UK government is currently envisaging the development of a commercial spaceport with accompanying regulations, to spur innovation in space access. In terms of possible future innovative space activities, the US Commercial Space Launch Competitiveness Act further grants rights to resources extracted by US companies on asteroids, the Moon and other celestial bodies. Luxembourg is also supporting the development of a legal framework about the future ownership of minerals extracted from asteroid mining. Both countries are associated with the US company Planetary Resources, which has ambitions to send its first mission by 2020 (Planetary Resources, 2015).

Regulations for space activities also include rules pertaining to intellectual property rights (such as patents, trademarks, designs and copyrights), giving innovators ownership of their knowledge creations and can facilitate the transfer of knowledge and technologies. The regimes are very much nation-specific, with space administrations providing specific rules *vis-à-vis* academia and the private sector in the case of R&D grants.

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Chapter 4.

Forward look: Where space innovation could make a difference

Based on current space innovation trends, this chapter features some forward-looking views, revisiting a decade later the initial scenarios that were first published in the OECD Space 2030 publications, which projected possible evolutions of the space sector. It also presents selected sector-specific developments and explores some of their possible roles in meeting some major societal challenges, like the digital divide and climate change management. Some space sector-specific developments like human spaceflight and space exploration are also examined.

Exploring future trends in the space sector

Projecting possible developments of any economic sector is a difficult exercise. Almost 14 years ago, the OECD conducted a 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 (i.e. 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; 2005). The project included alternative future scenarios to model possible trajectories of space activities, the drawing of technology maps (Table 4.1) and the elaboration of key recommendations to make the sector more sustainable. Many of these policy guidelines are still valid today, as discussed in Chapter 1. They aimed at implementing a sustainable space infrastructure, encouraging public use of that infrastructure and encouraging private sector participation.

Table 4.1. **Possible space innovations by 2030 (anticipated in 2004)**

Innovations anticipated in 2004	Situation in 2016
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, CO_2 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 3D 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.	Fractionated mission architectures are already being 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 already leading to new commercial ventures (constellations of very small satellites).

Source: Adapted from OECD (2004), *Space 2030: Exploring the Future of Space Applications*, http://dx.doi.org/10.1787/9789264020344-en.

To assess the long-term demand for space applications, a scenario-based approach was used to consider the role that the space sector might play in alternative visions of the future. Based on a large international expert consultation, three scenarios were developed. More than a decade later, most of the hypotheses remain valid.

The three synthesis scenarios provided indeed very different visions of the world, ranging from the optimistic outlook of "Smooth Sailing", which foresaw advances to improve human conditions in a spirit of international co-operation, to the darker picture depicted by "Stormy Weather", which described a world where economic blocks disagree on how to deal with major societal challenges with serious crises in international relations, while the environment sharply deteriorates in parts of the world. A medium scenario, "Back to the Future", saw more regionalisation, opposing geopolitical blocks with moderate economic growth in the west but substantial economic growth in the east and moderate technology progress. Even the more optimistic scenario was not without its darker side, notably the rise of non-state actors increasingly capable of using violence. Despite these differences, the scenarios shared some common ground with respect to their impacts on space developments:

- Military space plays an important role in all three scenarios, although to different degrees. Even in the relatively peaceful world of "Smooth Sailing", security concerns are high and a number of countries are anxious to strengthen their military space capability (e.g. Earth observation satellites, telecom for the military). This results in a robust demand for military and dual-use space assets worldwide.

- Civil space also plays an important role in all scenarios, although for different reasons. In "Smooth Sailing", its role in fostering international co-operation to solve world problems is central. In "Back to the Future", prestigious projects and attempts to increase soft power give importance to spectacular ventures to the Moon or to Mars. Space is also called upon to solve world problems, but in a less co-ordinated, more fragmented and less effective manner. Even in "Stormy Weather" the outlook for civil space is not bleak, although the resources devoted to it may be quite small. As in the other scenarios, the development of dual-use technologies remains a priority; prestige and soft power are also important drivers. Important gains can still be made if space firms are able to demonstrate that space solutions can bring about major savings for cash-strapped governments.

- Commercial space varies unsurprisingly more than military space across scenarios, as customers range from governments to retail consumers. Commercial applications thrive in the "Smooth Sailing"

> scenario, remain strong in the "Back to the Future" scenario, but are more constrained in the "Stormy Weather" scenario (international markets are smaller). It is worth noting that for many space firms, the "Back to the Future" scenario may be the most favourable because of the protection it offers against competition from foreign firms. In all three scenarios, commercial space benefits from rising military budgets for space.

When examining the systems and applications that were identified, and comparing them with current trends, a number of developments occurred much faster than anticipated (e.g. satellite-derived data and links used extensively for entertainment and e-commerce); a few are in development but not fully deployed, although there has been progress (e.g. traffic management for aircraft); and others are still in the promising stages (e.g. adventure space tourism, in-orbit servicing) (Box 4.1).

The next sections review and update a small selection of these applications, with a view to give an indication of the challenges and opportunities that further innovations could bring.

Will new satellite constellations help bridge the digital divide?

The digital divide is still a major issue in 2016. It is defined as the gap between individuals, households, businesses and geographic areas in their access to information and communication technologies, and particularly in their use of the Internet for a wide variety of activities. Satellite-based broadband is considered one of the technologies that could help bridge the digital divide, especially in areas where other terrestrial alternatives are not available or are too expensive to deploy. But despite the innovations shaping the sector and the growing involvement of private actors, with many new commercial constellations planned over the next five years, business success is still uncertain.

Currently, 57% of the world's population lives without regular access to the Internet, mostly in developing economies (ITU, 2015). A much higher proportion, 68%, has no mobile or fixed broadband subscription. Broadband is increasingly considered essential for economic growth and social inclusion in both developing and developed countries, and access to broadband is still also an issue in OECD countries (Figure 4.1). The 2016 issue of the "Broadband progress report" of the US Federal Communications Commission found that 39% of rural Americans lacked access to high-speed broadband (25 Megabit per second download/3 Mbps upload), in contrast to only 4% of urban Americans (US Federal Communications Commission, 2016).

Box 4.1. **Promising space systems and applications by 2030**

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

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)
- 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).

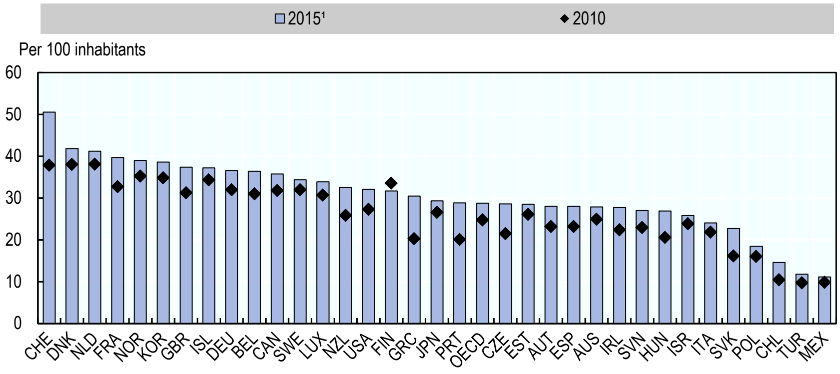
Outsiders:

- adventure space tourism (suborbital then orbital)
- in-orbit servicing
- power relay satellites.

Source: Adapted from OECD (2004), *Space 2030: Exploring the Future of Space Applications*, http://dx.doi.org/10.1787/9789264020344-en.

Figure 4.1. **Fixed broadband penetration in OECD countries**

Subscriptions per 100 inhabitants



1. Data is for Q1 and Q2 2015.

Source: OECD (2015), "Broadband database (Edition 2015)", *OECD Telecommunications and Internet Statistics* (database), http://dx.doi.org/10.1787/6c68455d-en.

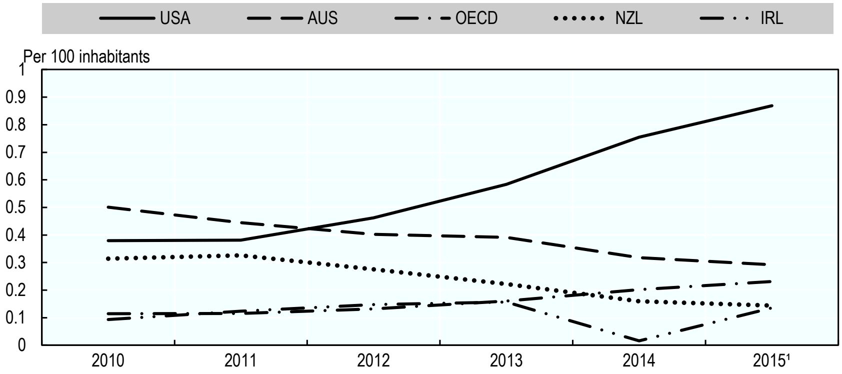
Broadband penetration has generally increased in OECD countries since 2010, but there are big national variations. According to the *OECD Broadband Database*, in the second quarter of 2015, OECD countries had on average 29 fixed broadband subscriptions per 100 inhabitants (Figure 4.1), with 3 countries (Switzerland, Denmark and the Netherlands) with more than 40 subscriptions per 100 inhabitants and 4 countries with less than 20 subscriptions per 100 inhabitants (Poland, Chile, Turkey and Mexico). Several countries experienced significant changes compared with 2010, with five countries (Chile, Greece, Portugal, the Slovak Republic and Switzerland) seeing the broadband penetration rate grow by more than 25%, compared to the OECD average of 14%. In Finland, the subscription rate fell between 2010 and the second quarter of 2015. In parallel, mobile broadband penetration in the OECD area has risen, with almost 1 billion subscriptions (OECD, 2015).

Satellite services are a growing part of the global communications infrastructure. Through unique capabilities, such as the ability to offer point-to-multipoint communications distribution with small receivers, to effectively blanket service regions, and provide a flexible architecture in hard to reach places, satellite services constitute an important complement to terrestrial telecommunications services. Satellite networks were the backbone of the intercontinental telephone network from the 1960s to the 1980s, and although fibre cables have supplanted their uses on routes with the highest traffic volume, satellite communications remain a significantly profitable business (around USD 18-22 billion annually for satellite communication operators). Satellite television remains the most successful space business, with direct-to-home satellite television broadcast almost universally available via one or more services, where the signal is received by satellite dishes and set-top boxes. In this favourable context, the rollout of satellite broadband services is still relatively new.

Satellite broadband penetration rates are still generally low in OECD countries, averaging 0.2 subscriptions per 100 inhabitants in the second quarter of 2015, with the United States having the highest subscription rate per 100 inhabitants at 0.9 subscriptions (Figure 4.2). Only four countries have penetration rates above 0.1 subscriptions per 100 inhabitants (Australia, Ireland, New Zealand and the United States), and among those, only the United States saw a positive growth in subscriptions between 2010 and 2015. Subscription rates fell significantly in Australia and New Zealand (New Zealand is currently extending its fibre infrastructure in rural areas).

Figure 4.2. **Satellite broadband penetration rates in the top 4 OECD countries**

Subscriptions per 100 inhabitants



1. Covers only the first two quarters of 2015.

Source: OECD (2015), *OECD Broadband Database*, www.oecd.org/sti/broadband/oecdbroadbandportal.htm.

Satellite broadband services have traditionally been delivered from the geostationary orbit at an altitude of 36 000 kilometres (km), where high latency (i.e. the time it takes from when a signal is broadcast until it is received at its destination) has been a problem. There are several ambitious projects in the pipeline which would rely on a very high number of smaller satellites in multiple planes in low-Earth orbit with latency comparable to that of terrestrial networks (Table 4.2). The reduced cost of satellite production and lower launch costs as described in the previous section are supposed to contribute to making the projects affordable, although the economic viability remains uncertain. At the moment, the OneWeb constellation is planned to deploy 648 satellites by 2020. OneWeb is partnered with Virgin and Qualcomm Inc. and counts Airbus and Bharti Enterprises among its investors (Azzarelli, 2016). Meanwhile, SpaceX announced in early 2015 plans to develop a constellation consisting of 4 000 satellites, and Boeing applied in June 2016 to the US Federal Communications Commission for a license to launch and operate a constellation of 1 400 to 3 000 satellites, also in low-Earth orbit (de Selding, 2016). These constellations would supplement terrestrial networks, providing bypassing possibilities for congested lines and extending networks to areas without infrastructure, while also proposing direct-to-home and mobile solutions both to individuals and companies (e.g. off-shore, in-flight broadband with rising air traffic, maritime transport, disaster management).

Table 4.2. **Selected satellite telecommunications constellations in lower and medium Earth orbit**

System/ operator	Status	Number of satellites	Orbit[1]	Main applications (radio spectrum frequency)
ORBCOMM	Operational	30	LEO	Narrowband data communications (e.g. e-mail, two-way paging, simple messaging)
Globalstar	Operational	45	LEO	Wideband mobile voice telephony and data services (L- and S-band)
Iridium	Operational	71	LEO	Wideband mobile voice telephony and data services (L- and S-band)
O3B (SES)	Operational	12	MEO	Broadband high-speed data services (Ka-band). Cellular backhaul and trunking, connectivity to mobile and maritime industries
OneWeb	Planned launches in 2017-19	600-900	LEO	Broadband high-speed data services (Ka- and Ku-band). Direct customers, cellular backhaul and enterprise connectivity to mobile and maritime industries
SpaceX	Uncertain (launch within five years)	4 000	LEO	Broadband high-speed data services (spectrum not yet allocated)
Boeing	Uncertain (filed for FCC license in June 2016)	1 300-3 000	LEO	Broadband high-speed data services (V- and C-band)
Leosat	Uncertain (feasibility study with Thales Alenia Space)	80-120	LEO	Broadband high-speed data services

1. LEO: low-Earth orbit (160 km-2 000 km altitude), MEO: medium-Earth orbit (2 000 km-35 000 km altitude).

Source: Adapted from US Federal Aviation Administration (2015), "2015 commercial space transportation forecasts", https://www.faa.gov/about/office_org/headquarters_offices/ast/media/Commercial_Space_Transportation_Forecasts_2015.pdf.

Despite growing demand for broadband accessibility worldwide, profitability and long-term sustainability of these projects remains to be confirmed. Similar constellations planned in the 1990s (i.e. Iridium, Globalstar and Teledesic) failed to find enough initial customers to attract further investments, but technologies were less advanced. The sheer size of the constellations also raises concerns about space debris and radio frequency interference. When it comes to space debris, operators insist that they will adhere to international guidelines, by which satellites would be designed to fall back to Earth and burn up in the atmosphere after the end of service. As for radio frequency interference, incumbent operators of geostationary satellite networks (some of which are investors in the new constellations) are concerned that satellites in low Earth orbit could jam the link between higher flying geostationary satellites and terrestrial satellite dishes. In any case, the promises of having to develop such large constellations are already impacting industrial processes and space manufacturing practices, as seen in Chapter 1.

Could big data from satellites play a major role in climate change management?

Meteorology was the first scientific discipline to use space capabilities in the 1960s, and today satellites provide observations of the state of the atmosphere and ocean surface for the preparation of weather analyses, forecasts, advisories and warnings, for climate monitoring and environmental activities. Three-quarters of the data used in numerical weather prediction models depend on satellite measurements (e.g. in France, satellites provide 93% of the data used in Météo-France's Arpège model) (OECD, 2014).

International co-ordination for climate monitoring is led by the Steering Committee of the Global Climate Observing System (GCOS). This group was created in 1992 by the World Meteorological Organization, the Intergovernmental Oceanographic Commission, UNESCO and the United Nations Environment Programme. Noting that climate change was at this time still poorly understood and documented in many countries, the GCOS championed the introduction of a range of "essential climate variables" or ECVs (physical, chemical or biological variables or a group of linked variables that critically contributes to the characterisation of Earth's climate) to more comprehensively and systematically monitor changes to the climate, in this way supporting the work of the Intergovernmental Panel on Climate Change (IPCC).

Earth observation satellites are firmly embedded in this international system to monitor climate change. Satellite data provide significant contributions to more than half of the 50 essential climate variables that are currently in use (Table 4.3). Some of these contributions can only be provided by satellite. This includes satellite radar altimetry, which measures the distance between the spacecraft and the Earth's surface below and can provide precise and continuous measures of global sea levels. Groundwater storage, recharge and discharge can be measured by changes and variations in Earth gravity, which, in turn are detected by satellites. In the case of the GRACE mission, which has been in operation since 2002, the gravity field is measured by taking laser range measurements between two satellites flying together in close formation. GRACE-FO, the follow-on mission, a joint project between NASA and the DLR, is scheduled for launch in 2017 (DLR, 2016). Satellite instruments are also responsible for measuring the chemical composition of the atmosphere and tracking the presence of carbon dioxide, methane, ozone and other greenhouse gases; the monitoring of sea ice, polar ice caps, ice sheets and glaciers (using altimetry, radar imagery and gravitational instruments like GRACE); and finally, the monitoring of extreme weather events through the observation of sea surface temperatures, wind speed and sea levels, and tracking storms via powerful optical satellites in geostationary orbit (ESA, 2015a).

Table 4.3. **Satellites' contribution to measurements of 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 (FAPAR), leaf area index (LAI), *above-ground biomass*, *soil carbon*, *fire disturbance*, *soil moisture*

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

Source: Adapted from ESA (2015a), *Satellite Earth Observations in Support of Climate Information Challenges*: *The CEOS Earth Observation Handbook*.

With new-generation satellites, both optical and temporal resolutions will be greatly improved, which will also lead to improved weather forecasting and climate modelling abilities, as well as better real-time monitoring of many variables in the next decade. Improved satellite instruments will allow a broader range of measurements, as new-generation satellites replace and supplement existing missions. Several new missions will be launched within the next five years, including Eumetsat's second-generation polar-orbiting satellites and third-generation geostationary Meteosats and the European Sentinels in the Copernicus programme, as well as several Chinese satellites (CEOS, 2015). Secondly, coverage and system resilience will be improved thanks to better international co-operation and more national providers and co-operative international missions. For instance, the Chinese FY-3 satellites will be the third pillar in the constellation of polar-orbiting systems, in addition to US and European satellites (World Meteorological Organization, 2015).

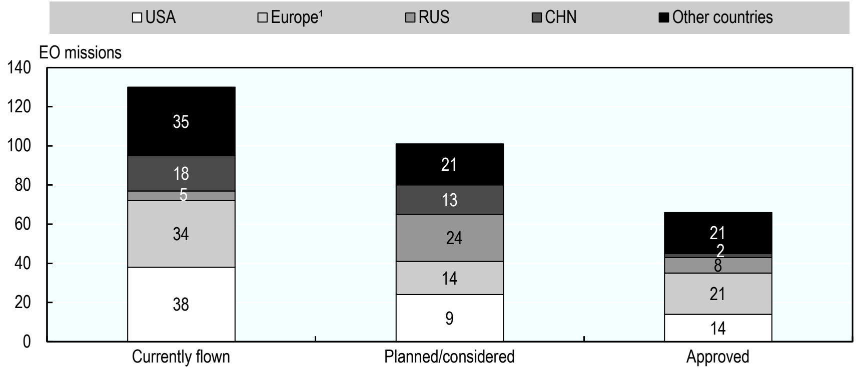
Approximately 130 Earth observation missions were operational as of October 2015, according to the database of the Committee for Earth Observation Satellites (CEOS, 2015), which is a co-ordination body for Earth observation satellite activities, originally established by the G7 countries in 1984. This includes missions and/or instruments to observe the atmosphere, land, oceans, ice and snow, as well as gravity and magnetic fields, and as such comprising weather satellites and many remote sensing satellites, operated by government agencies, thus excluding commercial constellations such as Skybox, GeoEye, WorldView, etc., which may appear in other databases for remote sensing. It should be noted that some of these missions are dual-use (e.g. Italy's CosmoSkyMED constellation), meaning that some of the instruments may also have commercial or military applications.

Many missions are also the result of international co-operation, with several agencies contributing instruments or other types of support (Figure 4.3). A satellite mission consists of one or several satellites (e.g. the GRACE mission consists of two satellites flying in formation), carrying one or several instruments. About 350 instruments are currently flown on missions supported by the CEOS (CEOS, 2016). The majority of missions is operated by the United States, Europe (including the ESA, Eumetsat and national agencies), the People's Republic of China (hereafter "China") and the Russian Federation. Future missions are in different stages of preparation and financial approval. So far, 66 missions have been approved to replace or supplement existing activities within the next 15 years, while another 100 are more uncertain, either planned or under consideration, some of which may eventually be abandoned (CEOS, 2016).

Innovation is progressing but continuity of observations remains a concern. Government programme cuts, satellite failures and delays pose a constant threat to measurement systems. Gaps in the time series of meteorological data were mentioned in the US Government Accountability Office's high-risk report for 2015 (US Government Accountability Office, 2015). The Steering Committee of the Global Climate Observing System reports that measurements of certain essential climate variables (solar irradiance and of sea-surface temperature at microwave frequencies) are at the risk of being discontinued (World Meteorological Organization, 2015).

Figure 4.3. **Current and planned Earth observation missions, 2016-31**

Status as of October 2015



Note: Only the nationality of the lead agency has been indicated to avoid double-counting.

1. Europe includes Earth observation satellites supported by the European Space Agency, the European Union, Eumetsat and national administrations of European countries.

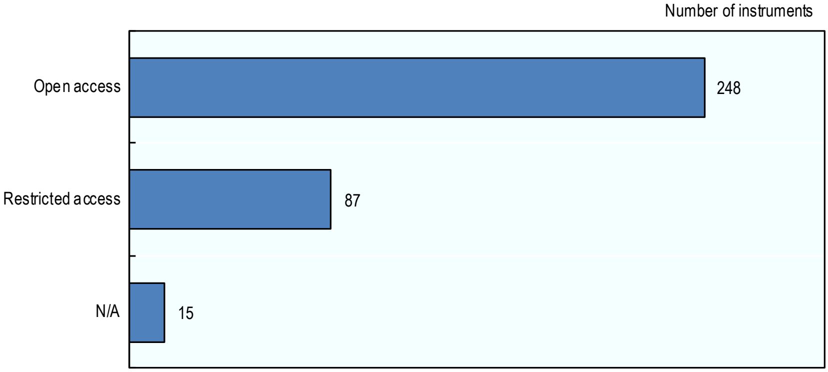
Source: Adapted from CEOS (2015), *CEOS Database*, http://database.eohandbook.com.

Storage and long-term preservation of data is also an issue. With increased optical and temporal resolution, satellite missions produce an increasing amount of data. For instance, it is estimated that each Sentinel satellite will produce 1.5 petabyte of raw data per year, whereas the German satellite data archive, which stores data from national Earth observation missions (Tandem-X, TerraSAR) and Sentinel missions, has a maximum 50 petabyte storage capacity (Schreier, 2015). In the United States, the NASA Big Data Task Force estimates that the NASA Earth Observing System Data and Information System (EOSDIS), the archives for Earth observation data, may surpass 350 petabytes of data by 2030 (NASA, 2016a). It may become more difficult to decide which data to archive for long-term conservation and which to use for further processing and then discard. This raises the issue of data access and distribution. To maximise the societal benefits of the data, data need to be efficiently shared and distributed, and raw data must be transformed into value-added products. Figure 4.4. shows the data accessibility of instruments flown on current Earth observation missions, which are supported by the Committee of Earth Observation Satellites.

Data accessibility is quite good, with more than 70% of the Earth observation data subject to some type of freely available open access mechanism, open access by advanced protocol (additional steps needed) or open access by simple registration. One-quarter of the data are restricted, providing exclusive national or regional access, for commercial and other reasons (for instance, no available distribution point) (CEOS, 2016). 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 or the NASA EOSDIS image archives.

Figure 4.4. **Data accessibility of selected satellite instruments**

Instruments flown as of 15 October 2015



Source: Adapted from CEOS (2015), *CEOS Database*, http://database.eohandbook.com.

There are discussions in the community on how the development of commercial downstream services could affect data accessibility policies in the long run. Public-private partnerships are one of the available options to pool costs and reduce government spending on satellite missions and on long-term data storage, but this could have a negative impact on data sharing and accessibility.

In the United States, where major institutional missions are planned, several start-ups have launched or are planning to launch small satellites for commercial weather services, and it has been suggested that government agencies could purchase commercial products to complement their own data and increase the resilience of the weather forecast system and future models (American Institute of Physics, 2016). The US National Oceanic and Atmospheric Administration (NOAA) has, for instance, developed a commercial space policy as of January 2016, which regulates and guides the organisation's use of commercial products and services (e.g. data acquisition, hosted payloads, rideshares, launch services). In line with these guidelines, the organisation could potentially purchase commercial data, provided existing service quality can be sustained (US Department of Commerce, 2016).

What discoveries could space sciences and space exploration uncover?

Space exploration is a key driver for investments in innovation and science, and it constitutes an intensive activity for space agencies, academia and industry. Space sciences and planetary missions have developed markedly over the years, with new actors joining in, and important advances are expected in space sciences in the coming decade, with several missions planned in both astrophysics and planetary exploration. In addition, several large-scale terrestrial infrastructures will start operations before 2030, with different ranges of telescopes. All of this will provide new and significantly more scientific data about the origins of the universe (early star and galaxy formation) and about planets that could harbour life (exoplanets, icy moons of Jupiter). These missions play also an important role in enticing public interest in space activities and motivating future generations of scientists and engineers.

Preparing space science and planetary missions is a highly complex and collaborative exercise, pushing innovative solutions into areas such as power generation, propulsion, navigation, instrumentation (optics, lasers, mirror coatings) miniaturisation and radiation hardening, to name a few. The scientific community, government agencies and industry suppliers work closely together over extended periods of time, enabling extensive knowledge transfers. It usually takes more than a decade between a mission selection and its launch. Then, in the case of planetary mission, it may again take years before a scientific probe arrives at its destination (i.e. typically up to two years for Mars). For example, the US National Research Council conducts decadal surveys to identify future national priorities in different areas of research. The James Webb Space telescope and the Wide-Field Infrared Survey Telescope (WFIRST) were the highest priority large-scale missions back in 2000 (US National Research Council, 2001) and 2010 (US National Research Council, 2010) respectively. The next survey will take place in 2020. These very complex missions are still to be launched and both are detailed below. In the case of the European Space Agency, its current missions are elaborated in the European Cosmic Vision 2015-25 strategy (ESA, 2015b).

One of the most anticipated missions in astrophysics is the James Webb Space Telescope (NASA, with participation from the ESA and the Canadian Space Agency) scheduled for launch in 2018 (NASA, 2016b). The telescope will be located 1.5 million km from Earth (compared to the Hubble telescope’s 570 km altitude in low Earth orbit), with a large, foldable mirror and the capability to capture low-energy near-infrared and infrared light, which should enable it to look back to the formation of the first stars. There are other high-priority missions planned, such as the infrared WFIRST telescope (NASA) in the mid-2020s destined to explore exoplanets; the

ATHENA high energy X-ray telescope (ESA) in the late 2020s, for the study of dark matter and black holes; and a gravitational wave observatory in 2034. NASA is currently identifying possible future projects that would dig deeper into existing research questions, including X-ray and far-infrared observatories, a multi-wavelength observatory, and an optical and near-infrared observatory optimal for exoplanets (NASA, 2016d). China's ambitious space sciences programme deserves special mention. The Chinese Five-hundred-meter Aperture Spherical Radio Telescope's (FAST) installation was finalised in July 2016 and is scheduled to be operational by fall 2016. China is furthermore planning five space science satellites within the next five years (including a collaborative mission with the ESA). They will focus on the observation of solar activities and their impact on the Earth's environment and space weather, the analysis of water recycling, and probing of black holes.

There are also many robotic space exploration missions underway and planned by space agencies. NASA's Juno spacecraft successfully entered Jupiter's orbit in 2016 for example. The spacecraft carries a titanium radiation vault to protect the most sensitive instruments from radiation inside Jupiter's powerful magnetic field (Jet Propulsion Laboratory, 2016). In 2022, another mission should be destined for Jupiter with the ESA Juice probe, which will explore Jupiter and, in particular, its moons, looking for traces of ice and water (ESA, 2015b). The Moon and Mars will be subject to several missions in the coming years. China, India and Korea are all planning missions to the Moon. India's project, the Chandrayaan II involves an orbiter, a lander and a rover, scheduled to launch in 2017-18 (ISRO, 2016). China plans a sample return mission in 2020 (China's State Council, 2016), while Korea envisages a lunar orbiter and lander in the late 2020s. Forthcoming missions to Mars include the ESA and Roscosmos Exomars rover, now scheduled for launch in 2020 (ESA, 2016). The first part of the Exomars mission, the Mars orbiter and Schiaparelli, a technology demonstration lander, launched in March 2015 should arrive in Mars' orbit in the last quarter of 2016 (ESA, 2016). China is also planning a Mars lander, scheduled for launch in 2021 (China's State Council, 2016). The next NASA Mars mission dubbed InSight is scheduled to launch in late 2018 (NASA, 2016d). Asteroids are also destinations for scientific discoveries, with, for instance, the OSIRIS-REx mission that will travel to the near-Earth asteroid Bennu to collect a sample of surface material to return to Earth for study, with a launch planned in fall 2016.

The issue of big data management has been raised elsewhere in this report but is particularly pertinent in the area of astrophysics and astronomy, where future installations will generate unprecedented amounts of data. The first phase of the Square Kilometre Array (SKA) telescope project in

South Africa is expected to produce 160 terabytes of raw data per second (SKA Telescope, 2015). The Large Synoptic Survey Telescope project in Chile is expected to produce a total data volume of 100 petabytes after processing over ten years of operations. The Dutch government, one of the partners in the SKA project, has established the ASTRON and IBM Center for Exascale Technology to carry out fundamental research into innovative technologies for computing, processing and storage (Netherlands Institute of Radio Astronomy, 2012). Exascale computing refers to systems capable of at least one exaFLOPS, or a billion billion calculations per second. Further needed innovations in data processing and artificial intelligence will be pushed by these ever-demanding large-scale scientific space programmes and contribute much to the science coming out of these projects in the next decade.

Are entrepreneurs bringing space exploration to new frontiers?

Space exploration has been dominated by government actors for decades, mainly for scientific and prestige reasons. This is likely to continue in the future, but commercial actors have started to play a more active role, driving space innovation towards unexpected areas. Several entrepreneurs share a vision of colonising space at some point in the future, either for human settlement or industrial purposes, while other investors focus on the exploitation of space resources from nearby asteroids. Although some projects are attracting much media attention, it remains to be seen how many, if any, of these projects, will reach fruition.

Investors from information technologies and other non-space sectors focus strongly on lowering the cost of access to space. So far, the emergence of new Internet company-related start-ups have triggered a revolution in small satellites, and it could also bring about cheaper launch technology, by employing new manufacturing and processing techniques, and by taking into account reusability at the systems design level (see Chapter 1). Examples include SpaceX with its launchers Falcon 9 and Falcon-Heavy (maiden launch scheduled later in 2016 (SpaceX, 2016), with reusable first-stage engines, and Blue Origin, which is currently developing the reusable B4-engine for use on its own orbital launch system and possibly other US launchers as well. Additionally, Blue Origin has further developed the reusable suborbital manned rocket, New Shepard, which is a vertical take-off, vertical landing vehicle (Blue Origin, 2016).

In addition to sending satellites into orbit, an important milestone for many of these companies will be the commercial transport of astronauts to the International Space Station. Only China and the Russian Federation can launch astronauts to orbit, since the retirement of the US space shuttle in 2007. NASA is contracting SpaceX and Boeing to develop, test and certify crew capsules for the transport of four astronauts and cargo to the station. Currently, NASA has a contract with the Russian Space Agency for transport on the Russian Soyuz launcher. If the schedule holds, SpaceX would be the first to launch its Dragon capsule on a Falcon 9 in the last quarter of 2017 (Messier, 2016). Boeing's launch schedule was revised, and its CST-100 Starliner is scheduled for launch in early 2018 (Foust, 2016). A programme review carried out by the US Government Accountability Office found that both companies had still several important test milestones to pass, and that delays could be envisaged (US Government Accountability Office, 2016). NASA has extended its contract with the Russian Federal Space Agency through 2018 to ensure that it has continued access to the International Space Station.

Suborbital space tourism is also one of the activities pursued by entrepreneurs. Several start-ups, including Virgin Galactic, Xcor and Blue Origin, backed occasionally by large corporate groups, are at advanced stages of testing. All three aim to use fully reusable space systems for their services. Virgin Galactic, which seemed the most advanced, has had several setbacks, especially in 2014 when SpaceShipTwo crashed during tests, killing one of the pilots, but the new SpaceShipTwo, which was awarded an operator licence by the Federal Aviation Administration in summer 2016, should soon undergo flight tests (Virgin Galactic, 2016a). SpaceShipTwo aims to carry two pilots and six passengers and should be launched airborne, from a Boeing 737, and then land horizontally on the runway (Virgin Galactic, 2016b). Xcor Aerospace is developing Lynx, a horizontal launch and landing spaceplane, with one passenger seat available in the front next to the pilot (XCOR Aerospace, 2016). Both planes conduct tests in the Mojave Spaceport in California. The New Shepard launcher from Blue Origin should be proposing vertical launches, with a pressurised six-passenger capsule atop a booster (Blue Origin, 2016). The capsule's return to Earth should be slowed down by parachutes and retro-thrusters.

Future space tourism activities should be carried out from dedicated, licensed spaceports, some of which already exist and can be adapted, while some of them have been specifically constructed in anticipation of future developments. In the United States alone, there are ten commercial spaceports; in Alaska, California, Florida, Oklahoma, Texas and Virginia. Three of these are located next to government launch facilities (Vandenberg in California, Cape Canaveral in Florida and Wallops in Virginia) (US Federal Aviation Administration, 2016). Other countries have also expressed interest in constructing spaceports, such as the United Kingdom. Spaceports are often strongly supported by regional governments as a means to attract or boost local industry. However, the question remains whether space tourism will generate enough flights and launches to ensure profitability.

Several commercial projects target the exploration of Earth's nearest neighbours. The most prominent example is SpaceX's unmanned mission to Mars, with a possible launch envisaged as early as 2018 (Davenport, 2016). The plan includes a landing with the Dragon-2 spacecraft and repeated supply missions with 26-month intervals, preparing for manned missions which could possibly take place in the late 2020s. NASA, which will not be attempting any manned Mars missions before the 2030s, has expressed interest in providing technical support for the landing attempt, in exchange for Martian entry, descent and landing data (NASA, 2016c). A less ambitious, but equally important, initiative is the Google Lunar XPRIZE, described in Chapter 3. Some USD 20 million will be awarded to the first privately funded team who is able to land a rover on the Moon, travel 500 meters and transmit back high-definition video and images. Out of 16 participating teams, 2 now have launch contracts for 2017 (one with SpaceX and the other with RocketLab). The remaining teams have until the end of 2016 to make verified launch agreements (XPRIZE Foundation, 2016). Should one, or several, of the teams succeed, it could have a significant impact on future commercial exploration efforts. These efforts could not only focus on the Moon, but also on asteroids and other celestial bodies. The Moon could therefore prove to be an important test bed for habitation and resources extraction.

The exploitation of space resources is another avenue pursued by private investors. The asteroid mining company Planetary Resources has identified a list of interesting near-Earth asteroids for future satellite reconnaissance missions, looking for asteroids with water or metals (platinum) suitable for robotic extraction. The company launched a technology demonstrator in 2015 (the Arkyd-3 spacecraft) and has recently raised enough funds to deploy and operate Ceres, a constellation of ten micro-satellites equipped with infrared and hyper-spectral sensors to map surface temperature and measure water content, with launch planned in 2019. Originally equipped to search for water on asteroids, these sensors will for the moment be directed towards the Earth for commercial Earth observation applications (a memorandum of understanding has been signed with Bayer for co-operation and R&D for precision agriculture) (Planetary Resources, 2016a; 2016b).

Commercial exploration and exploitation of space was not an issue in the 1960s when the Outer Space Treaty was drafted, and it includes no specific provisions on commercial exploitation. As seen in Chapter 3, several countries are now drafting or modifying their national space legislation to accommodate such activities (e.g. Luxembourg and the United States).

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(92 2016 07 1 P) ISBN 978-92-64-26400-7 – 2016

Space and Innovation

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Consult this publication on line at ***http://dx.doi.org/10.1787/9789264264014-en***.

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ISBN 978-92-64-26400-7
92 2016 07 1 P

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