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Millan, Robyn M.; von Steiger, Rudolf; Ariel, Meir; Bartalev, Sergey; Borgeaud, Maurice; Campagnola, Stefano; Castillo-Rogez, Julie C.; Fléron, René; Gass, Volker; Gregorio, Anna

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Review

Small satellites for space science A COSPAR scientific roadmap

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Abstract

This is a COSPAR roadmap to advance the frontiers of science through innovation and international collaboration using small satellites. The world of small satellites is evolving quickly and an opportunity exists to leverage these developments to make scientific progress. In particular, the increasing availability of low-cost launch and commercially available hardware provides an opportunity to reduce the overall cost of science missions. This in turn should increase flight rates and encourage scientists to propose more innovative concepts, leading to scientific breakthroughs. Moreover, new computer technologies and methods are changing the way data are acquired, managed, and processed. The large data sets enabled by small satellites will require a new paradigm for scientific data analysis. In this roadmap we provide several examples of long-term scientific visions that could be enabled by the small satellite revolution. For the

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purpose of this report, the term "small satellite" is somewhat arbitrarily defined as a spacecraft with an upper mass limit in the range of a few hundred kilograms. The mass limit is less important than the processes used to build and launch these satellites. The goal of this roadmap is to encourage the space science community to leverage developments in the small satellite industry in order to increase flight rates, and change the way small science satellites are built and managed. Five recommendations are made; one each to the science community, to space industry, to space agencies, to policy makers, and finally, to COSPAR.
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Keywords: Small satellites; Space science

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0. Executive summary

In early 2017, an international study team of science and engineering leaders under the auspices of COSPAR embarked on a 2-year activity to develop an international scientific roadmap on Small Satellites for Space Science (4S).[1] For the purposes of this study, the committee defined "small satellites" to have an upper mass limit in the range of a few hundred kilograms. The mass limit is less important than the processes used to build and launch these satellites. Because CubeSats have played a critical role in the small satellite revolution, significant discussion on CubeSats and CubeSat technology-enabled small satellites is included. CubeSats are small satellites built in increments of 10 cm cubes (1 cube is called 1U or "unit", two 10 cm cubes together are known as 2U, and so on). This report is motivated by recent progress and results summarized in an article in Space Research Today (Zurbuchen et al., 2016) and a study by the US National Academies of Sciences, Engineering, and Medicine (NASEM, 2016).[2] The committee on the roadmap for small satellites for space science was tasked with addressing six specific questions:

1. What are the status and use of small satellites, in particular CubeSats, for science, their technological capabilities, and their key successes to date?
2. What is the scientific potential of small satellites both as stand-alone targeted missions, but also as secondary payloads, and as constellations and swarms?
3. What is the role of participating agencies and industry in developing standardized approaches to the development of spacecraft (hardware and software), and also ground-systems, etc. that enables this science?
4. What are the policies that support the growth of the number and types of CubeSats and CubeSat technology enabled small satellites, related to communications and frequency allocation, orbital debris, and launch vehicles?
5. What are successful models for international collaboration between teams developing and operating small missions, and how are data being shared and preserved for the future?
6. How can participating universities and international organizations learn from each other to share lessons learned and drive international collaborations in this rapidly moving field?

The COSPAR roadmap was developed by a study team that covers the broad range of scientific disciplines that use space-based observations, including Earth science, solar and space physics, planetary science, and astronomy. The study team includes scientists, engineers, and policy experts working in universities, public research institutions, and industry. The report aims to address the above questions in a way that is of value to space agencies internationally and their supporting governments, as well as non-profits and other private sector organizations that would be interested in promoting global SmallSat-based missions. Moreover, we hope to encourage the science community to leverage developments in the small satellite industry, and to pursue partnerships with industry and each other internationally, in order to increase flight rates and change the way small science satellites are built and managed, ultimately leading to significant advances in space science.

This roadmap document is in some ways similar to a trail map billboard posted in many mountain resorts for hiking (or skiing), depicting the village in the foreground as our neighborhood, some high and forbidding peaks in the distance representing the visionary goals we long to reach, and a system of trails leading us there across the mountainous hazards. Thus our roadmap is structured into three main parts: Section 1, "Our Neighborhood", provides an overview of the history and current landscape, including current status of technology and near-term scientific potential of small satellites and CubeSats. Section 2, "Visions for the Future", describes examples of the type of science missions that could be achieved in the more distant future – a decade and beyond. The science concepts and priorities of the future should ultimately come from the science community, however, the visions outlined in Section 2 serve to focus the discussion. In Section 3, "Obstacles and Ways to Overcome Them", we describe some institutional roadblocks and means to overcome them. In particular, the roles of agencies, industry, policies, and models of international collaboration and exchange are discussed.

The ultimate destination is a world in which international teams of scientists pursue novel and far-reaching

[1] A list of acronyms is provided in the Appendix A.
[2] Available at https://www.nap.edu/catalog/23503/achieving-science-with-cubesats-thinking-inside-the-box.

goals. This roadmap provides some possible paths to reach such goals. We articulate a number of findings which are distributed throughout the sections. These findings lead to five recommendations:

Recommendation 1 – To the science community:

The science community as a whole should acknowledge the usefulness of small satellites and look for opportunities to leverage developments in the small satellite industry. All branches of space science can potentially benefit from the smaller envelope, the associated lower cost, and higher repeat rate. Scientific communities from small countries in particular may benefit from investing their budgets in small satellites.

Recommendation 2 – To space industry:

Satellite developers should seek out opportunities to partner with individual scientists and universities as well as larger government agencies. This might include data sharing arrangements, selling space on commercial spacecraft for scientific instruments, etc. Currently, publicly available operational data is very valuable for achieving science objectives. Commercial entities should be open to agreements that would continue to make such data available under a free, full, and open data policy for scientific use. Such partnerships can also contribute to workforce development.

Recommendation 3 – To space agencies:

Large space agencies should adopt procedures and processes that are appropriate to the scale of the project. Agencies should find new ways to provide opportunities for science, applications, and technology demonstrations based on small satellites and with ambitious time to launch. Agencies should additionally take advantage of commercial data or commercial infrastructure for doing science in a manner that preserves open data policies. Finally, space agencies should work together to create long-term roadmaps that outline priorities for future international missions involving small satellites.

Recommendation 4 – To policy makers:

In order for scientific small satellites to succeed, the scientific community needs support from policy makers to: (1) ensure adequate access to spectrum, orbital debris mitigation and remediation options, and affordable launch and other infrastructure services; (2) ensure that export control guidelines are easier to understand and interpret, and establish a balance between national security and scientific interests; (3) provide education and guidance on national and international regulations related to access to spectrum, maneuverability, trackability, and end-of-life disposal of small satellites.

Recommendation 5 – To COSPAR:

COSPAR should facilitate a process whereby International Teams can come together to define science goals and rules for a QB50-like, modular, international small satellite constellation. Through an activity like e.g. the International Geophysical Year in 1957–1958 (IGY), participants would agree on the ground rules. Agency or national representatives should be involved from the beginning. The funding would come from the individual participating member states for their individual contributions, or even from private entities or foundations. The role of COSPAR is one of an honest broker, coordinating, not funding. COSPAR should define criteria that must be met by these international teams for proposing.

The results of an international effort to build small satellite constellations would be valuable for all of the participants, and would be more valuable than the individual parts. Such a large-scale effort would enable the pursuit of visionary goals, and ultimately lead to both technological and scientific breakthroughs. Small satellites enable new models of international collaboration, with involvement by many more nations, in worldwide, ambitious projects. COSPAR is in a position to help foster this international collaboration, creating a precedent for setting up community science in a very open way. Our final recommendation is a means to facilitate progress towards really big ideas such as our four Visions for the Future or other ideas that we haven't yet imagined.

1. Our neighborhood

This section provides an overview of the small satellite landscape (Section 1.1) and near-term scientific potential (Section 1.2) of small satellites.

1.1. History and current status of small satellites and CubeSats

The small satellite industry is changing very rapidly. Here, we present a brief history of small *scientific* satellites and a brief overview of the industry at a snapshot in time. A more general review of modern small satellites is provided in Sweeting (2018).

1.1.1. Traditional small satellites for science

Small satellites in the mass range above approximately 100kg have aptly demonstrated their utility for scientific missions, and have been essential contributors to Space Science knowledge for decades, specifically in the subdisciplines of Heliophysics,[3] Astrophysics, and Earth Sciences.

In the U. S., most scientific small satellites are supported by the NASA Explorers Program which provides flight

[3] Heliophysics encompasses studies of the space environment in the interplanetary medium including study of the Sun, heliosphere, geospace, and the interaction between the solar system and interstellar space.

opportunities for scientific investigations in Astrophysics and Heliophysics. Since it's beginning, with Explorer-1 in 1958, the program has supported more than 70 U.S. and cooperative international scientific space missions (more than 90 individual satellites). "Explorer satellites have made impressive discoveries: Earth's magnetosphere and the shape of its gravity field; the solar wind; properties of micrometeoroids raining down on the earth; much about ultraviolet, cosmic, and X-rays from the solar system and the universe beyond; ionospheric physics; solar plasma; energetic particles; and atmospheric physics. These missions have also investigated air density, radio astronomy, geodesy, and gamma ray astronomy. Some Explorer spacecraft have even traveled to other planets, and some have monitored the Sun."[4] The early Explorers, launched between 1958 and 1962, massed less than 50 kg. Capabilities increased rapidly, but so did the mass. By 1989, the 66th Explorer mission, Cosmic Background Explorer (COBE) had a dry mass of 1408 kg. To address the rapid increase in mass and the resulting increase in cost and decrease in launch cadence, in 1988, NASA started the modern Explorers Program which enabled the development of small sciencecraft with masses in the range of ~60–350 kg. Missions within this mass range encompass a total of about 17 satellites, including satellites from the University Explorer line (UNEX), the Small Explorer line (SMEX) and a single 5-satellite Medium Class Explorer (MIDEX). The launch mass of ten SMEX missions is shown in Table 1.

Table 1
Launch mass of selected small satellites from NASA's Modern Explorers Program. Data taken from https://nssdc.gsfc.nasa.gov/multi/explorer.html, with exception of AIM and NuSTAR which were taken from the mission websites.

MISSION	MASS (kg)
SAMPEX	158
FAST	187
TRACE	250
SWAS	288
RHESSI	230
GALEX	280
AIM	197
IBEX	80
NuSTAR	350
IRIS	200

The Explorers program has been extremely successful in terms of scientific return. However, it falls short with respect to increasing the launch cadence. Between 1958 and 1980, 62 Explorers were launched (2.82/year), while between 1980 (the start of the Shuttle era) and 2018, only 33 were launched (0.87/year), more than a factor of 3 decrease. The time between the last two solar physics mission launches is 11.5 years: RHESSI in February 2002 to IRIS in June 2013. IRIS was the last SMEX mission launched, now more than five years ago. Increases in management oversight have likely contributed to an increase in development time. The high cost of launch may also be a driving factor in the launch cadence decrease. For reference, NASA's most recent Explorers mission, TESS (A MIDEX with launch mass 362 kg) cost $200 million (Wall, 2018), not including launch cost which was an additional $87 million,[5] more than 30% of total mission cost.

NASA's Earth Ventures line of missions was recently established to provide opportunities for small satellite missions in Earth Sciences. The first Venture-class satellite mission, CYGNSS (Cyclone Global Navigation Satellite System), measures ocean winds, and is demonstrating the utility of satellite constellations for Earth science. Each of the eight simultaneously-operating satellites has a mass of ~28 kg. CYGNSS was selected for development in 2012[6] and launched in December 2016.[7]

European activities on small satellites have generally been supported at different levels by national programs, by the European Union FP7 and Horizon 2020 Space program, and by ESA, the European Space Agency. A short history of ESA small satellites is given in Dale and Whitcomb (1994), and briefly summarized here. Small missions in Europe were first considered in association with the Space Science: Horizon 2000 strategic plan in 1985. At that time, the Cluster mission was being developed and procurement rules similar to those used for the NASA's AMPTE mission were considered. However, it was concluded that, "the changes needed to apply a similar 'small satellite' approach to Cluster were too wide-ranging and the project proceeded along more classical lines". In 1990, ESA issued a 'Call for Ideas' for small missions; 52 proposals were received and evaluated. Two missions were selected for further study: SOLID, a mission to measure solar oblateness, irradiance periodicities and diameter variations, and CUBE, a mission to survey the cosmic ultraviolet background. In November 1992 a specific request for small-mission proposals was released. Although some 13 small-mission proposals were evaluated, none were recommended for further study. The report concluded that, "While the ESA Science Programme Directorate has, as yet, no fixed policy on the practicality and potential for the introduction of a small-satellite programme, there is a recognised need to reduce the overall costs of missions, which would allow more flight opportunities and a small-spacecraft programme." The report also pointed out that smaller nations might not have the infrastructure needed to design, build and launch a small mission, so, ESA could potentially provide flight opportunities or act as a

[4] History of the Explorers Program, Retrieved on May 27, 2018, from https://explorers.gsfc.nasa.gov/history.html.

[5] CONTRACT RELEASE C14-049 Retrieved from https://www.nasa.gov/press/2014/december/nasa-awards-launch-services-contract-for-transiting-exoplanet-survey-satellite on 2018, June 26.

[6] https://www.nasa.gov/home/hqnews/2012/jun/HQ_12-203_Earth_Venture_Space_System_CYGNSS.html.

[7] https://www.nasa.gov/image-feature/cygnss-satellites-launched-aboard-pegasus-xl-rocket.

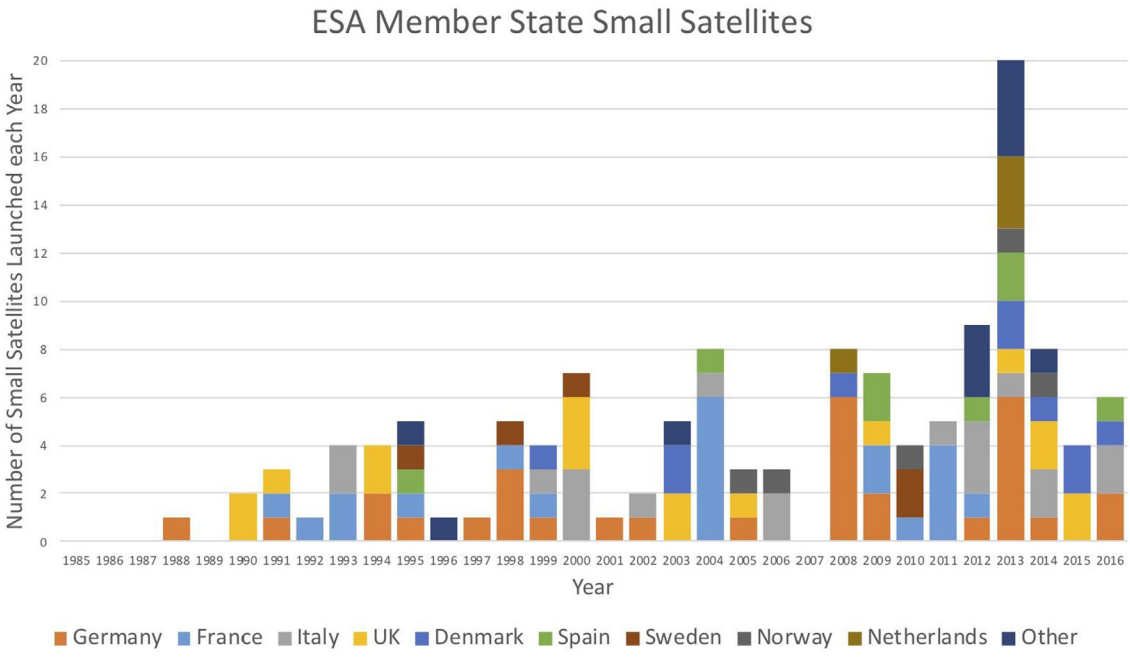

Fig. 1.1. Small Satellites (<200 kg) launched by ESA Member States from 1985 to 2016. For comparison there were 6 ESA small satellites launched during the same timeframe. Data collected for Lal et al. (2017), provided courtesy of B. Lal.

'go-between' for national programmes. In fact, the Belgian PROBA series of microsatellites was funded through ESA's small satellite program. The 94-kg PROBA-1 spacecraft, launched in 2001, is the longest flying Earth observing mission.[8] PROBA-2 and PROBA-V have also been operating for a number of years, collecting data on solar activity and vegetation/land-use, respectively. ESA's first lunar mission, SMART-1, weighed in at just over 350 kg. The spacecraft was launched in September 2003 as a rideshare to GTO and also provided a test of solar electric propulsion.[9]

More recently, in 2012, ESA announced that it will fund a new regular class of small missions, "S-class", in part to provide smaller member states the opportunity to lead missions.[10] Approximately 70 letters of Intent were received in response to the first call for proposals,[11] demonstrating a significant interest in small satellites. One of these missions was selected in 2012, CHEOPS (CHaracterising ExOPlanets Satellite), and is scheduled to launch in 2019. The second S-class mission, SMILE, is being developed jointly with the Chinese Academy of Sciences (CAS) to study solar wind-magnetosphere-ionosphere interactions. Despite being an S-class mission, the SMILE spacecraft is not really small; carrying four major instruments, the spacecraft has a dry mass of 652 kg and 1960 kg with propellant included (Raab et al., 2016). Thus, similar to the NASA Explorers program, ESA opportunities for satellites in the ~100 kg range are limited, and mission development times approach ten years.

ESA's involvement in scientific microsatellites has been sporadic, and it is the ESA member states, often on a national basis, that have provided a growth of launches in the small/micro satellite class, opening the space sector and making it affordable to new international players. From 1988 to 2016, ESA launched only 6 satellites with mass below 200 kg, while individual ESA member states launched a total of 131 small satellites (Fig. 1.1).[12] For example, in the early 90s, a Swedish-German mission, Freja (214 kg),[13] was launched to study the aurora. Other early players include Denmark which successfully conceived, designed, built and operated the geomagnetic mapping mission "Ørsted" (61 kg), launched in 1999. Ørsted provided information about Earth's dynamo (Hulot et al., 2002), improved our understanding of ionospheric and magnetospheric current systems (Papitashvili et al., 2002), and provided data that has been used as the source of the IGRF (International Geomagnetic Reference Field) model for half a decade. The French space agency, CNES, has launched a number of small satellites and developed the ~100 kg Myriade platform which has been used for both Earth science and military missions, beginning with Demeter, launched in 2004, and most recently, Taranis, which is slated for launch in 2019.[14] More recently, the

[8] https://www.esa.int/Our_Activities/Observing_the_Earth/Proba-1.
[9] http://sci.esa.int/smart-1/38890-smart-1-mission-to-the-moon-status-first-results-and-goals/.
[10] https://www.bbc.com/news/science-environment-17335339.
[11] http://sci.esa.int/cosmic-vision/50265-received-letters-of-intent/ Retrieved July 8, 2018.
[12] It should be noted that some of these may have received funding through ESA programs.
[13] https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1992-064A.
[14] https://myriade.cnes.fr/en/home-49.

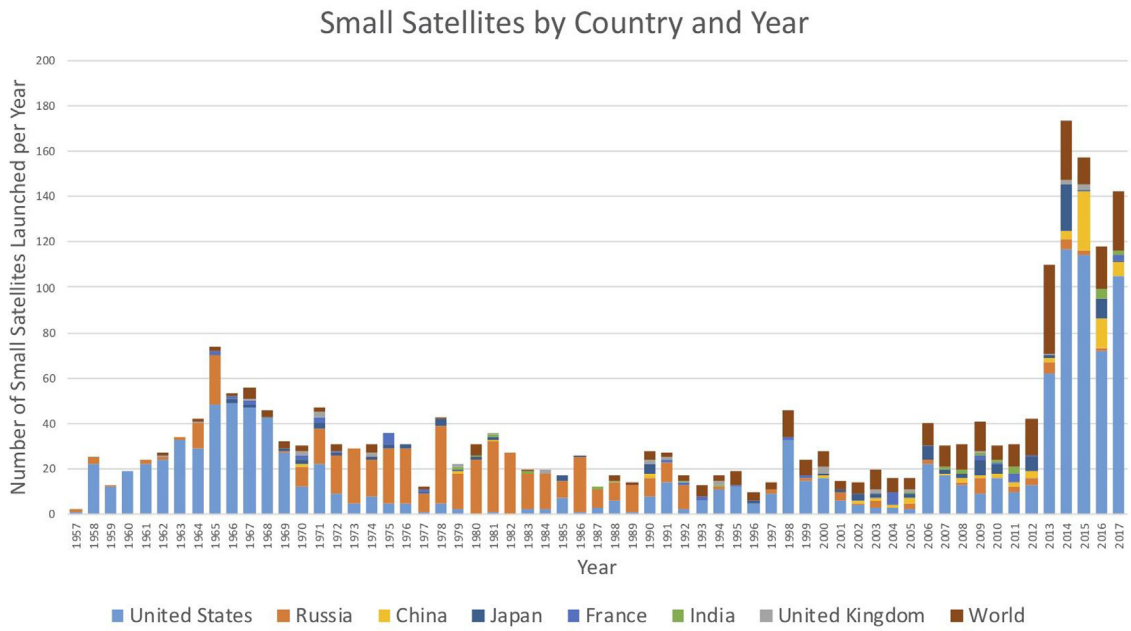

Fig. 1.2. Small (<200 kg) satellite launches per year from 1957 to 2017 by country. Figure reproduced from Lal et al., (2017), "Global Trends in Small Satellites", figure E-2, with permission from the Institute for Defense Analyses.

Italian Space Agency (ASI) started a small satellites initiative, PLATiNO, which aims to establish a national capability for scientific and other missions through development of a multi-purpose small satellite platform.[15]

Russia has a long history of launching small satellites beginning with Sputnik-1 in 1957. Universities in Russia have been particularly active in developing small satellites for science. For example, Tatyana-2 is an international microsatellite (~100 kg) mission led by Moscow State University, launched as a secondary payload in 2009 to study transient luminous events in Earth's atmosphere.

In some countries, small satellites are being developed primarily for industrial or operational use rather than science. For example, in Japan, the science agency JAXA has been pursuing tech demo microsatellites such as PROCYON, but otherwise mostly builds large satellite missions. Small satellites are primarily viewed as means for industrial development and a way to improve life (e.g., using small satellites for Earth observation applications such as tsunami prediction). For example, Hokkaido and Tohoku Universities recently initiated a program to launch 50 microsatellites by 2020 for natural disaster monitoring.[16] The program has participation from a number of countries in the region; 50-kg Diwata-1 was the first satellite built fully by the Philippines, and was deployed from the ISS in April 2016.[17] In the last five years, the majority of small satellites were launched by the U.S., but an increasing number of nations are developing small satellites (Fig. 1.2). In particular, the number of small satellites launched by China is significant, though most of these are military or industrial use. For a comprehensive assessment of current international small satellite programs see Lal et al. (2017), Appendix E.

Worldwide, the number of satellites used for science is a tiny fraction of the total number of small satellites launched; the majority of small satellites are used for remote sensing or technology development (Fig. 1.3). Small satellites in the mass range less than 200 kg offer an enormous potential for science, discussed further below.

1.1.2. CubeSats

Over the past decade and a half, a new class of satellites, called CubeSats, with masses between 1 and 12 kg has exploded upon the scene. Employed initially for hands-on technical training of college and university students (e.g., SwissCube launched in 2009, see Noca et al., 2009), approximately 1030 of these CubeSats have been launched through the end of 2018.[18]

CubeSats, so-called because the initial version of these satellites was in the shape of a cube measuring $10 \times 10 \times 10$ cm (known as 1U), are a class of nanosatellites typically launched and deployed into space from a

[15] 'A Multi-Purpose PLATiNO SmallSat is the Plan by SITAEL and the Italian Space Agency', *SatNews*, December 19, 2017, http://www.satnews.com/story.php?number=275392102.

[16] http://www.satnews.com/story.php?number=900912903. Retrieved 4 March 2019.

[17] https://www.rappler.com/science-nature/earth-space/130956-diwata-microsatellite-deployment-space. Retrieved 27 May 2019.

[18] Erik Kulu, Nanosatellite & CubeSat Database, https://www.nanosats.eu/.

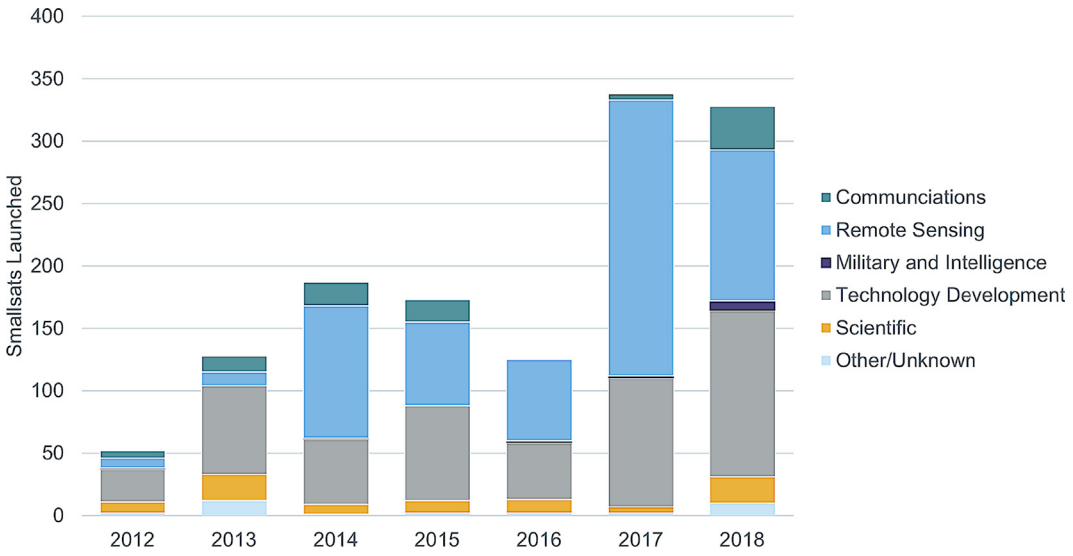

Fig. 1.3. Number of SmallSats by use. Image credit: Bryce Space and Technology (https://brycetech.com/reports.html).

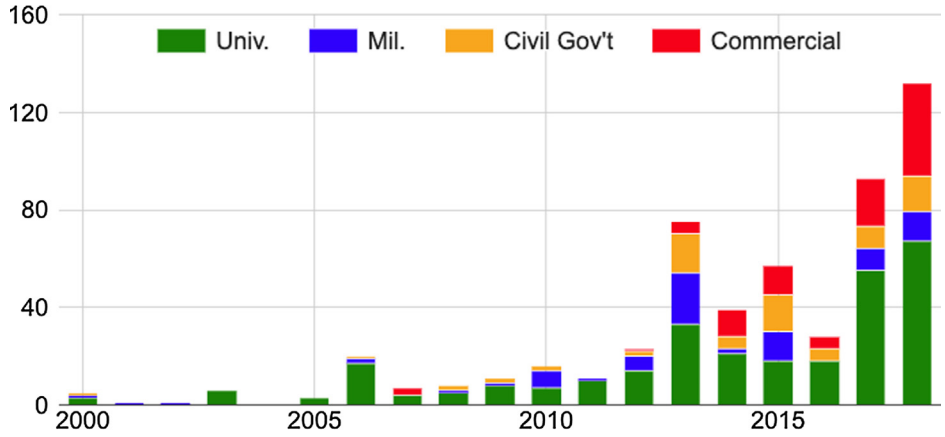

Fig. 1.4. Annual number of CubeSats launched by type of organization responsible for design/construction/operation. The more than 450 commercial constellation CubeSats developed by Planet and Spire beginning in 2014 are omitted from the chart for readability. Chart created by M. Swartwout using data through the end of 2018 (data from https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database).

standardized container or canister, most frequently hitching a ride into space as a secondary or tertiary payload along with one or more larger spacecraft. The standardization of canisterized "CubeSats" allows for smaller and larger form factors consisting of fractional or multiple Us: 0.5U, 1U, 1.5U, 3U, and 6U CubeSats massing up to 12 kg have been launched.

For this roadmap, it is instructive to briefly review the history of the explosive growth of CubeSats, with focus on scientific applications. Fig. 1.4 illustrates the annual launch rate of all CubeSats (and pre-CubeSat nanosatellites) launched world-wide between 2000 and 2018. The more than 450 CubeSats launched by Spire and Planet as elements of their respective constellations beginning in 2014 are not included in the chart since their numbers completely dwarf the others. The majority of CubeSats launched were targeted at education, technology demonstration, or commercial use. Of the more than 1000 CubeSats launched through December 2018, 107 have been identified as scientifically motivated. Some of these have returned publication quality data, revealing aspects of the space environment not well studied by their larger brethren.

Fig. 1.5 shows the number of *scientific* CubeSats launched by year. Approximately half of these have only been launched since early 2017, including 36 which are part of the QB50 constellation, discussed in more detail below. 49 of the 107 scientific CubeSats have been declared successful, meaning that the primary mission objectives have been met or the satellite is taking actions that are anticipated to achieve primary mission success. However, some of the recently launched CubeSats are still in commissioning or early operations, thus their scientific productivity is yet to be ascertained. The number of "successful" missions can thus be expected to increase in time.

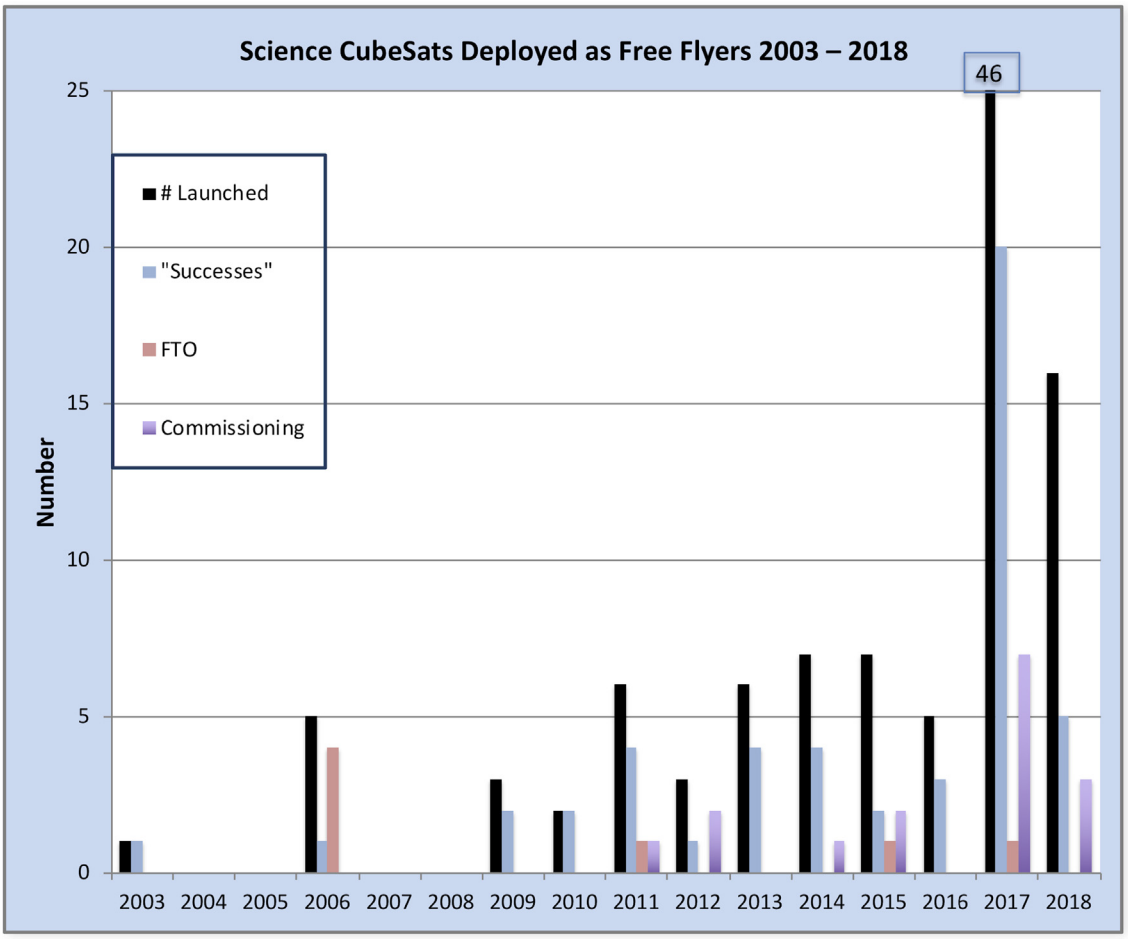

Fig. 1.5. Scientific CubeSats: 107 launched from 2003 to 2018; 46 in 2017 alone. 7 of the 107 were lost due to launch failures (labeled FTO in the plot; FTO = Failed to Orbit). Two mission status categories not plotted are those that were Dead on Arrival (21), and those whose mission status is not known/reported (14) (data taken from Swartwout, https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database).

In 2017, 36 CubeSats were launched to explore the upper atmosphere as part of the EU-organized QB50 constellation.[19] The constellation included CubeSats contributed by many countries, such as Australia, the U.S., Canada, China, Taiwan, South Korea, Israel, South Africa, Turkey and the Ukraine. The QB50 project administration provided each group with extensive technical and administrative support, including professional design reviews, a science payload and complete launch campaign. Some teams also received a full ADCS bundle free of charge. The teams were required to invest an additional 600–700 k€. The QB50 project can be viewed as a sort of pathfinder for international constellation missions, in which individual countries contribute a complete spacecraft rather than a single instrument or subsystem. This is discussed further in Section 3.5.1.

The majority of scientific CubeSats built in the U. S. have been supported by the National Science Foundation (NSF). Until recently, NASA CubeSats were primarily focused on technology development. After the success of the NSF CubeSat program, funding opportunities for scientific CubeSats increased at NASA, and more than twenty scientific CubeSats have launched or are in development as of this writing.

In Europe, the interest in CubeSats for science has also been increasing. Starting in 2005, the European small satellite effort initially focused on hands-on educational projects with 1U to 3U CubeSats produced by universities. In 2010, interests changed towards larger 3U to 12U CubeSats produced also by industries and agencies for technology demonstration. In Germany, a dedicated educational CubeSat program for universities was initiated in 2009, leading to 6 launches and many missions in preparation. Now, Ireland is building its first satellite, a 3U science CubeSat that will measure cosmic gamma ray bursts.[20] Since 2013, more than 10 MEuro were dedicated to ESA GSTP (General Support Technology Programme) for 7 In-Orbit Demonstration (IOD) CubeSat missions. These include several LEO constellation demonstrators with applications in NO_2 pollution monitoring, weather predic-

[19] https://www.qb50.eu/.

[20] https://www.rte.ie/news/business/2017/0523/877210-satellite/.

tion and space weather. A Ka-band interferometry swarm (KRIS) will demonstrate a capability for measuring ocean currents and sea surface heights. The demonstrators also include Lunar CubeSats for mapping ice on the moon and studying meteor impacts, and a stand-alone deep space CubeSat (M-ARGO) (Walker, 2018). The European Commission explicitly referred to small satellite missions in its programmatic work program 2018–2020, "The development of new and innovative approaches, such as the use of Cubesats and other small space platforms, or the use of Commercial off-the-shelf (COTS) components is encouraged as long as it leads or contributes to the implementation of space science and exploration with significant scientific outputs." There is little question that the rise of CubeSats has accelerated the use of small satellites for science.

Finding 1.1 – Small satellites across the full spectrum of sizes, from CubeSats to ~300 kg microsatellites, have enabled important scientific advancements across the space sciences.

Finding 1.2 – Small satellites, particularly CubeSats, have enabled access to space for more nations, and have provided opportunities for countries with new or small space programs to participate in much larger international projects.

Finding 1.3 – The emergence of CubeSats has resulted in a significant increase in launch cadence. However, the launch cadence of larger, traditional small satellites has *decreased* in the past few decades, and the development time and cost have not decreased.

1.1.3. Launch opportunities, commercialization, and other developments

One of the limitations in the early development of the smallest satellites was the limited availability of launch opportunities. The 1960s had the first boom of rideshares, followed by a lack of rideshares for a number of years. The number of rideshares increased substantially around 2007, primarily due to the advent of the CubeSat standard and launchers. Standardization has permitted the CubeSat-carrying canisters to be qualified for launch as hitchhikers on more than a dozen different launch vehicles, including the International Space Station. This standardization, along with relatively low cost to develop and launch CubeSats, has led to explosive growth in application areas well beyond education and training. Recently, CubeSats are being used by the commercial sector as elements of global constellations of hundreds of satellites.

The increased interest of small satellites in the commercial sector promises to generate new launch opportunities and drive down launch costs. A comprehensive analysis of market drivers and access to space is given in Chapters 3 and 4 of Lal et al. (2017), respectively. Today, relatively frequent and cheap launch opportunities into low-Earth orbit (LEO) exist. These include launch from the international space station and piggyback opportunities on PSLV (India), Dnepr and Cosmos (Russia), Long March (China), Vega (Europe), and Falcon (USA). In some cases, rockets are shared by many small satellites (such as the PSLV-launch in February 2017, which carried 104 small satellites). There are several new companies building rockets for small satellites (e.g., Rocket Labs and Virgin Orbit). Brokerage organizations offer integration of spacecraft and find launch opportunities by contacting organizations that have launch capability to the desired orbit. A more detailed discussion of launch-related policy issues is discussed in Section 3.2.3.

The commercialization of small satellites and entry by new players is also increasing the availability of commercial off-the shelf complete subsystems which has the potential to significantly reduce cost and development time for scientific satellites. Commercial parts are already being used for scientific CubeSats, and reliable mass production of parts has already been demonstrated. For example the company ISIS (Innovative Solutions in Space)[21] has supplied components and subsystems for 260 small missions. NASA's Small Spacecraft Virtual Institute[22] now provides a parts search tool for users to obtain information about commercial parts survivability. Such resources will help provide a justification for using such parts in scientific satellites that are bigger than a CubeSat.

The developments in the small satellite sector could create a new paradigm for small scientific satellites. The combination of low launch costs, COTS parts, and ability to purchase a complete satellite could drive down the cost of a mission to the point that it will be cost effective to streamline testing, structural verification and analysis. In addition, smaller facilities can be used for testing of small satellites thus reducing cost. The commercial sector is already developing new ways to build and test small satellites. For example, OneWeb Satellites recently set up production lines to manufacture up to three satellites per day using aircraft manufacturing technologies.[23] OneWeb has

[21] ISIS, Motorenweg 23, 2623 CR, Delft, The Netherlands, https://www.isispace.nl.

[22] https://www.nasa.gov/smallsat-institute.

[23] http://www.oneweb.world/press-releases/2017/oneweb-satellites-breaks-ground-on-the-worlds-first-state-of-the-art-high-volume-satellite-manufacturing-facility.

ordered 900 of the 150 kg satellites for less than a million dollars per unit (Iannotta, 2019).

Finding 1.4 – The rapid increase in CubeSat launch cadence can be attributed to standardization which increases rideshare opportunities, cost reduction due to availability of COTS parts, and an explosion of their use in the private sector.

Finding 1.5 – The cost effectiveness of increased rideshare opportunities and larger launchers, in combination with smaller spacecraft and low-cost COTS parts has already enabled large constellations, e.g. Planet and QB50, opening up new opportunities for science.

Over the past three decades, advances in technology have revolutionized the way we live, work, and drive. Yet, the technologies that have given us the internet, smart phones, and much safer and smarter cars are not in our missions flying in space. Instead, most science missions are constructed from parts that existed more than a decade ago. This is necessary for large, expensive missions which must use qualified parts with a high reliability. However, a lower cost mission can tolerate more risk, taking advantage of newer technologies that haven't been space qualified to the nth degree. So far, this is only happening with CubeSats and not with the traditional, larger (~100 kg) small scientific satellites.

The result is that traditional small science satellites have not seen the reduction in cost or development time that is being achieved in the commercial sector. Since the restart of the NASA Explorers program in 1988, the average time from selection to launch of a SMEX mission has been 5.6 years. This does not include the time between the NASA Announcement of Opportunity and the selection, about 9 months, nor does it include the preparation time for development of a mission concept that is sufficiently mature to have a reasonable chance of selection, which may take a few years. As a result 7.5 ± 2 years pass between an instrument concept and the start of scientific analysis.

Small science missions take too long and are more expensive than they need to be, leading to long wait times between proposal opportunities, and low proposal success rates. This only reinforces the risk aversion that is present in the selection process and management structure of even the small missions led by national space agencies. Scientists are discouraged from innovating and taking risk because they may only get one or two chances in their entire career to lead a mission. This risk aversion potentially leads to mediocre or incremental science. The boom in commercial small satellites offers the chance to find a new way of doing business, presenting a real opportunity to change the paradigm for small satellites in space science (Section 3.3 and 3.4).

Finding 1.6 – The science community has not yet fully capitalized on advances in technology or the increased activity in the commercial sector in order to reduce the cost or development times of traditional small satellites. A lack of frequent flight opportunities persists, potentially discouraging innovation by sponsoring agencies and scientists.

1.2. Scientific potential of small satellites and CubeSats

In this section we examine the near-term scientific potential of small satellites, and highlight a few mission concepts that are currently under development. This section is not intended to be comprehensive, rather, we hope to illustrate the wide range of science applications currently employing small satellites. We also consider current limitations and challenges for using small satellites for space science.

1.2.1. Overview

The importance of traditional small satellites has been recognized and reaffirmed by the science community, particularly in Astrophysics, Heliophysics, and Earth Sciences. The most recent U.S. Decadal Surveys[24] in all of these disciplines recommended augmentations of NASA's traditional small satellite programs (i.e., Explorers and Earth Ventures). Even smaller satellites, such as CubeSats, are enabling new kinds of science. The 2016 US National Academies report, "Achieving Science with CubeSats" (NASEM, 2016)[25] provided a comprehensive overview of the scientific potential of CubeSats. The report concluded that CubeSats don't replace larger missions, rather they can be used to achieve targeted science goals and can also enhance larger missions by providing supporting measurements. In solar and space physics, the report found that CubeSats can provide novel measurements, for example from high risk orbits, augment large facilities, and have the potential to enable constellation missions. Constellation missions have important applications in Earth sciences as well. Because of their shorter development time, CubeSats also have the ability to mitigate gaps in long-term Earth monitoring and are potentially more responsive to new observational needs. In Astrophysics, the small size of CubeSats limits the aperture and thus the types of

[24] Decadal Surveys, published by the U. S. National Academies, can be found at: http://sites.nationalacademies.org/ssb/ssb_052297.

[25] Available at https://www.nap.edu/catalog/23503/achieving-science-with-cubesats-thinking-inside-the-box.

science that can be done with a single CubeSat. However, the report highlighted a few capabilities, including CubeSats that stare at a single object for long periods for both exoplanet studies and stellar variability studies. CubeSat constellations may also pave the way towards space interferometers. In planetary sciences, CubeSats can provide unique vantage points and explore high-risk regions, perhaps in tandem with a larger "mother ship". They also serve as microgravity laboratories. The report noted that CubeSats have already delivered high-impact science in some of these targeted areas.

The rapid development of CubeSat technologies has already enabled new kinds of SmallSat missions. The CYGNSS mission provides a good example. The eight 28-kg spacecraft are not CubeSats, but used commercial parts and a tailored mission assurance approach. The resulting cost was $5M/spacecraft (not including payload), compared to $165 M/spacecraft for the MMS mission (Tumlinson, 2014). A precursor of CYGNSS was TechDemoSat-1, weighing in at 157 kg (Foti et al., 2017). It was launched in 2014 to demonstrate the method, also used by CYGNSS, of using Global Navigation Satellite Systems-Reflectometry (GNSS-R) for observing hurricanes. While TechDemoSat-1 already fit the envelope of a small satellite, the CubeSat developments leveraged by CYGNSS allowed for the factor of 5 decrease in mass, thus enabling a small constellation of satellites that can monitor the development of a hurricane on relevant timescales.

1.2.2. Near-term science potential: Missions on the horizon

A number of recent missions and missions under development utilize small satellites. SmallSat missions don't have to be small missions; missions using a number of distributed small satellites have been launched recently and more are on the horizon.

In the U.S., the newest Explorers, TESS (362 kg, launched in April 2018 to search for nearby extrasolar planets) and ICON (291 kg, expected to launch in 2019 to study the ionosphere) are both MIDEX missions, each costing in excess of $200 M. The last SMEX missions were launched in 2012 (NuSTAR) and 2013 (IRIS). However, in response to recommendations in both the Astrophysics and Heliophysics Decadal Surveys, NASA has recently increased the cadence of SMEX and MIDEX opportunities. In Astrophysics, the Imaging X-Ray Polarimetry Explorer (IXPE) will launch in 2020 to study X-ray production in compact objects such as neutron stars and black holes. Five Heliophysics SMEX concepts were selected for further study in 2017 along with several missions of opportunity, some of which employ CubeSats.[26] A downselection to one or two missions is expected within the next year.

The number of NASA-funded scientific CubeSat launches has increased significantly in recent years (2 launched in 2015 versus 8 launched in 2018 and at least 9 more planned for 2019).[27] Among those recently selected, GTOSat, will be the first scientific CubeSat to operate in geostationary transfer orbit. It will provide key observations of the radiation belts and, with its radiation-hardened 6U bus, could serve as a pathfinder for future magnetospheric constellation missions.[28] In Earth Sciences, the currently flying CYGNSS and future TROPICS missions are demonstrating the utility of a constellation approach to Earth Science. In particular, TROPICS, consisting of 12 CubeSats, will provide 30-minute revisit rates critical for monitoring rapidly developing storm systems (Fig. 1.6). Future LEO constellations could exploit GPS-based relative positioning techniques for precise autonomous determination of the relative positions of the formation members, which is required for formation acquisition and maintenance, and scientific objective achievement (Causa et al., 2018).

In Europe, traditional small satellites continue to be used for science at a relatively low rate but pursuing important science goals. The CNES MICROSCOPE mission (330 kg) was launched in 2016 to test the Equivalence Principle to one part in 10^{15}, 100 times more precise than can be achieved on Earth (Touboul et al., 2017). PROBA-3, one in the series of ESA PROBA missions, is expected to launch in 2020. It consists of two spacecraft with masses 340 kg and 200 kg, flying 150 m apart to create an artificial solar eclipse, allowing for study of the solar corona. The mission will also demonstrate precision formation-flying.[29] The first ESA S-class mission, CHEOPS (~300 kg) will launch in 2019 to characterize known exoplanets. In particular, CHEOPS will measure planetary radii, which combined with the mass as measured from the ground, will allow for determination of the exoplanet density for the first time.

The number of CubeSat missions on the horizon seems to be growing in Europe. ESA foresees a 8 MEuro GSTP budget for one or more projects with 3 year duration, targeting significant improvements in system performance or new applications. An example CubeSat mission is HERMES (High Energy Rapid Modular Ensemble of Satellites),[30] an Italian mission for high energy (keV-MeV) astrophysics, a science domain previously limited to large space missions. HERMES consists of a constellation of nanosatellites (<10 kg) in low Earth orbit, equipped

[26] https://www.nasa.gov/press-release/nasa-selects-proposals-to-study-sun-space-environment.

[27] NASA science CubeSat missions were identified using October 2017 presentation by Larry Kepko, "SMD CubeSat Program Update" retrieved from https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/Kepko-SmallSats-APAC_October%202017.pdf on February 20, 2019. Launch dates were taken from CSLI website: https://www.nasa.gov/content/past-elana-cubesat-launches except for MarCO launch date which was taken from the MarCO mission website: https://www.jpl.nasa.gov/cubesat/missions/marco.php.

[28] https://www.nasa.gov/feature/goddard/2018/nasa-s-new-dellingr-spacecraft-baselined-for-pathfinding-cubesat-mission-to-van-allen-belts.

[29] http://www.esa.int/Our_Activities/Space_Engineering_Technology/Proba_Missions/About_Proba-3. Retrieved July 8, 2018.

[30] http://hermes.dsf.unica.it/index.html.

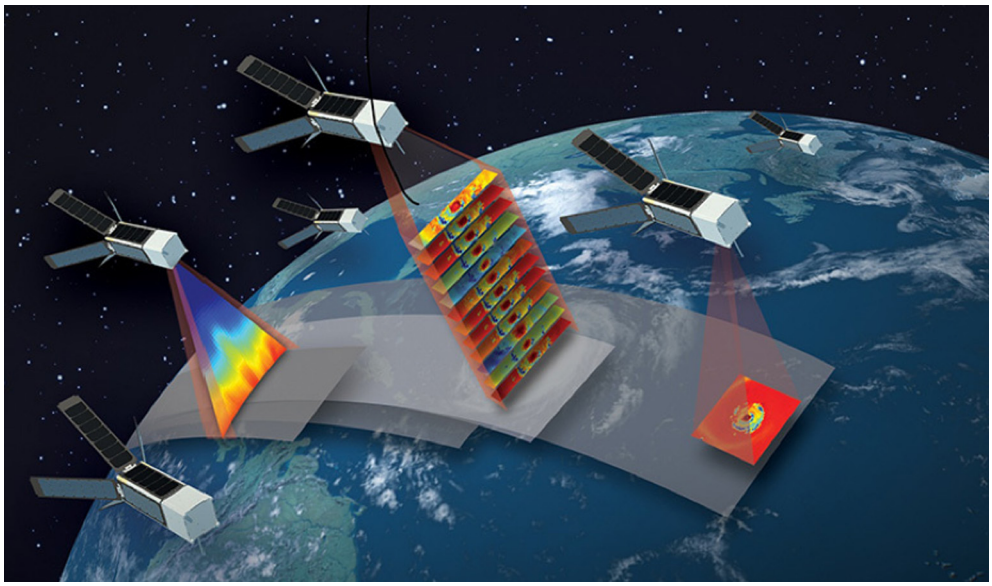

Fig. 1.6. Mission overview of the proposed NASA TROPICS mission. Image Credit: TROPICS Team, MIT Lincoln Laboratory (The Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of SmallSats (TROPICS), MIT Lincloln Lab, https://tropics.ll.mit.edu/CMS/tropics/Mission-Overview).

with X-ray detectors with at least 50 cm^2 of active collecting area between a few keV and ~1 MeV, and very high time resolution (μs). The main science goal is to study and accurately localize high energy astrophysical phenomena such as Gamma-Ray Bursts, electromagnetic counterparts of gravitational waves (caused by coalescence phenomena of compact objects, such as those recently observed by the Advanced LIGO-Virgo observatories), and high-energy counterparts of Fast Radio Bursts. A technology pathfinder consisting of three units is under development, with a launch goal around 2020, to be followed by a scientific pathfinder mission. The final goal is a constellation of tens of units on different orbits, to provide transients positions with accuracy better than 1 degree over the full sky.

A number of international collaborative small satellite missions are currently under development. The Israeli and French space agencies (ISA/CNES), have jointly built and launched VENμS (Vegetation and Environment monitoring on a New Micro-Satellite). This 250 kg (dry mass) small satellite, is equipped with a super spectral camera that observes in 12 wavelengths simultaneously. The satellite provides frequent revisits (up to two days) of scientific sites spread worldwide to study the evolution of vegetation, and also serves as an in-flight qualification of a unique electrical propulsion system based on Hall-Effect thrusters. Such a system allows for minimizing the mass of propellant and utilization of non-toxic xenon, while achieving flexible orbital maneuvers. The SHALOM Mission is a joint initiative of ISA and ASI to develop several small satellites in the fields of communication and earth observation that enable the discovery and identification of contaminants on the earth's surface, in bodies of water, and in the atmosphere.

Low frequency radio space interferometer concepts are currently being explored by several nations (Fig. 1.7). The OLFAR (Orbital Low Frequency ARray) concept comprises a large constellation of small spacecraft in orbit around the Moon (Rotteveel et al., 2017). The first step towards realizing this mission was recently taken with the launch of the Netherlands Chinese Low Frequency Explorer (NCLE) on 21 May 2018 (Castelvecchi, 2018).

In the future, an interferometer could even be used at infrared or optical wavelengths. A collaboration between CalTech, Jet Propulsion Laboratory (JPL), University of Surrey, and the Indian Institute of Space Science and Technology (IIST) is developing the AAReST (Autonomous Assembly of a Reconfigurable Space Telescope) mission concept to produce an optical telescope with "primary mirror" made up of distributed 10-cm-diameter circular mirrors attached to a cluster of CubeSats (Sweeting, 2018).

In recent years, micro- and nano- satellites have also started venturing into deep-space, beyond low Earth orbit, taking advantage of ride-share opportunities. These missions so far try to answer focused science investigations or test new technologies, in contrast with typical deep-space missions which use high-TRL parts and carry a suite of instruments.

PROCYON (Proximate Object Close flyby with Optical Navigation), the first micro-sat deep-space mission (67 kg launch mass), and the first deep-space mission by a University, was launched in 2014 as piggyback of Hayabusa 2. It escaped the Earth gravity and returned one year later for a distant flyby. PROCYON validated a fully capable bus, with low, middle and HG antennas, reaction wheels and cold gas jets, electric propulsion systems, telescope and cameras. PROCYON was proposed, developed, and

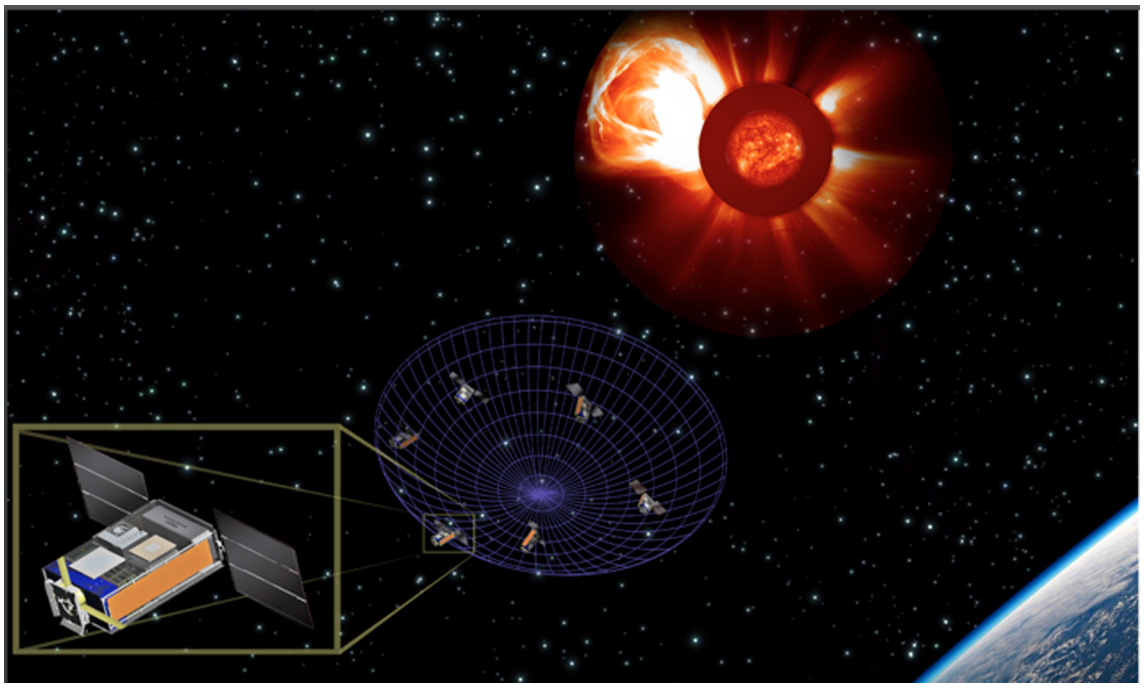

Fig. 1.7. A number of space interferometer concepts are currently being explored including the NASA SunRISE mission concept shown here which would use a small constellation of 6U CubeSats to measure solar radio bursts. Image Credit: SunRISE team.

launched in just about 14 months, and most of the mission team consisted of students of the University of Tokyo. Two Japanese follow-on missions, EQUULEUS and OMOTENASHI, are both 6U CubeSats being developed by JAXA and University of Tokyo. EQUULEUS will use water resistojet thrusters to be the first CubeSat to go to the Lunar Lagrange point. OMOTENASHI will be the smallest Lunar lander. A demonstration mission, EGG, was recently deployed from the ISS to test a deployable aeroshell that might be used in the future for atmospheric entry or orbital insertion.

The two Mars Cube One (MarCO) CubeSats recently completed their mission to Mars, where they provided data-relay capabilities for the Entry, Descent and Landing operations of the InSight lander. ESA's Hera mission (previously AIM/AIDA) will carry two CubeSats stowed in a mothership which will deploy close to the target Didymoon (Perez et al., 2018).[31] INSPIRE (Interplanetary Nano-Spacecraft Pathfinder in Relevant Environment) (Klesh et al., 2013) and DISCUS (Deep Interior Scanning CubeSat) (Bambach et al., 2018) are further demonstration projects with the objective to open deep space to CubeSats. The two spacecraft will carry a science vector magnetometer and an imager. Thirteen more CubeSats are almost ready to fly to the Moon and beyond thanks to the Exploration Mission 1, the maiden flight of SLS.[32]

In the future, a range of spacecraft will be available to serve a palette of mission types. These could range from high tech chipsats (atto- or femtosats) to traditional large spacecraft with augmented capability based on miniaturized space technology. Large spacecraft with piggyback small satellite probes may operate within the solar system. The probes may be a part of the primary mission or they may be on-board as a result of a rideshare.

1.2.3. Limitations and technological challenges

The recent US National Academies report (NASEM, 2016) on CubeSats provides an overview of technologies needed for scientific advancement, along with recent technology developments. In particular, advances in propulsion, communications, sensor miniaturization, radiation tolerant parts, and sub-arcsecond attitude control were called out, among others. The IDA report on small satellites (Lal et al., 2017) provides a more recent assessment of technology trends for small satellites in general, ranging from high bandwidth communications and onboard processing to advances in miniaturization to orbital debris surveillance (Lupo et al., 2018; Santoni et al., 2018) and removal technologies. Many of the technology developments driven by commercial markets are also needed for science missions. Current technology innovation trends addressing some of the limitations of small satellites in low earth orbit include:

- *Noise reduction in miniaturized components:* Software approaches based on filter technologies reduce the susceptibility to noise.

[31] https://phys.org/news/2019–01-cubesats-hera-mission-asteroid.html.
[32] NASA's new Space Launch System (SLS).

- *Attitude and orbit control capabilities:* recent miniature reaction wheel developments improve attitude control at low power consumption and electric propulsion systems provide orbit control. Thus, even for a 1U-CubeSat, improved instrument pointing and formation capabilities are being realized (e.g., OCSD,[33] UWE-4 and TOM missions). A fully magnetic attitude control subsystem is presented by Colagrossi and Lavagna (2018).
- *Communication link capacity:* new developments on optical links promise capacities beyond 100 MB/s at clear sky (e.g., OCSD, QUBE and TOM missions), but also very miniature X-band transceivers are becoming available (e.g., MarCO mission).
- *Extending the lifetime:* advanced FDIR (fault detection, identification and recovery) methods and redundancy concepts guarantee reasonable lifetime in orbit, even for commercial off the shelf components (e.g., UWE-3 has operated without any interruption for more than 3 years despite encountered SEU and latch-ups).
- *Ground segment:* several university ground station networks have been initiated (e.g., GENSO, UNISEC) to support frequent transmission of data from small satellites in order to relieve the on-board data storage and processing requirements. Commercial networks (e.g., KSAT lite) are providing global coverage for SmallSats.

The data return of scientific small satellites thus far, particularly CubeSats, has been limited by availability (and cost) of ground stations. Communications may become even more difficult with the development of large constellations for both commercial and scientific use. Constellations of hundreds or thousands of satellites, especially with imaging capabilities for Earth Sciences, will produce massive amounts of data. Sweeting (2018) states: "Over the next decade, the amount of data that will be cumulatively downlinked by small satellites is expected to reach 3.9 exabytes (exabyte = 10^{12} MB). Traditional RF capabilities are unlikely to be able to meet this demand…". Several efforts are underway to develop low power optical terminals in space capable of transmitting data at rates up to 10 Gb/s (Sweeting, 2018). Nevertheless, on board processing in order to limit the amount of data transmitted to the ground may be required. Advances in data processing (e.g., artificial intelligence) may prove useful and necessary for the science missions of the future. Commercial constellations and operational systems are also likely to require data distribution systems that are useable in close to real time. Such systems may provide new opportunities for science missions.

Finding 1.7 – Technologies further enabling formation flying, inter-satellite communication, data-compression and mega-constellation deployment will be in demand as scientific ambitions increase.

Unique challenges exist for deep space missions. We address these in more detail since they aren't as well covered in the reports referenced above.

Telecommunications: Currently, deep-space Cubesats are designed for low-data volume measurements which limits scientific observation. Moreover, deep-space missions need X-band or Ka-band on-ground antennas, and therefore the support of large space agencies with their ground station networks. In the past, ground station time has been negotiated for small missions (on an opportunistic basis and with low priority to other missions), but typically for one or two spacecraft at a time. The democratization of deep-space exploration could require supporting dozens or hundreds of nanosats, especially during the launch and early operation phase. For example, most of the 13 cubesats launched with EM-1 will have to perform a critical maneuver within two days of deployment, for which they need downlink and uplink for operations and for precise orbit determination (two-way Doppler, DDOR). Current developments in optical link equipment and X-band transceivers open new perspectives for solutions. An increasing number of worldwide distributed, smaller ground stations will provide continuous coverage in the future, similar to the radio amateur supported UHF ground station networks of the CubeSat community in UHF/VHF.

Power generation: At significant distances from the sun, energy generation requires large solar arrays (as for ROSETTA) or use of alternative energy sources. Nuclear generators (as for Cassini, or Galileo) have flown on interplanetary spacecraft but are currently not available for CubeSats. Thus, only the very limited storage resources of batteries can be used, demanding very careful operations in order to not waste those scarce resources.

Propulsion: Most CubeSat propulsion systems to date have been cold or warm gas systems due, in part, to their relatively low cost and low level of complexity. A broad array of various types of electric propulsion systems for CubeSats and microsatellites are in development by multiple companies at Technical Readiness Levels (TRL) between 5 and 7.[34]

In LEO, one CubeSat mission, AeroCube 8 has already demonstrated miniature electric propulsion system capabilities.[35] For deep space missions, (total impulse/volume) must be increased, complemented by larger fuel storage

[33] https://aerospace.org/story/communicating-and-converging-cubesats. Retrieved February 22, 2019.

[34] https://sst-soa.arc.nasa.gov/04-propulsion.

[35] http://spl.mit.edu/news/aerocube-8-cd-launch-mit-spls-electrospray-propulsion-space.

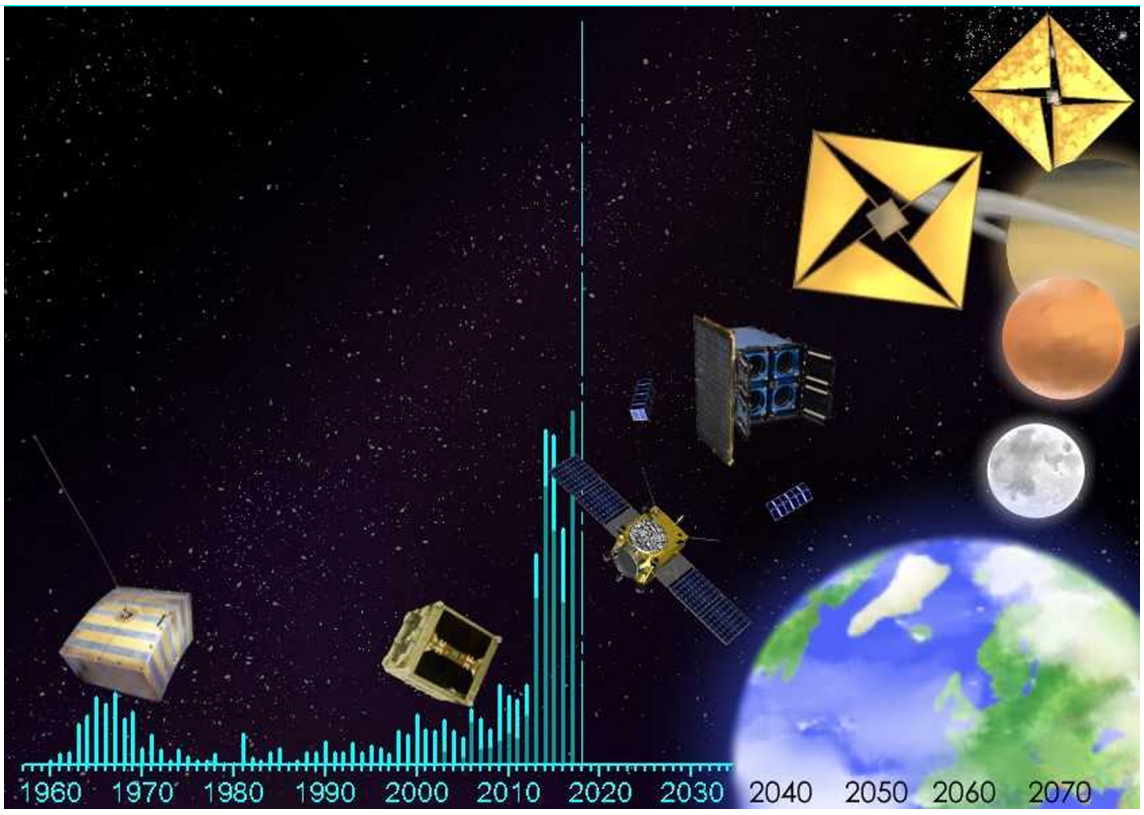

Fig. 1.8. The light blue bar graph shows the evolution from 1957 to present (based on data from Swartwout). The CubeSat numbers are indicated with dark blue. With the MarCO mission that just completed its mission to Mars, the upcoming SLS-EM-1 and the Hera mission to Didymos/Didymoon, rideshares extend beyond Low Earth Orbit. All three missions have adapted the CubeSat format. Future missions may require lower overall spacecraft mass and hence new spacecraft concepts. For instance CubeSat swarms deployed from deep space pods or laser propelled ultra-small chip-sats. Artist: Katrine Grønlund (Image of Oscar-1 used with permission: http://www.arrl.org/space-communication; DTUsat-1 image courtesy the DTUsat-1 team; Image of Hera mission: https://www.esa.int/Our_Activities/Space_Engineering_Technology/Asteroid_Impact_Mission/Asteroid_Impact_Deflection_Assessment_mission; Image of Isispace QuadPack CubeSat deployer used with permission: https://www.isispace.nl/product/quadpack-cubesat-deployer/). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

capacities. Innovative technologies like solar sailing are being considered and may provide solutions.

Mission design: Orbital mechanics and navigation is especially challenging for small deep-space spacecraft, which have limited orbit control capabilities, yet need to reach similar destinations as larger-class spacecraft. Mission design is as critical and complex for small satellites, as it is for large satellites, and sometimes even more so, relying on expert manpower and advanced tools. For this reason, mission design activities for SmallSats are mostly carried out by space agencies. Support toward the development of open-source (and ITAR-free) mission design tools would reduce the costs of deep-space nanosats and enable the participation of new stakeholders.

Operations: Like mission design, operations for a small satellite can be as complex and expensive as for a large mission. Operations of deep-space missions are mostly carried out with a man-in-the-loop approach. Autonomy would reduce mission costs, but it is currently not implemented to its full potential on expensive missions because of the associated risk. Deep space missions will benefit from automation efforts in the near-Earth environment currently being developed for swarms and formations. Deep-space nanosats, however, must rely on an even higher degree of autonomy because of the limited ground station availability. Support towards the development of autonomous operation and navigation technologies would enable deep-space exploration by small satellites, and eventually reduce the cost of large-class missions as well.

Launch Opportunities: Increased access to space is also needed to increase the cadence of science flight opportunities. As discussed in Section 1.1.3, launch opportunities have improved significantly for near-Earth missions. The promise of small satellite launchers currently being developed (Table 4.1 in IDA report, Lal et al., 2017) will enable CubeSats to go to a larger range of orbits, without the restriction of going where the bus is going. For example, Rocket Labs' Electron just launched 13 CubeSats into LEO in December.[36] However, for deep space missions, rideshares are more limited (Fig. 1.8). In 2015, NOAA's DSCOVR satellite was launched on a Falcon-9 to the Earth-moon L1 point with unused capacity of 2500 kg,

[36] https://www.rocketlabusa.com/news/updates/rocket-lab-successfully-launches-nasa-cubesats-to-orbit-on-first-ever-venture-class-launch-services-mission/ Retrieved February 22, 2019.

and NASA's TESS mission was launched into a trans-lunar injection orbit with 3000 kg of lift capacity to spare.[37] The opportunity to routinely open up launcher capacity on lunar, lagrange point or interplanetary missions for small spacecraft would be a game changer for deep space CubeSats. Such opportunities may soon become reality: NASA recently committed to flying an ESPA ring with every science mission in order to make the excess capacity available to small spacecraft.[38]

Finding 1.8 – Significant technology advancements are opening up new opportunities for small satellites, addressing challenges that have so far limited their science return. However, there are particular additional challenges associated with deep space exploration.

In summary, the emergence of CubeSats is driving important advances in technology that are already enabling non-CubeSat small satellite missions, such as CYGNSS. While the scientific promise of CubeSat missions is high, the number of missions launched with the intent to conduct scientific investigations is less than 12% of the total number of CubeSats launched through 2017. The number of missions using larger small satellites is even smaller. Nevertheless, CubeSats or CubeSat-enabled small satellites are already being flown in large commercial constellations. The scientific potential for constellations consisting of dozens, or more, nanosatellites for space science has yet to be borne out. However, the potential for purposefully designed scientific investigations comprised of CubeSats, larger small satellites, or both working together synergistically holds great scientific promise.

2. Visions for the future

In this section we turn the attention from our neighborhood to the peaks in the distance, which represent visions for the future: developments or missions that are out of reach with current or imminent technology, in some cases for several decades. Section 2.1 deals with Earth and Geospace science, where a global system of hundreds or even thousands of small satellites, all communicating with each other and with the ground, will have enormous impact not only on science, but also on society (although the latter is outside the scope of this document). Section 2.2 explores the potential of sending a swarm of small satellites to a solar system body such as, e.g., comet 1P/Halley when it returns to the inner solar system in 2061. Section 2.3 describes the potential of a synthetic aperture optical telescope made up of small satellites, which might be capable of imaging stars other than the Sun. Finally, in Section 2.4, we consider the possibility of an interstellar mission based on the Breakthrough Starshot initiative that has attracted much public attention recently. These four visions are not meant to be comprehensive or authoritative in any way, but rather serve as examples of what might become possible when projecting the potential of small satellites into the future by several decades.

2.1. Potential of small satellites for Earth and Geospace sciences

CubeSats and SmallSats have the potential to make unique contributions in a range of science domains within Earth observation and Solar and Space Physics. In particular, SmallSats will enable large constellation missions, thus providing a new tool for doing science from space. In Earth science, applications include surface imagery, meteorology, studying pollution, and measurements of the solar irradiance, to name just a few examples. In space physics, the importance of studying the Sun-Earth system using a systems-science approach was highlighted in the last US Decadal Survey. The recent National Academies report on CubeSats (NASEM, 2016) emphasized the importance of multipoint measurements to accomplish this and hence a major advantage of SmallSats.

This section briefly describes a few notional missions that are nearly within reach due to opportunities created by SmallSats. The idea for such mission concepts is not new (e.g., Esper et al., 2003); the challenge for this vision is less about needed technologies, and more about feasibility within available budgets. However, developments in the commercial sector (Fig. 2.1) may provide pathways to reducing cost and achieving such visions.

2.1.1. Mega-constellation for Earth science

There are countless applications in Earth science for a large constellation (i.e., hundreds to thousands) of LEO satellites. Smaller constellations consisting of about 5–10 small satellites are already flying, such as CYGNSS (Ruf et al., 2018), discussed in Chapter 1. Specific mission profiles will differ in terms of spatial, temporal, and spectral resolution depending on the application, but, generally speaking, the use of SmallSats (similar to large EO satellites) to monitor the Earth should strive towards providing as much data, as often, as accurate, as precise, and as complete (wavelength, polarization) as possible.

Using small satellites for monitoring the Earth has the following main advantages:

- Using a large number of these satellites in a constellation increases the revisit frequency, which allows for studying changes over short time intervals, or for tracking purposes.

[37] https://spacenews.com/government-agencies-prepare-for-piggyback-flights-secondary-payloads/ Retrieved February 22, 2019.
[38] https://spacenews.com/nasa-bolsters-smallsat-science-programs/ Retrieved June 8, 2019.

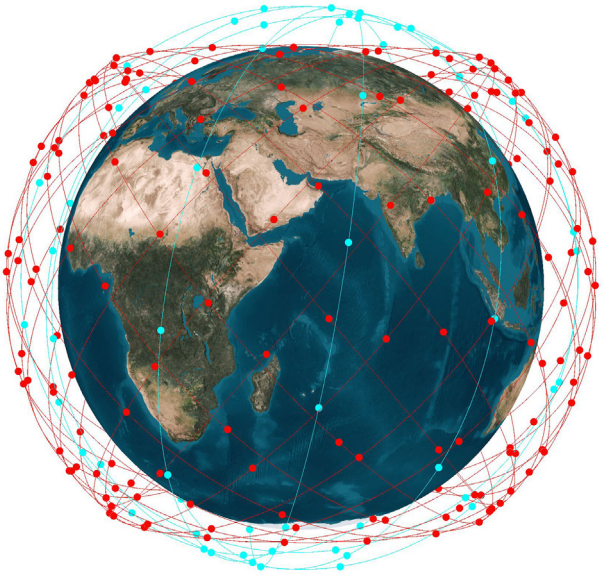

Fig. 2.1. Schematic of a large commercial satellite constellation. Image Credit: Telesat.

- The production of a large number of these satellites may enable cost reduction based on standardization and miniaturization.
- As launch costs are proportional to the mass, it is cheaper to launch small satellites, even to build a constellation, compared with the cost of a single large satellite.
- Small satellites can be used for demonstrating the feasibility of new mission concepts for larger missions.

However, these advantages should be traded against the laws of physics (e.g. resolution $\simeq\lambda/D$) which still need to be obeyed. Technology used for large satellites needs to be adapted to the constraints set by small satellites, mainly size and mass. In order to compensate for the small size of a small satellite, spatial resolution can be improved by using higher operating frequencies or by artificially increasing the aperture D. For example, techniques such as synthetic aperture radar and interferometry could be feasible with constellations of small satellites. Both are associated with technical challenges (e.g. high-frequency receiver/transmitter and control/stability, propulsion) but one should not exclude such promising developments in the future.

Another important potential for SmallSats is working in symbiosis with large satellites in order to complement their capabilities. Such an approach is already used by Landsat or by the Copernicus/Sentinel-2 system, combined with Planet data, for which accurate multispectral data are complemented by daily high-resolution images. Another example is the ESA Earth Explorer mission called Fluorescent Explorer (FLEX), which is being designed to fly with Copernicus Sentinel-3. This synergy of missions can also be used to develop techniques for ensuring the cross-calibration of measurements between different missions and ensuring the quality of these data for science applications.

Innovative concepts for small satellites, e.g. passive receiving-only radar antennae flying together with other, larger satellites acting as the transmitters for bistatic measurements, are under development. The recent ESA definition phase of the L-band SAOCOM Companion Satellite (CS) demonstrated that a passive small SAR could be developed to significantly improve the science mission objectives of the main mission (flying with the larger SAOCOM mission). The agility and some of the techniques associated with small satellites, if properly mastered, could open (as in some cases already happening today) many other new applications linked for instance to video capabilities, real-time imaging, and instruments directly commanded by the users on the ground.

Worth noting is that one should not only consider high revisit rate *vs.* (spatial) resolution, concluding that the former is more important to customers than the latter (which is usually, but not always, true). In fact spectral and/or radiometric parameters can also be "key application enablers" for atmosphere or hydrosphere observations and even for "classical" land imagery. Furthermore, actual mechanisms and feedback loops can be captured by multi-point measurements, perhaps even using different techniques such as optical and SAR. This would allow for capturing interactions between the various cycles, which would be a paradigm shift rather than an incremental improvement in spatial or temporal resolution.

In order to realize such a mission, opportunities exist for science to take advantage of developments in the commercial sector. As discussed in Chapter 1, commercial interest in small satellites for Earth Observation is growing at a rapid rate. For example, in 2017, 328 small satellites were launched, 103 of which were in a single launch (Planet with ISRO/PSLV launched on 14 Feb. 2017). Out of the 328 satellites, two thirds were used for Earth observation, with masses from <10 kg (89%), 10–100 kg (7%), up to 100–500 kg (4%); the remaining one third was for technological and scientific applications (31%) and for communications (2%) (all numbers from CATAPULT, 2017). It is worth noting that the total mass of these 328 satellites was less than the 8-ton ENVISAT launched by ESA in 2002 carrying ten different instruments.[39]

Scientific constellation missions could leverage the technology (standardization and miniaturization), and learn

[39] Interestingly, the cost per kg per instrument for ENVISAT yielded approximately 0.3 M$/kg, which was very competitive compared to present-day SmallSats with typically single instrument payloads launched in 2017, whilst also considering that ENVISAT lasted for ten years from 2002 to 2012 (twice its nominal design lifetime).

from industrial manufacturing and I&T methodologies. Finally, opportunities may exist for commercial data buys or for putting science instruments on commercial platforms. So far, such partnerships are challenging to develop, though successful examples do exist.

Regardless of the model employed, some key elements of the data acquired by small satellites should be considered including:

- *Sustainability of the data:* how to ensure, from a science perspective, that the data acquired by these missions are based on a long-term commitment needed by most science users;
- *Data policy:* How to guarantee a data policy which is as open, full and free as possible for all the data, which is a precondition for a good science development plan[40];
- *Potential conflict of acquisitions between commercial and science requirements:* Many recent developments of SmallSats are driven by commercial entities which make available large datasets of EO data. When these data are used for scientific purposes, it's important to ensure that commercial interests do not jeopardize the science potential of such missions;
- *Compatibility:* SmallSats should be considered an element within a bigger ecosystem, often flown to add additional capability to the institutional satellites such as the Copernicus Sentinels.
- *Data downlink:* Large amounts of data may require on-board data processing/handling to downlink only useful data (e.g. cloudy images to be disregarded by on-board processing).
- *Data usage:* Once the data are on the ground, the forthcoming challenges for SmallSats are more in the exploitation of large data sets (big data, artificial intelligence, merging different types of data - satellite and non-satellite) - rather than in the development of the satellites themselves.

More generally speaking, the development of SmallSats for science should answer the need of the users' community in order to avoid a technology push approach, which might generate a deluge of uncalibrated and useless data. This would also avoid overselling of SmallSats, i.e. making promises that cannot be kept, which might be detrimental to the further use of this type of satellite by the science community. The importance of open data policies and international sharing of data cannot be overstated. The Move-Bank initiative, a database for collecting and distributing data of migrating animals collected by biologists worldwide, may be used as a model or inspiration for such a data share initiative.[41]

2.1.2. Magnetospheric constellation mission

The important role of small satellites for magnetospheric research is well accepted (e.g., Shawhan, 1990), and the space physics community has discussed the need for a large magnetospheric constellation mission for decades (e.g., Angelopoulos and Panetta, 1998; Fennell et al., 2000). Smaller constellations of 3–5 spacecraft, such as Cluster, THEMIS, SWARM, and MMS, have already enabled transformational science. THEMIS serves as a particularly good pathfinder for using SmallSats; its five 77 kg (dry mass) satellites, launched on a single Delta II rocket, have been operational for almost 12 years. However, the leap from 5 satellites to dozens or hundreds of scientific satellites has not yet occurred.

The magnetosphere, ionosphere, and thermosphere together act as a coupled system, responding to driving by the solar wind from above and the lower atmosphere from below. Understanding how the energy of the solar wind couples into this system and the interaction between adjacent regions of space requires multipoint measurements over broad regions. Like weather stations distributed around the globe or buoys across the ocean, distributed measurements throughout the magnetospheric system, coupled with sophisticated computational models (Fig. 2.2) (Spence et al., 2004), will transform our ability to understand and make predictions about the space environment.

Such a mission concept has so far continued to be decades away. However, the rapid pace of development of small satellites gives reason to be optimistic. Efforts are underway to develop minitiarized instrumentation. For example, the 6U Dellingr CubeSat, developed at NASA's Goddard Space Flight Center, provided a test bed for a small science magnetometer and mass spectrometer. The CSSWE CubeSat developed at the University of Colorado used a miniaturized version of the Van Allen Probes REPT energetic particle instrument. The Goddard team is currently working on a radiation hardened bus (GTOSat) based on the Dellingr design. The next critical step will be learning how to manufacture and test large numbers of identical satellites, an area about which the science community must learn from industry.

It may also be possible to leverage commercial space to realize some components of a large constellation. For example, hosted payloads on commercial LEO satellites could target specific measurements at the ionospheric boundary. An already-existing example is the AMPERE project, funded by the US National Science Foundation, which uses the ADCS magnetometers on the Iridium satellites to detect field aligned currents in the auroral region (Anderson et al., 2000). The project was achieved with a

[40] https://earth.esa.int/web/guest/-/revised-esa-earth-observation-data-policy-7098, 2010, or European Commission Delegated Regulation No 1159/2013, https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32013R1159&from=EN.

[41] https://www.movebank.org/.

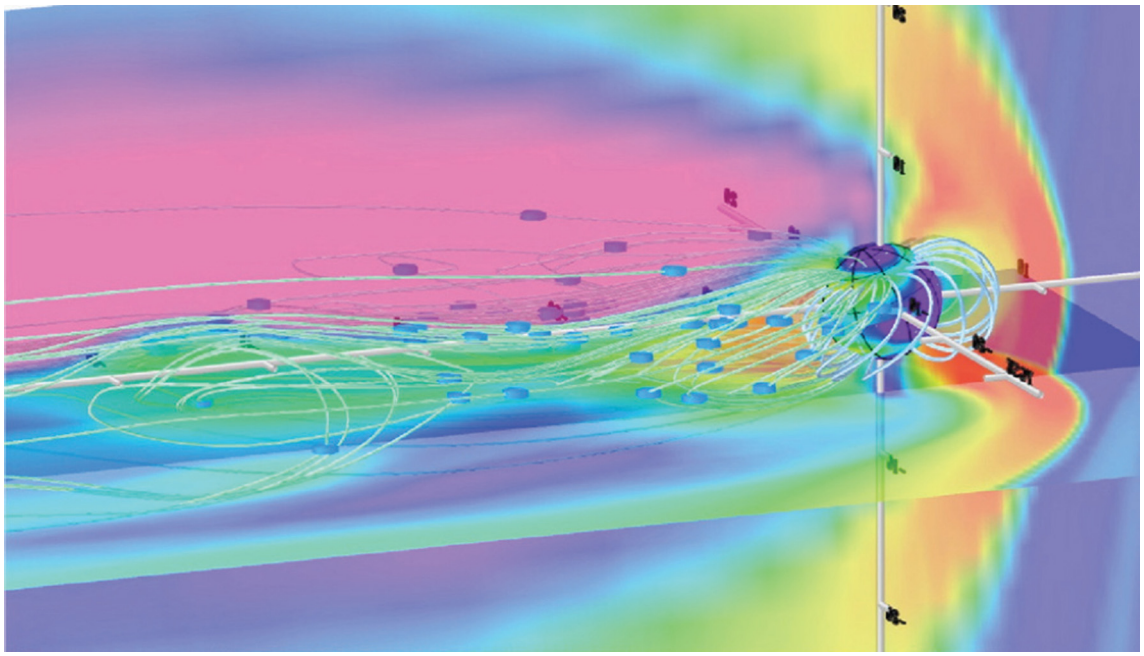

Fig. 2.2. The Magnetospheric Constellation (MagCon) mission concept from a NASA mission definition study showing 36 spacecraft superimposed on a magnetohydrodynamic (MHD) simulation of Earth's magnetosphere. Figure reproduced from Spence et al. (2004).

public private partnership between the commercial space industry, university researchers, and NSF (government). A more recent study used magnetometers on the Planet Labs Inc. CubeSat constellation (Parham et al., 2019). Providing a different view, the recently launched GOLD mission makes measurements of the upper atmosphere from geosynchronous orbit. GOLD uses a science instrument – a UV spectrograph – that is hosted on SES-14, a commercial communications satellite built by Airbus for SES Government Solutions.

International collaboration is another means to achieve an ambitious vision such as a magnetospheric constellation. In fact, the QB50 project discussed in Section 1.1 included plasma instruments (Langmuir probes) on some of the spacecraft. Although the project had goals other than scientific research, it can serve as a model of international collaboration that enabled a large number of small satellites to be built and launched in a coordinated way (see also Section 3.5).

2.1.3. Conclusions and findings

SmallSats enable new science, applications and commercial developments at all levels (upstream, downstream, national, international) especially via constellations and convoys of multiple satellites combined with readily available platforms and short R&D update cycles. However, development in Earth sciences cannot be done cheaper, faster, better using SmallSats alone, and these SmallSats should be considered elements of a larger measurement ecosystem.

Nevertheless, this new generation of satellites offers opportunities worth exploring and developing to support a better understanding of Earth as a system, including addressing observational gaps and providing more frequent measurements. In order to be beneficial for the science community, one should ensure that key issues linked to a free, full, and open data policy, generation of useful and well-calibrated data, and ensuring a long-term and sustainable stream of data, are taken into account when considering the development of this promising new domain.

Finding 2.1 – An opportunity exists for transformational advancements in Earth and space sciences using large constellations of satellites. This vision may be achieved with stand-alone science missions or through partnerships with industry that make use of the increasing number of small satellites in orbit The scientific community would benefit tremendously from the data acquired by this large number of satellites assuming these are governed by a free, full, and open data policy for research purposes.

2.2. Swarm exploration of a solar system body

This section elaborates on one high-impact planetary science concept, then provides a couple of additional examples of science applications that would benefit from large constellations (networked or not) of CubeSats or SmallSats.

2.2.1. Exploration of "Once in a Lifetime" planetary bodies

This concept targets planetary objects with very long periods (referred to as LPOs), i.e., bodies that cross our solar system and approach Earth only once in a person's

lifetime. These bodies include Oort cloud comets (200+ years), Manx objects and, now, interstellar objects (ISOs), such as the recently discovered 'Oumuamua (Meech et al., 2017). This is not the first, and certainly not the last interstellar visitor in our solar system. Long-period comets are the most primitive witnesses of the early solar system. Interstellar visitors are suggested to be ejecta of extrasolar planets subject to catastrophic collisions. Hence the scientific value of exploring these objects is unbounded, especially as a recent study suggested that these collisions could have offered a means to transfer life organisms among extrasolar systems (Berera, 2017). This discovery carries implications on a fundamental level regarding the place of humanity in the universe and the prospect to sample extrasolar planets.

A very broad range of measurements are sought for long-period and Manx comets and ISOs. They include basic physical properties characterization (shape, density, morphology, dynamical properties), compositional properties (elemental composition, mineralogy, isotopes of at least hydrogen, oxygen, nitrogen, and carbon), geophysical/interior properties (porosity, cohesion, magnetic field), geological traits that might inform on origin and possible long-term evolution, and interactions, in particular of a coma when it exists, with the solar wind. Instruments small enough to perform these measurements already exist but their operation might prove challenging, as described in more detail below. Instruments of choice include dust spectrometers (mineralogy, dust coma density) because they can operate when interacting with high-velocity material; in situ remote sensing instruments such as submillimeter wave spectroscopy (e.g., the MIRO instrument on Rosetta), which allows constraints on isotopic properties of volatiles from a safe distance; other in situ remote sensing instruments include color imagers, and spectrometers covering a broad range of wavelengths. Elemental measurements are more complex to implement in that they require close interaction with the target for some extended collection time. Elemental abundances may be obtained in part from measuring the plasma generated between the target's coma and/or dust and the solar wind.

The exploration of LPOs is challenging for many reasons: (1) the orbital properties of these bodies are not known with enough lead time to develop a mission; (2) they have a broad range of inclinations; (3) the encounter velocities are in excess of 50 km/s, hence the encounters may be very short; (4) LPOs may be geophysically active or made of multiple coorbiting elements. The only attempt to explore a comet with a longer period (~75 years) up-close was the encounter with Comet Halley in 1986. Its visit was deemed such an important event that six spacecraft were sent by different space agencies: ICE (NASA), VEGA 1 and 2 (Roskosmos), Suisei and Sakigake (ISAS, its first science mission), and Giotto (ESA). The deployment of three spacecraft at once was and remains the first instance of its kind. The missions were coordinated by the IACG (Inter-Agency Consultative Group), which was created for this purpose. NASA's ICE did not in fact "encounter" Halley as it stayed outside the shock front, yet it was important to help showing the others the way.

The challenges in implementing a mission to an LPO or Halley during its 2061 return may be addressed by sending a very large number of spacecraft separately by multiple space agencies, and in a coordinated manner (Fig. 2.3). It is simply too big an endeavor to expect any single space agency to send a very large number of assets with a diversity of capabilities commensurate with the broad science knowledge sought at these bodies, within today's budgets. On the other hand, the enormous interest generated by the visits of LPOs and 'Oumuamua on a worldwide scale indicates that an international effort to coordinate future exploration of these bodies is a worthy and realistic endeavor.

Constellations, formations, and swarms of small spacecraft have been identified as game changers for enabling new space science (NASEM, 2016). In recent times, there has been a tremendous development in regards to the technology maturation level achieved by SmallSats (NASA, 2015). Smallsats offer a number of advantages, in particular advanced distributed spacecraft architectures that can be used to address the above challenges and enable wholesome science investigations over a short observation window. This includes: (1) a loose coordination to synthesize a single, large, virtual instrument (Bandyopadhyay et al., 2016); (2) innovative distributed, possibly heterogeneous measurement, and data analysis techniques; (3) autonomous operations; (4) communication relay strategies; and (5) novel orbital organization approaches for constellations or more effective swarming and to enable observations from multiple vantage points.

We (collectively) do not know how to approach objects with velocities in excess of 50 km/s. The Halley comet missions, while bold, had a modest science return in comparison to the level of resources engaged, because the violence of the heavy dust environment destroyed some of the instruments. However, these missions were milestones that sparked the development of miniaturized instruments in Europe and Japan's line of science missions. Similarly, we expect that objects of major science significance like debris from extrasolar planets and pristine building blocks of our solar system can foster novel approaches to space exploration and hopefully coordination among space agencies. A major aspect of this type of concept targets technology challenges related to manufacturing and operating large numbers of assets, resilient approaches to handling risk, and defining an effective framework to engage prospective sponsors, possibly from the international community. Private companies with internal and government support are paving the way for large-scale manufacturing of capable space platforms at low recurring costs, and offer a business model that could be a model for future endeavors.

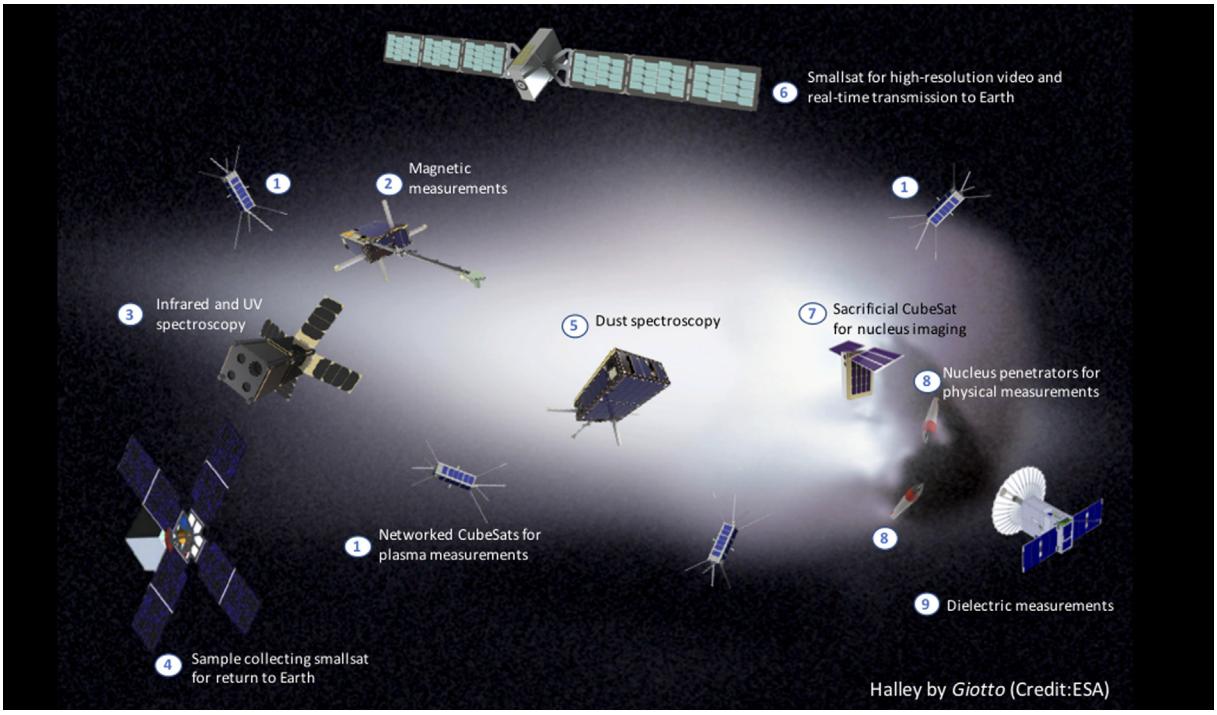

Fig. 2.3. Example of concept meant to explore comet Halley using a fractionated constellation during its next visit in 2061. This figure illustrates the types of measurements needed to fully understand this unusual comet (it does not belong to the two classical reservoirs of comets, Jupiter Family and Oort Cloud). Image Credit: ESA.

It is envisioned that up and coming telescopic facilities such as the Pan-STARRS2 Observatory combined with the Pan-STARRS1 telescope, and later the Large Synoptic Survey Telescope (LSST) when it comes online in the early 2020s, will enable the discovery of LPOs a decade and more before these objects reach perihelion. This timeline is a priori sufficient to implement and launch spacecraft that may encounter the LPO as it approaches its perihelion, which should involve crossing Earth's orbit in most cases. Clever mission design frameworks need to be thought out ahead of time to address the aforementioned challenges.

2.2.2. Discovering exoplanets

This idea follows in the footsteps of the ASTERIA[42] 6U CubeSat Mission (Arcsecond Space Telescope Enabling Research in Astrophysics) that was successfully launched and deployed from the International Space Station in the Summer of 2017. ASTERIA is primarily a technology demonstration and an opportunity for training early career scientists and engineers. The mission introduces capabilities that enable long-term pointing and photometry monitoring at specific stars believed to host exoplanets. The main scientific objective of the mission is to search for transits of planets in front of their stars, expressed in the form of variations in the brightness of the latter. The capability to point for hours pertains to a large number of other astrophysical applications, for example to measure star properties. If ASTERIA is fully demonstrated, then it would make sense for a follow-on mission to send a large number of similar CubeSats, each of which would target a different star. The CubeSats may differ in the nature of the measurements they are performing, for example by carrying different filters (Cahoy, 2015). Slightly larger spacecraft may allow for more complex techniques such as infrared or ultraviolet spectroscopy. For example, the recently selected SPARC mission (Star-Planet Activity Research CubeSat) is planning to assess stellar radiation environment via photometry monitoring in the ultraviolet (Shkolnik et al., 2018). The key to this type of concept is to dedicate one CubeSat per star target of interest. Thus, it makes it relatively easy for international collaboration once the concept of operations is agreed upon, i.e., everyone can launch as they see fit, and join different phases. It may allow for citizen science as well.

2.2.3. Giant planet magnetosphere and atmosphere exploration

This idea builds on the prospect that large missions to giant planets could have enough mass margin to carry several CubeSats that may be deployed in the atmospheres or magnetospheres of these planets. The icy giants Uranus and Neptune have been identified by NASA[43] as targets of prime interest for the next decade. Understanding the

[42] https://www.nasa.gov/mission_pages/station/research/experiments/2513.html.

[43] https://www.lpi.usra.edu/icegiants/mission_study/.

intrinsic magnetic fields and magnetospheres of these planets are important objectives of a future mission. Similar to Earth, giant planet magnetosphere characterization is best approached via multi-site measurements. Preliminary analyses identified that simultaneous magnetic field measurements covering a broad range of latitudes and longitudes and pursued for at least a full rotation period (of the order of 10 h) would yield groundbreaking results in comparison to the current approach of this type of measurement. The CubeSats may be released sequentially for extended temporal sampling. High-quality magnetometers are small enough to fit within 3U CubeSats (see for example the INSPIRE[44] mission) and the latter may also include a transponder for gravity field measurements. This type of geophysical measurement is best realized if the CubeSats perform their measurements in a synchronized manner via telecommunication networking (among CubeSats or between CubeSats and mothership). Networking provides additional advantage, for example CubeSats flying by different hemispheres could perform sounding of the planet atmosphere via radio-occultation.

A different application could target planetary atmospheres where the deployment of many CubeSats in multiple sites would inform on chemical (e.g., volatile, isotopes) composition and its lateral variations. That type of investigation would not require networking among CubeSats.

While there is strong interest from the community for this type of investigation at icy giants and other planetary bodies, the pathway for adding CubeSat-class spacecraft to flagship-class missions is not yet defined. A compromise may be sought where CubeSats are developed following design rules driven by the more expensive mission, with the risk that they might become too expensive for multiple of them to be carried in the first place. Approach to risk and mission assurance might also make it more difficult for a mission from a space agency to carry CubeSats developed by foreign entities.

There are a number of technology roadblocks that need to be addressed before these three or any other major deep-space missions can be undertaken with small satellites. Telecommunications, power generation, propulsion, and mission operations pose specific challenges different and more severe from missions in Earth orbit, as already discussed in Section 1.2.3.

Finding 2.2 – Small satellites provide opportunities to significantly enhance infrequent interplanetary missions with, e.g., landers or sacrificial satellites, and networks of small satellites that could enable missions to "once in a lifetime" objects.

[44] https://www.jpl.nasa.gov/cubesat/missions/inspire.php.

2.3. Small satellite synthetic aperture telescopes

Many of the primary scientific goals of astrophysics require making observations of the faintest objects in the universe and forming images of stars and planets with sufficiently high spatial resolution to resolve their disks. These are tasks for large collecting area and/or large effective apertures.

NASA's James Webb telescope, for example, to be launched in 2021 and costing some $9 billion, is about the largest practicable telescope that can be origami-folded into the largest available launcher fairing. A different approach will be needed for the next generation of telescopes if, say, double the aperture is required (Sweeting, 2018). Small satellites with mirror segments could either be assembled (or auto-assemble) to larger structures in space (see Fig. 2.4, Saunders et al., 2017) or even operate together in free formation flight.

Specialized constellations of SmallSats will in the near future be able to make synthetic aperture telescopes with both large collecting area and/or large effective apertures. These new generation telescopes would be able to image planets, resolve stellar systems, and detect and image near-Earth asteroids at costs that are significantly less than has occurred in the past.

For decades, radio astronomers have used synthetic apertures to achieve high spatial resolution and large collecting areas. As a consequence the methods for reconstructing images from distributed arrays of telescopes are well understood. Observatories on the ground by, for example, the VLTI and CHARA arrays have demonstrated visible synthetic aperture systems implemented by combining individual telescopes using beam directing mirror systems, evacuated tubes, and automatic phase delay controls. It is possible, though challenging, to apply the techniques demonstrated on the ground in space.

This is not a new idea. The Space Interferometry Mission (SIM) that started in 1998 was intensively studied, but ultimately dropped for technical and cost reasons. The Laser Interferometer Space Antenna (LISA) is underway as a joint NASA/ESA mission to detect gravitational waves. LISA requires pointing precision well beyond that of an optical synthetic aperture array. The LISA Pathfinder mission has flown and has exceeded its design requirements.

The lessons learned from the SIM and LISA Pathfinder missions together with new small atomic clocks, optical communications between telescopes, and precision interferometric location techniques could be used to create a distributed array of 200 kg one-meter telescopes. Sub-nanosecond clock synchronization can be achieved using pulsed optical links (Anderson et al., 2018). The collection area would depend on the number of telescopes in the array; an effective ten meter telescope would require about one hundred spacecraft with one meter telescopes, and a 30 m system would need about a thousand satellites. New manufacturing techniques being developed by industry

Fig. 2.4. Concept of the Autonomous Assembly of a Reconfigurable Space Telescope (AAReST) mission consisting of an arrangement of 10 cm diameter circular mirrors attached to a cluster of CubeSats. Image Credit: AAReST Team, California Institute of Technology (http://www.pellegrino.caltech.edu/aarest1/).

for EO constellation missions could be applied here. Manufactured in quantity, a reasonable target cost per spacecraft could be ~$500,000. So, the cost of a 10 and 30 m distributed array could be ~$50 M and ~$500 M, respectively. The cost of the design and development plan might be $100 M. The launch costs would be comparable to the cost of building the satellites, so it is not unreasonable to expect a 10 m and 30 m telescope to cost $200 M and $1100 M respectively. This is significantly less than the James Webb space telescope even if the cost estimates are low by a factor of three or more.

Developments in photonics technology provide another approach for executing a phased array optical telescope. New fabrication developments have allowed the construction of a 1.2 m flat panel phased array. The first mission could be a 1.2 m system on a small satellite. The next step might be to build a folded array of one meter panels. Unfolding a stack of 9 planar arrays, a 3×3 panel telescope, would produce a collecting area of 13 m^2, equivalent to a 4 m telescope, with a spatial resolution of 0.028 arcseconds in the mid visible. The array panels could use small lenses on each of the photonic waveguides. Each lens could have a nano grating on its surfaces to generate a spectral shift with angle. Because the telescope is pointed electronically, images in different spectral bands could be obtained. Alternately, each wave guide could have a tunable photonics Fabry-Pérot interferometer for high spectral resolution. The elements of the array would be connected with a single-mode optical fiber to computer controlled photonics phased delays in the spacecraft's correlator.

Another interesting possibility is a spacecraft with a one meter photonics telescope on the spacecraft and another that is deployed on a long (e.g. 100 m) arm. This is challenging from both the mechanical and the thermal stability perspective even though the arm does not need to be rigid to optical wavelengths. Its role would primarily be to provide and keep the relative location of the telescopes. At some arm length the mechanical and thermal challenges will become more demanding than those associated with flying in free formation, but today it is anyone's guess at what scale the transition will occur.

A 100 m system would have a spatial resolution of about 5×10^{-9} rad or a milliarcsecond in the mid visible. In a 1000 km near-Earth orbit, it could resolve a 5 mm feature on the Earth's surface, features on the Moon as small as two meters, and 19 m on an asteroid at 100 lunar distances, respectively. It could resolve features of 5×10^5 km on a star at ten light years. On nearby stars the system would be able to resolve starspots and apply the techniques of helioseismology that have been developed to determine the solar temperature, density, and rotation rate in the stellar interior.

It is very much hoped that the James Webb space telescope will live up to expectations and deliver groundbreaking observations in 2021 and onward. But it is equally clear that the next step after this can only be made with a

distributed system that seems way out of reach technologically at this time. The situation is somewhat reminiscent of ESOs Very Large Telescope (VLT), made of four 8 m telescopes, that saw first light in 1998, but only recently did it become possible to combine their signals to make a single 16 m telescope.[45] In space, it will be small radio telescopes that will make interferometry possible first, and from there we can work our way through infrared into the optical band. In parallel, progress made in attitude control with the LISA Pathfinder and the forthcoming LISA mission will bring the necessary precision to combine optical signals so that it may eventually become possible to, e.g., image an Earth-like planet in another stellar system.

Finding 2.3 – Monolithic large telescopes in space cannot grow further after JWST. A new approach such as distributed apertures on small telescopes is needed to make further progress.

2.4. Interstellar missions

Today, interstellar missions are impeded by the vast distances of space in combination with the limited lifespan of human beings. Thus, in order to enable future interstellar missions, the velocity of spacecraft must be increased, either by increasing the initial acceleration or the time over which acceleration is applied.

The concept of solar sails utilizes the solar radiation pressure for propulsion. This removes the need for carrying propellant tanks, thus reducing system mass and complexity. However, as the solar radiation pressure is very low, large sail areas are needed and very long acceleration times must be endured. The successful JAXA-built spacecraft IKAROS demonstrated the technology on a Venus bound mission launched in 2010 (Tsuda et al., 2011). The Planetary Society's LightSail-1 mission deployed a solar sail in orbit in 2015.[46] More recently InflateSail, launched in 2017 as one of the QB50 satellites, did the same with a 3U CubeSat (Viquerat et al., 2015).

A similar concept is the laser sail in which the propulsive photons are generated on Earth. One such mission concept is the Breakthrough Starshot initiative proposed in 2016 by Stephen Hawking, Mark Zuckerberg, and Yuri Milner.[47] This effort strives to lay the groundwork for a mission to Alpha Centauri within the next generation. The concept builds on two major ideas: shrink current-day spacecraft to a total mass of about 1 g and leave the propulsive system based on a laser on ground. They show that with such a system, spacecraft velocities of up to 20% of the speed of light are feasible (Lubin, 2016). With such high velocities, it will be possible to leave the solar system and conduct interplanetary missions within the average lifespan of space researchers.

The technical challenges of the Starshot initiative are formidable. The initiators admit that, "A number of hard engineering challenges remain to be solved before these missions can become a reality", and go on to list some 29 of them while claiming that, "no deal-breakers have been identified". For example, the feasibility of a sail with the required properties is far from clear as it requires managing multiple, conflicting priorities, and engineering a solution that partially satisfies all of them (Atwater et al., 2018). Moreover, the nanocraft will be subject to potentially damaging collisions with interstellar gas and dust (Hoang et al., 2017). The communication with Earth will suffer from a very poor link budget that will need to be addressed by either repurposing the sails for communications and/or distributing the satellites along the way as relay stations. Finally, the question of what kind of scientifically useful measurements could be obtained also remains. Even so, a mission to a star other than the Sun remains the ultimate vision for the future and is well worth exploring further.

2.4.1. Challenges and impact

The basic idea of leaving the propulsive system on Earth opens up a new class of missions and research projects not confined to interstellar missions. An Earth-based infrastructure for laser propulsion would also allow for faster interplanetary missions. It may specifically constitute the base for a fast response system for missions to unexpected targets.

A wide range of technologies will have to be developed before any such missions are launched. These include new energy systems capable of storing energy in the GWh range and delivering this energy to the ground-based laser system almost impulsively at bursts reaching 500 GW. But also powerful lasers, ultra-thin sails with ultra-reflective coatings, more energy-efficient communications systems, and new integration techniques for the actual spacecraft have to be developed. Many of these technologies may be used for terrestrial applications as well, improving society in general. For instance, the needed development of the laser power supply may lead to an increase of the efficiency of terrestrial power plants and distribution systems, or help in solving the energy storage problem that renewable energy sources have to tackle.

2.4.2. Pre-interstellar missions

Prior to interstellar missions, the mere testing of the spacecraft system and design within the solar system will allow for a new branch of scientific studies, such as:

- A fast response system to explore the unexpected, e.g. eruptions on solar system bodies or the interstellar asteroid A/2017 U1 'Oumuamua (Gaidos et al., 2017);

[45] https://www.eso.org/public/news/eso1806/.
[46] http://www.planetary.org/explore/projects/lightsail-solar-sailing/.
[47] http://breakthroughinitiatives.org/initiative/3.

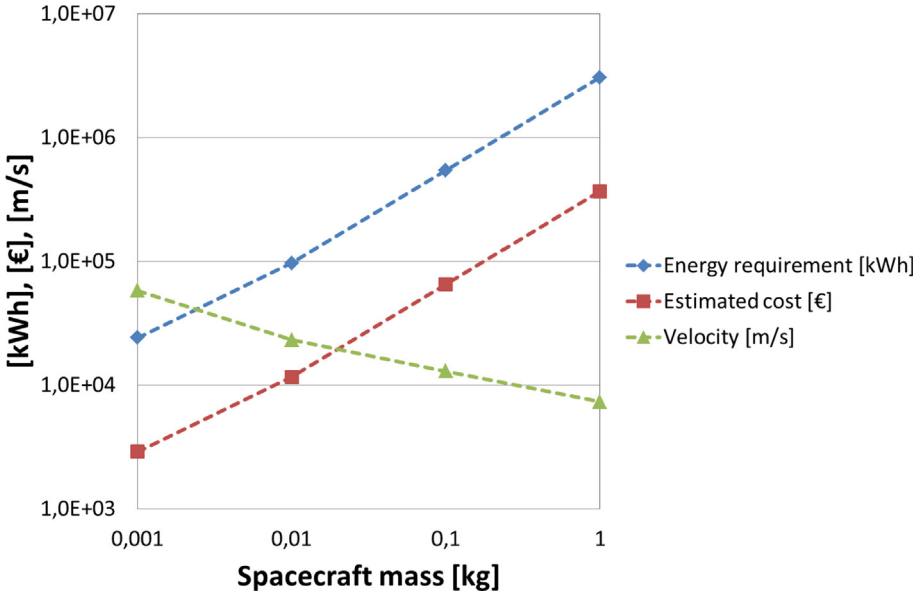

Fig. 2.5. Graph illustrating the relation between the spacecraft mass and laser array energy consumption, cost, and final velocity, in units given in the legend.

- 3D mapping of asteroid belt objects using a swarm;
- Multi-point studies of the heliosheath and termination shock.

With velocities approaching a fraction of the speed of light, intra-solar system travel times are dramatically reduced. Further, once the development and construction of the necessary ground-based infrastructure is done, the launch cost is reduced to the maintenance cost of the Earth-based infrastructure and the energy required to accelerate individual spacecraft. This may open up deep space for a much more diverse scientific audience similar to what CubeSats have done.

The Earth-based laser propulsion system consists of a laser array and is thus fully scalable. This means that ramping up the accelerative force only requires that extra lasers are added to the laser array. This also allows for a trial-and-error approach to the mission scenarios. Fig. 2.5 illustrates energy expenditure, energy cost[48] (0.12 €/kWh) and ultimate velocities of spacecraft with increasing mass being accelerated by the same array. It assumes a laser array of 10 MW with an array size of ~120 × 120 m^2 propelling spacecraft of masses from 1 g to 1 kg. Since heavier spacecraft accelerate more slowly, they remain within the vicinity of the laser for a longer time, which increases overall energy consumption and cost. The laser array size has been determined by extrapolating from values given by Lubin (2016).

Small laser-propelled spacecraft are the only ones that could catch up with objects moving at tens of km/s and be cheap enough to be on standby in Earth orbit. Although this speed is far from the ultimate design speed of 0.2 c (60,000 km/s) for the starshot, it could represent a good intermediate step. If for example a 1 g spacecraft in Fig. 2.5 is accelerated to ~1/1000th of the ultimate speed, roughly 60 km/s, it could have made a rendezvous with A/2017 U1 'Oumuamua at closest approach in about 8 days. That would require that 'Oumuamua had been spotted in time (which was not the case). If we assume that a hot pursuit was started at the time when 'Oumuamua was discovered it would have taken about a month to catch up. Fig. 2.6 shows the trajectory of 'Oumuamua from a distance of 1 AU before closest approach to a distance of 12 AU after closest approach. Using the final velocity of the three spacecraft with masses of 0.001, 0.01 and 0.1 kg in Fig. 2.5 it is possible to calculate how far they travel daily. The distance from Earth is set to 0 AU until the day they are launched towards 'Oumuamua (which is assumed to happen on the 20th of October – the day after discovery). By calculating the distance between 'Oumuamua and the launch position, it is possible to estimate how long it will take for the spacecraft to catch up with 'Oumuamua, as illustrated in Fig. 2.7. It is seen that the 10 MW laser array is not capable of accelerating the 0.01 kg and 0.1 kg spacecraft to a final speed that will allow them to catch up with 'Oumuamua. Either a more powerful laser array or a better sky survey system that provides earlier alerts will be needed. The energy cost at today's European electricity prices would amount to approximately 3′000 € per 1 g spacecraft accelerated.

After the acceleration phase, the "ChipSats" are coasting, which means that any orbit perturbations must be a result of external forces. By simply tracking the chipsats,

[48] http://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Electricity_prices_for_non-household_consumers,_first_half_2017_(EUR_per_kWh).png.

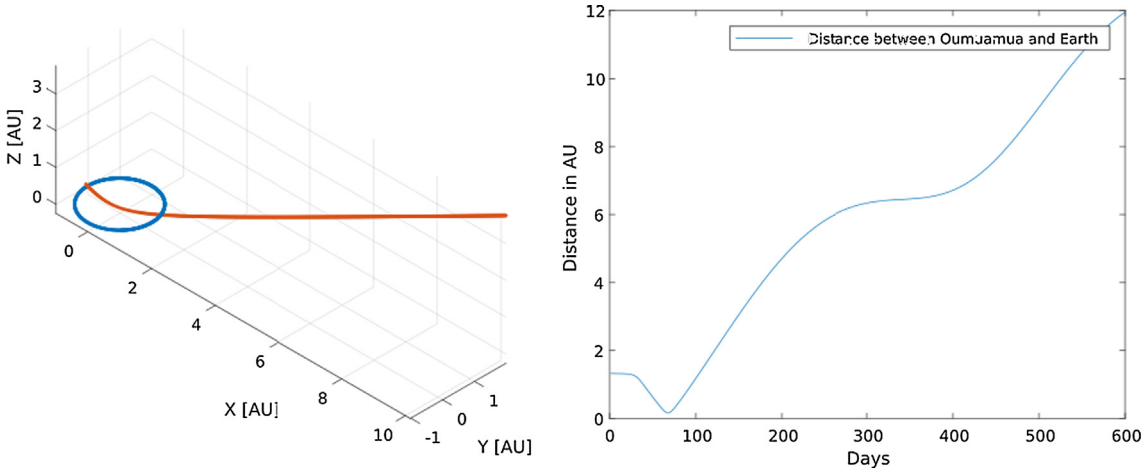

Fig. 2.6. Left: the trajectory of 'Oumuamua as it passed Earth orbit. Right: the overall distance between Earth and 'Oumuamua. Position data used for the illustration is taken from JPL Horizons database and web interface (https://ssd.jpl.nasa.gov/horizons.cgi). 'Oumuamua was discovered after closest approach.

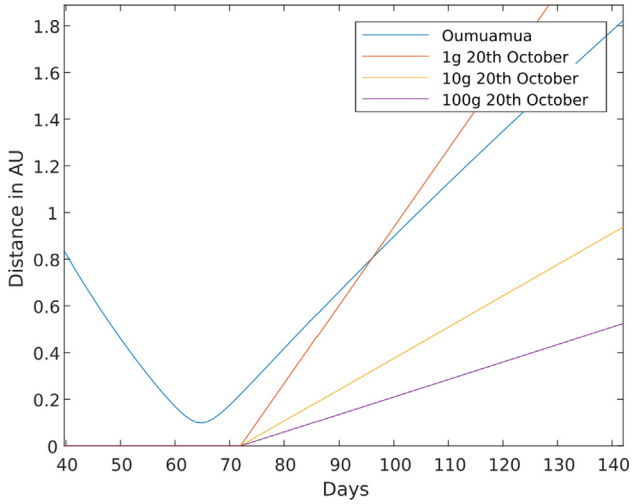

Fig. 2.7. The blue line shows the distance between 'Oumuamua and the position of Earth at the 20th of October 2017. In this simulation the S/C are accelerated from that point in space and at that date. The three lines (red, yellow and purple) indicate three different spacecraft masses all accelerated with the same 10 MW laser array. It is seen that only the 1 g spacecraft will gain sufficient velocity to catch up with 'Oumumua. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the nature of such forces may be studied. Adding for instance a magnetometer to the spacecraft would allow the study of the space traversed while keeping the data return scalable. Imaging instruments will further enhance the capability of the spacecraft but also increase the demand for data bandwidth. In the proposal by Lubin (2016), the laser array is used both for acceleration and for communications using the optical array as a receiver. Alternatively, a network using other deep space spacecraft as relays may be envisioned, similar to the relay system demonstrated by NASA using its Mars orbiters to communicate with rovers. The two MarCO spacecraft launched with InSight demonstrated a CubeSat version of such a relay system in November 2018.

2.4.3. Politics

The infrastructure for interstellar propulsion requires large investments. Laser arrays are envisioned to cover from 10^6 to 10^8 m^2 depending on the power output, which shall be between 1 and 100 GW. In terms of size the construction is comparable to the LHC at CERN (8.6 km in diameter) and much larger than ESO's ELT,[49] both of which are the results of international collaboration and funding. Though no cost estimates have been made, it is likely that a number of space entities need to partake in the construction in order to secure the needed funds. The initial Breakthrough Starshot proposal suggests a large array of lasers to be placed at one location, selected from a mission requirements point of view. However, it might be easier to obtain the required funding for the structure by dividing the array into smaller entities placed at locations chosen from both a national political point of view as well as mission requirements. Spreading the array over multiple nations will also, by necessity, strengthen the international space collaboration just as the international space station has done. However, distributed laser arrays may introduce laser phasing issues.

When operating, the laser array emits laser power in the GW range, thereby endangering any object that happens to be in the light beam, including satellites orbiting Earth. Depending on the mission type and spacecraft size, operations may span between ten minutes and several hours. With more than 40,000 objects in orbit around Earth, close coordination will be paramount to ensure safe operations. Conversely to the hazardous potential, the propulsive power of the system may also serve purposes of international relevance such as collision avoidance of low Earth

[49] https://www.eso.org/sci/facilities/eelt/.

orbit spacecraft (Stupl et al., 2012) and asteroid deflections (Thiry and Vasile, 2014).

2.4.4. Technology

Developments in CMOS technology and space technology in the form of CubeSats have shown that shrinking physical size and mass is possible while maintaining most or all capabilities of a system. Though the Starshot mission is based on available technologies, many of these are either not yet adapted for deep space missions or are still at a low technology readiness level (TRL). To date, the lowest mass tech demonstrators are the Sprite satellites based on one single printed circuit board. They have been launched on two occasions, but have not yet performed separately, i.e. detached from the mother spacecraft.[50] Thus a suite of enabling technologies needs to be either transformed or developed further to facilitate the Starshot mission.

The envisioned laser wavelength is 1056 nm, i.e. in the IR regime. Though Earth's atmosphere is fairly transparent at this wavelength, high grounds such as mountain regions would still be preferable locations. In the fully developed system, Lubin proposes an ultimate laser array with an optical power on the order of 1–100 GW. Typical wall plug efficiency (WPE) of lasers is around 20% (Botez et al., 2015), though 50% have been reported (Pietrzak et al., 2015). Thus for the largest single site system a nearby power plant capable of delivering up to 500 GW over a period of 10 min would be required. For comparison, a large nuclear power plant typically have a power output of 2 GW[51] and the Space Shuttle outputs 45 GW at take-off. Delivering power to such systems is clearly one of the major infrastructural challenges which will require substantial political support in the country or region in question. The enormous, almost impulsive energy requirements could be somewhat relaxed by dividing the array into minor sub-arrays. This will introduce a new challenge of phasing the laser beams, though.

2.4.5. Predicting when to launch – The technology race

The need for miniature interstellar spacecraft will either introduce or accelerate a spacecraft mass reduction trend. It is possible that such a trend has already been instigated by the advent of the CubeSat format. Here we attempt to estimate the rate of such a trend by combining the predictions given by a spacecraft version of Moore's law with Newton's second law, which gives the travel time $t_C = (d\, m_{S/C})/(t_a\, F)$ that it will take a spacecraft of mass $m_{S/C}$ to reach a star at distance d if accelerated initially by a force F during a time t_a.

To the best of our knowledge, there are no in-depth studies of a mass reduction rate for spacecraft. The mass reduction rate is the time it takes before a given performance may be obtained at half the mass. Two smaller surveys have been conducted, one looking at 115 missions divided into four mission types (Fléron, 2017) and another conducted on 47 communication satellite missions (Fléron, 2018). The first study indicated a mass reduction rate of 36 months for Earth observing missions, but showed no apparent trend for the three deep-space mission types. The second, studying communication satellites, indicated an 18-month mass reduction rate, which seems very high but due to the relatively small data set this may be inaccurate. Another way of estimating the mass reduction rates is by looking at the simplest satellites – satellites that only emit a beacon. With only one function they are easy to compare. Sputnik, Cute-1 and the Sprite satellites were such beacon satellites (Fig. 2.8).

Assuming that CubeSats have instigated a Moore's law for spacecraft as indicated, then the mass reduction rate may be used to calculate the optimum launch time for a given mission. To illustrate the process let's assume a mass reduction rate of 4 years and an initial mass of 1000 kg in the year 2000. All missions are assumed to use the same Earth-based laser array for propulsion as defined by Lubin (2016). Thus the accelerating force, F, remains the same throughout the years. The 1000 kg mass of the first spacecraft mass was chosen arbitrarily inspired by the New Horizons spacecraft of 478kg launched in 2006 and the Juno spacecraft of 3625 kg launched in 2011. It also corresponds roughly to the mass of the Voyager probes, which were launched in the 1970s and today are the first interstellar probes (but will take 75,000 years to reach the distance of the αCen system). As a result of the expression for the travel time above, the chipsats and similar technology will go deeply interstellar first. Even if interstellar missions using larger crafts are launched in the near future, these will be overtaken en route by the ChipSats simply because these will attain higher coasting velocities, see Fig. 2.9.

This last remark should not be mistaken as a recommendation to just wait until ChipSats and the laser launch system are mature enough before attempting an interstellar

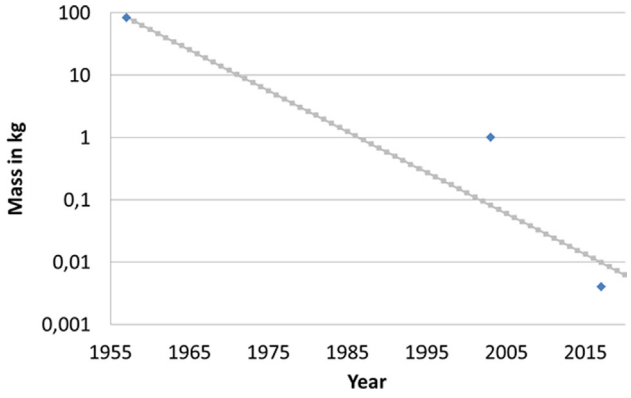

Fig. 2.8. The mass evolution of beacon satellites Sputnik (1957), Cute-1 (2003), and Sprite (2017). The grey trend line has a halving rate of 55 months.

[50] https://www.scientificamerican.com/article/reaching-for-the-stars-breakthrough-sends-smallest-ever-satellites-into-orbit/.

[51] https://en.wikipedia.org/wiki/List_of_largest_power_stations#Nuclear.

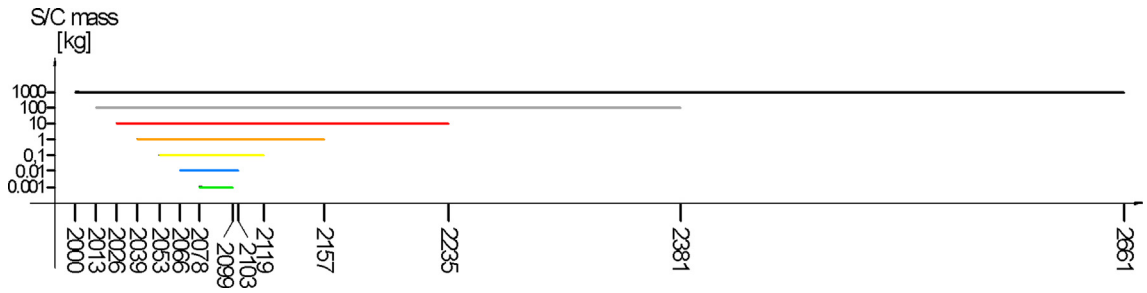

Fig. 2.9. The launch and arrival times (at Proxima Centauri) as a function of the spacecraft mass. The evolution of spacecraft mass is assumed to follow a spacecraft version of Moore's law. Here the half time for spacecraft mass is set to 4 years (Fléron, 2017). Data for spacecraft velocities have been taken from Lubin (2016).

mission. In fact the first interstellar mission, Voyager 1, although not declared as such, was launched already in 1977, as mentioned above. Currently, an Interstellar Probe mission is under study, although not as a small satellite, that should be able to reach 1000 AU in fifty years (McNutt et al., 2018), about six times faster than Voyager. The COSPAR Panel on Interstellar Research (PIR) draws upon recent and ongoing studies of the requisite science and miniaturized instrumentation technologies to lead to an international consensus on approach and implementation of such missions. Even though the ultimate goal of reaching another star seems far out at present, any attempt of getting there will help pave the way and lead to technological advances and scientific discoveries.

Finding 2.4 – Engaging in exciting visionary goals such as Starshot, even if it turns out to be impossible in the end, will require us doing new things and developing new ideas and technologies that will have many applications by themselves.

3. Obstacles to further development and progress, and ways to overcome them

In this section we address the obstacles between the current state of affairs described in Section 1 and the visions for the future in Section 2, and try to identify ways and means to overcome them. Here we concentrate on institutional obstacles as opposed to scientific or technological ones: How can the scientific community, the space agencies, industry, and the policy makers (governments and international organizations) cooperate in a way to maximize the return of small satellites for space science?

Perhaps the biggest limitation to scientific progress in using SmallSats for science is imposed by high mission cost (especially launch cost, discussed in greater detail below), which limits the number of science missions and leads to a risk-averse posture of agencies necessitated by large and expensive missions. This in turn may stifle innovation by scientists who may become risk-averse in their proposals because of the review process and limited proposal opportunities. These issues could be mitigated by taking advantage of developments in the commercial sector and by increased international collaboration which distributes cost and risk. While there are additional difficulties with international collaboration, including timing issues in the decision making of missions involving more than a single agency, differences in their legal backgrounds, and others, a core challenge remains lack of coordination across these three sectors.

Government agencies have critical roles to play in both supporting utilization of small satellites, as well as promoting approaches that do not hinder innovation. Also, agencies are in a position to advocate for science-friendly policy decisions. They are the primary means by which, through advocacy, regulations that hinder greater scientific utilization of small satellites can be addressed. They also represent the primary mechanisms for leading and participating in multi-national collaborations. Increased support for such collaborations could encourage the entry of new actors (government agencies acting as centres of technical know-how and providing technical service), connecting them with mission developers, demonstration missions, and institutional users.

Industry plays an important role in advancing areas important for science. For example, the increased availability of low-cost, high-reliability parts could bring down the cost of small scientific satellites. Lessons from industry in large-scale manufacturing and testing of small satellites could help make scientific constellation missions feasible. New models for low-cost access to space, such as the development of small launch vehicles and launch brokers may also drive down the launch costs of science missions.

Finally, there are cultural barriers preventing the full potential of scientific satellites from being realized. The culture within governments and the scientific community doesn't fully value small satellites. Their development and management approaches tend to emphasize low risk and high reliability, yet the culture in which SmallSats will thrive is one that allows for experimentation, risk-taking, and failure.

This chapter is divided into five sections. We first discuss the role of government agencies in supporting the development of small scientific satellites. This includes addressing issues related to funding and policy. We then discuss how

both the science community and government can leverage developments in industry, and address the cultural changes required to fully realize the scientific potential of SmallSats. Lastly, we discuss collaborative models that can further the development of SmallSats for science and produce the robust workforce needed for future innovation.

3.1. Funding

Government agencies are the primary provider of funding for important science missions and for promoting development of the technologies that enable them. Scientifically-motivated agencies in the United States that play leading roles in utilization of small satellites are NASA and the US National Science Foundation (NSF), the latter restricted to CubeSats. It is noteworthy that the NSF took the bold lead for the support of scientific investigations utilizing the CubeSat standard as far back as 2008. By providing modest funding for its CubeSat initiative (~$900 k for each three-year mission),[52] NSF supported a fledgling community at a critical time. One can argue that this willingness to take a risk and develop a totally new program, helped pave the way for the scientific CubeSat revolution. Funding through NASA's Science Mission Directorate for scientific CubeSats has increased significantly, and proposal calls for Explorer missions and Missions of Opportunity now allow for CubeSat-based missions concepts.

Other U.S. agencies such as the National Oceanic and Atmospheric Administration (NOAA) and various organizations within the Department of Defense are using or exploring utilization of very small satellites to accomplish their missions. Notably, while not yet deploying government-owned nanosatellites, NOAA is in the second phase of awarding contracts to purchase climatological, atmospheric, and land imaging data from commercial providers who gather data from constellations of nanosatellites.[53]

In Europe, ESA is the main player and has been involved in small satellites since the 1990s. Funding opportunities for SmallSats have been somewhat sporadic, as described in Section 1.1.1. There are also efforts of individual nations (e.g., SwissCube) and of the European Union, specifically with the FP7 and Horizon 2020 program. There are already existing initiatives of national space agencies to support the formation of international partnerships such as, e.g., Venμs, an Earth observation and exploratory mission of the Israel Space Agency (ISA) and the French space agency (CNES), or the SHALOM mission, a joint initiative of ISA and ASI – the Italian Space Agency (Section 1.2.2).

On a global level, Appendix E of the IDA report on Global Trends (Lal et al., 2017) gives a comprehensive list of international small satellite activities and trends. It should be noted, however, that some of the countries so far focus more on industry than on science using SmallSats, e.g. the INDIA/ISRAEL@75 program, cf. Section 3.5.3. Moreover, as described in Section 1.1 and shown in Fig. 1.2, most SmallSats are launched by only a few countries. Thus, the use of SmallSats for science is largely undeveloped in most countries.

In addition to funding complete science missions, there are other areas where government investment can play a critical role in promoting the use of SmallSats for science. For example, government agencies can provide mechanisms for the development of cross-cutting technologies that enable more sophisticated space-borne capabilities in smaller packages. According to Lal et al. (2017),[54] since 2013, NASA Space Technology Mission Directorate (STMD) has invested about $80 million in SmallSat programs, primarily towards development of constellations, communications, mobility and propulsion. Notably, 60% of the funds went to industry. Other non-science US government agencies (e.g. Department of Defense) have also invested significantly in technology advancement that could benefit science missions. Lal et al. (2017) also identified specific areas in which government agencies should invest. These include "pre-competitive" R&D in areas such as mobility and propulsion, constellations and autonomy, thermal control, communications, deep space systems and avionics, deployable systems, debris mitigation and control technologies, and others that science users consider important. They also include investment in risk reduction (i.e., by providing opportunities for on-orbit demonstration missions). And lastly, they include investment in what are called "industrial commons" (i.e., shared knowledge and capabilities) in areas such as reliability testing and data curation. In creating industrial commons, governments should, to the extent possible, leverage existing organizations and learn from successful models.

Agencies are also in a position to enable frequent consolidated launch opportunities for small satellites, thus providing new opportunities for proof-of-concept and dedicated science and application development missions, with ambitious time to launch timeframes (e.g. 3 years from inception to launch). Government agencies can also promote the development of mission concepts to address observational gaps and ensure continuity of critical space measurements such as those required in Earth Observation.

The desire of agencies to impose technical standardization is a common theme. If setting standards, agencies should be mindful that depending on the specific circumstances, standardization can both benefit and hinder technological advances. Agencies are encouraged, if setting standards, to be loose, setting only the most necessary standards, and keeping those broad and flexible so as not to hinder innovation. By not imposing innovation-stifling

[52] https://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_166650.pdf. Retrieved February 23, 2019.

[53] https://www.nesdis.noaa.gov/content/noaa-continues-push-toward-innovative-partnerships-second-round-commercial-weather-data. Retrieved February 8, 2019.

[54] https://www.nasa.gov/sites/default/files/atoms/files/nac_march2017_blal_ida_sstp_tagged.pdf. Retrieved February 22, 2019.

programmatic constraints, agencies can take actions that promote free and open competition that favorably advances the capabilities of small space-borne systems.

Funding mechanisms other than the traditional national space agencies are emerging. Universities and university consortia, similar to those formed for building large ground-based telescopes, private foundations, private donors, and Kick Start projects are now developing space missions larger than CubeSats.[55] However, most funding for SmallSats remains in the United States, and some in Europe (principally the United Kingdom). This is likely because most other countries are focusing their space-oriented resources to developing operational communication and Earth observation systems rather than science. Given the low cost of SmallSats, it is feasible to jumpstart space science programs without significant investment.

Finding 3.1 – There are specific areas that governments should support that the private sector is not likely to. These areas include technologies such as mobility and propulsion, constellations and autonomy, thermal control, deep-space systems and avionics, and debris mitigation and control technologies. One critical gap is support for "commons" and infrastructure technologies—activities such as database curation, facilities for reliability testing, and launch support. The government should also more actively participate in activities that require coordination across the community, standards being one such area.

Finding 3.2 – Set-aside funding mechanisms to support scientific SmallSats are needed, particularly outside of the US and Europe. Given that SmallSats have been shown to be useful for scientific advancement, there is a benefit in creating funding streams that specifically support small scientific satellites.

3.2. Role of policies that support the growth of small satellites

It is not just technology developments and government funding that would improve the alignment of small satellites with scientific use. There are several policy impediments that need to be addressed to ensure better use of small spacecraft for science. In this section, we discuss four that we believe are the most critical: access to spectrum; export controls; low-cost access to launch; and restrictions related to orbital debris.

3.2.1. Spectrum access

Electromagnetic spectrum for data transmission to Earth as well as accessing specific deep space bands is critical for any activity in space, and a scarce resource, at least for the time-being (until laser-based communications become the norm). As a result, access to spectrum is carefully coordinated and regulated at domestic and international levels, and it is illegal for any space object including small satellites to emit any type of radio signal without authorization. The framework for how the radio frequency spectrum is used is outlined in the Radio Regulations treaty ratified by the Member States of the International Telecommunications Union (ITU). Within that international framework, countries manage their national use of the spectrum. In the United States, for example, for small satellites owned and operated by NASA or other science agencies, the National Telecommunications and Information Administration (NTIA) typically grants authority to use a frequency (though does not issue a license, which is done by the Federal Communications Commission (FCC)). When frequency usage is approved, the FCC and NTIA submit their frequency assignments to an FCC liaison, who submits them to the ITU, which maintains an international register. Scientific satellites have dedicated spectrum in all countries that have space programs. However, most scientific CubeSats, including NSF-supported CubeSats, have so far used frequencies in the amateur band with an amateur license. This is becoming more difficult and will likely not be possible in the future. Scientific satellites must now obtain an experimental FCC license and it is not currently clear which frequencies are accessible to grant-funded, university owned and operated CubeSats.

While spectrum-related issues are not qualitatively different for small satellites as compared with larger ones, the speed with which small satellites can be developed and launched is outpacing the ability of the current coordination process for spectrum allocation and management. In the United States, the FCC has been inconsistent and erratic in granting licenses, sometimes providing approval for a design and form factor, but sometimes not, even when the design is identical.[56] The challenge is exacerbated for international and joint projects where spectrum systems of multiple countries may need to be aligned.

There are other challenges as well. The expected large growth in small satellites[57] will place increasing pressure on the establishment for coordination in UHF, S, and X bands as well as other space allocated bands, since many commercial operators use spectrum that is being used or could be used by university or Federal government agencies.

[55] e.g., ASU-Milo Project, MethaneSat-Environmental Defense Fund, and BeyondGo, a kick start.

[56] See more at: https://spectrum.ieee.org/tech-talk/aerospace/satellites/the-fccs-big-problem-with-small-satellites.

[57] By some accounts (e.g., Aerospace Corporation reports) in the next decade, we may see up to 20,000 satellites launched in LEO, most of them under 500 kg. However, accounts vary. According to Northern Sky Research, fewer than 4000 satellites are likely to be launched in this timeframe, and according to Euroconsult, more than 6500.

As more satellites are launched, the competition for spectrum would get even more intense, not just among satellites in LEO but also with satellites in GEO (for example, LEO satellites crossing the equator will have to change bands to avoid interfering with the GEO satellite, whose frequency rights take precedence). The shared use of spectrum involves conducting interference analyses and extensive coordination, most of which must be completed as part of the regulatory licensing process. This is an additional element of risk for small satellite developers. Also, as RFI becomes more of a problem, an enforcement of current national and international mechanisms to regulate radio frequency to prevent interference might further step up, challenging the science community to continually stay apprised of changes to the system. On the other hand, it is also critical for ground-based radio astronomy that protected bands remain protected. Thus such regulations are good for science as well.

There are other issues that small satellite operators must face just the same as traditional satellite operators, some of which relate to competition between spectrum use for space-based versus terrestrial application. Several bands under consideration for terrestrial use (e.g., spectrum above 6 GHz as part of 5G growth) are adjacent to critical bands such as those used for remote sensing from space. As a result, degradation in ability to use these bands is a growing concern (Mistichelli, 2016).

There are some issues specific to the SmallSat community. The procedure for receiving permission for spectrum use is long, complicated, and in many countries, spread across multiple agencies. Most researchers working on science small satellites are typically unfamiliar with these roles and regulations, and sometimes discover too late in the development process, and risk getting denied a license. Small satellite developers typically favor lower frequencies, where equipment is less expensive and more readily available, but lower frequencies are the most congested parts of the radio spectrum. The increasing use of small satellites may increase the need for higher bandwidth which has its own set of costs and challenges. Regulatory authorities also prefer to know details of satellite orbits when filings are made, but these parameters may be uncertain for some researchers until late in the process, for example when they find out who would launch their satellites as a rideshare.

3.2.2. Export control

Most countries have laws and regulations in place to protect the acquisition—especially by entities or countries they consider adversaries—of technologies or products that they believe safeguard their national security and foreign policy objectives. Space technologies and products comprise critical subsets of these technologies and products as they are almost always dual use, in that most space-oriented technologies and products, even when designed and used for science, can in principle be used for military purposes.

While export control regulations typically do not apply to general scientific, mathematical or engineering principles in the public domain (typically basic and applied research), they are often hard to interpret by university-based and other scientific researchers. In some countries, concepts such as "deemed exports"--which refers to items or information provided to a foreign individual--are often difficult to understand and adhere to, and the responsibility for complying with these laws often resides with faculty members and students not trained in such matters.

There is ongoing debate between government and academia regulated by export control regimes regarding the extent to which these restrictions harm legitimate scientific activity. Institutions of higher education in the United States argue that overly hawkish export control regulations could inhibit the best international students from studying in the US, and prevent cooperation on international projects. Over the years, export laws and regulations have become more complicated, and more aggressively enforced by government agencies. In the United States where this information is publicly available, university personnel have been prosecuted for breaches. Harmonizing international collaborations while ensuring export compliance of their research is becoming a precarious balancing act for scientists. In some cases, this can discourage scientists from participating in international collaborations.

It is also unclear if overly intrusive export control regulations are necessarily in a country's best interest. According to the inventor of the CubeSat, Bob Twiggs, a former professor at Stanford University's Space Systems Development Lab, "ITAR (or International Traffic in Arms Regulation, the US system of export control) is driving research out of the United States, isolating the United States and causing markets to be developed outside of the United States. Foreign students who are at the cutting edge of GNSS, electronics, control systems and rocket systems cannot do research in the United States."[58] The Executive Secretary of the US National Space Council has said that "burden(some) and outdated parameters can have the unintended effect of compromising national security by incentivizing space industries to move overseas, and for manufacturers to change their supply chain."[59] The same rationale applies to the scientific small satellite enterprises as well.

Small satellites provide unique opportunities for collaborations across nations, far more so than more traditional space activities. While small satellite projects do avoid many of the stringencies of export control regulations because of their use of COTS and other mainstream components and minimal use of sensitive technologies, there are no formal exclusions for small satellites for science use.

Clearly, in principle, export controls serve a useful function in improving national security by protecting against the transfer of critical technologies that should not be transferred. However if they include provisions that are too strong in preventing knowledge transfer, it can be detrimen-

[58] From: https://www.satellitetoday.com/telecom/2008/08/01/itar-balancing-the-global-playing-field/.

[59] From: https://www.hudson.org/research/14341-full-transcript-space-2–0-u-s-competitiveness-and-policy-in-the-new-space-era.

tal to the country's long-term national security, in that it hampers the free exchange of knowledge that is essential to the success of space research in an increasingly globalized scientific community. Any export control regime that governs small satellites needs to find the balance between enabling progress of science including through robust international collaborations without impairing national military and economic development interests. This balance will come from a regular and robust dialog between space researchers using small satellites and policymakers regarding making periodic changes to the lists that include technologies of interest to the small satellite community (Broniatowski et al., 2005). For the SmallSat scientific community in particular, providing better clarity on the rules and regulations, including clearer interpretations, will go a long way in ensure adherence not only to the letter of the law, but also its spirit.

3.2.3. Access to space

In the past, small satellites have typically been launched through one of three principal ways: obtaining a rideshare on a rocket with a primary payload, such as a satellite or cargo for the ISS; ridesharing with a group of other small satellites on a "cluster launch" as was the case of the launch of 104 satellites on the 2017 PSLV launch; and buying a dedicated small launch vehicle, such as Orbital ATK's Pegasus rocket. Most launches of small satellites to-date have been as secondary payloads.

In the United States, NASA supports science SmallSats through the Educational Launch of Nanosatellites (ELaNa) Program under the CubeSat Launch Initiative (CSLI), and also subsidizes launches on commercial (such as cargo resupply launches to the ISS) and other (the EM-1 flight of SLS is expected to have 13 science and technology CubeSats) launchers. Scientists have other support options as well: outside the government, United Launch Alliance (ULA) provides competitive free rides for university-based CubeSats.[60] To enable making connections with launch providers, companies like Spaceflight Industries and TriSept Corporation act as brokers for launch coordination and integration.

Today, globally there over a 100 launch companies dedicated to SmallSat launch.[61] While a large portion of these launchers may not come to pass (most are in the development phase), the sector shows a dynamicism not seen in the SmallSat or launch communities in the past. For science users, a plethora of viable (and low cost) options for access to various parts of space is welcome news.

Despite the opportunities, there is a pent-up demand for affordable launch for scientific small satellites. The NASA CSLI has 38 CubeSats manifested and 66 launched of 162 selections as of December 1, 2018.[62] The Venture Class Launch Services (VCLS) program under CSLI is reducing the backlog via manifest of CubeSats on dedicated launch vehicles such as those offered by FireFly Space Systems, Rocket Labs, and Virgin Galactic. The first launch under the VCLS program was conducted by Rocket Labs on December 16, 2018, launching 13 CubeSats into Low Earth Orbit (10 under the VCLS program).

New launch options to serve the SmallSat community are emerging (e.g., Cappelletti et al., 2018); there are more than 50 companies developing small rockets to launch small satellites (Sweeting, 2018). However, rocket technology development is a notoriously high-risk enterprise, and many of these efforts are likely to fail. Moreover, small rockets tend to have a higher specific cost; while large rockets are expensive (Fig. 3.1), they offer the greatest economy as a rideshare option (Fig. 3.2). For example, the $62 million dollar Falcon 9 launches 22,800 kg or $2720/kg which nearly a factor of 50 less that the cost to launch 1 kg on a Pegasus XL. On the other hand, rideshares offer the least amount of flexibility with respect to choosing an orbit or inclination of operation, or even the ability to have propulsive capabilities, factors that are important determinants of conducting good space science.

Nevertheless, launch remains a chokepoint for smaller satellites. If small satellites grow in number and utility as expected, low-cost launch availability will need to increase. While the announced large rockets such as New Glenn from Blue Origin, Falcon Heavy from SpaceX (which has already flown twice), and Vulcan from ULA could support the SmallSat science community, they first need to address the issue of SmallSat integration.

A driver of low-cost access to space is the development and success of commercial space, as this would lead to a large increase of the launch flight rate, which could result in a low per-flight cost of launch. Depending on how the industry develops, it may also reduce opportunities for scientific SmallSats. Other factors (e.g., reusability) could also affect the cost of access to space. Until such a time, governments need to continue to subsidize launch of spacecraft for science applications.

3.2.4. Orbital debris considerations

Space is becoming increasingly more crowded, and the growth in the number of satellites in LEO is expected to be dominated by small commercial (not science) satellites. Varying accounts ascribe between 3600–6200–25,000 small satellites (satellites weighing less than 500 kg) to be launched between 2017 and 2026.[63] The concern is not just the increasing number of satellites, but also the fact that (depending on their altitude) they will stay in space as debris for longer than their useful life.

[60] http://www.ulalaunch.com/ula-reveals-transformational-cubesat-launch.aspx.

[61] https://www.spaceintelreport.com/count-em-101-new-commercial-smallsat-dedicated-launch-vehicles-in-development/.

[62] https://www.nasa.gov/content/cubesat-launch-initiative-selections.

[63] If all of the more than 160 constellations—most of them leveraging small satellites – came to fruition (an unlikely scenario), there would be more than 25,000 satellites in LEO. 90 percent of these satellites would focus on communications, and the remaining on earth observation and remote sensing.

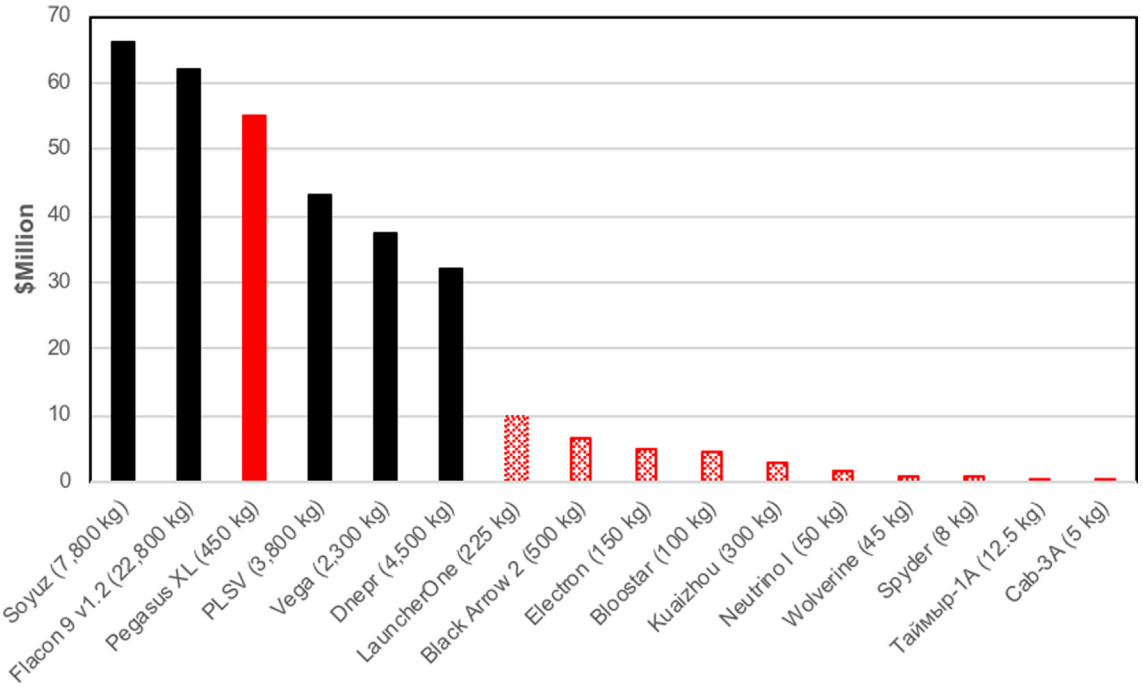

Fig. 3.1. Price of launcher versus maximum launcher capacity, ordered by cost. Black bars represent large launchers and red bars represent small launchers; shaded bars represent launchers in development. Figure reproduced from Lal et al., (2017), with permission from the Institute for Defense Analyses. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

As the number of these spacecraft increases, the probability of collisions increases as well, especially if satellites are not able to be tracked well or are not maneuverable. Due to high speed in LEO (~10 km/s), even sub-millimeter debris poses a realistic threat to human spaceflight and robotic missions. Small satellites, and especially Cubesats, in near-Earth space are increasingly being seen as the major orbital debris challenge of the coming decades (Bastida Virgili and Krag, 2015; Matney et al., 2017). Even though the fraction of scientific small satellites is small, the scientific community must contend with being viewed as part of this challenge.

Concerns related to collisions focus largely on the proposed "mega" communications constellations. A recent report from Aerospace Corporation evaluated the effect of adding two large constellations—that of SpaceX and OneWeb—to the current constellations in LEO (Iridium, Orbcomm, and Globalstar) and found that within its first 20 years in orbit, the first constellation is expected to cause one collision annually; this number could grow to approximately eight per year at its peak collision rate, which occurs about 190 years after launch.

As the number of small spacecraft (especially in low Earth orbit) increases, there will likely be growing restrictions on operators, including for science, even though it is not spacecraft for science that are the root cause of the coming debris challenge. Restrictions are likely to be directed toward CubeSats rather than SmallSats in general because, up until recently, CubeSats typically did not have on-board propulsion, ability to be tracked if they were not actively emitting signal, or maneuverability. These restrictions are likely to address three areas in particular: (1) ensure all small satellites can be tracked, either actively or passively; (2) mitigate radio frequency interference (RFI) as discussed in the spectrum section above, and (3) abide by stricter guidelines to de-orbit after they stop functioning. On the last point, it is worth noting that in recent years, many experts have come to believe that the international guidelines that recommend CubeSats de-orbit within a 25-year period after their operational period ends are no longer sufficient, and may need to be updated.

The science community has an opportunity to avoid potential future problems by continuing to proactively seek technological solutions, such as low-cost means for CubeSats to be maneuverable and trackable, avoid RFI, and de-orbited in a timely way. More R&D may be needed to assess which are cost-effective.

3.2.5. Summary and findings

There are four key policy challenges that need to be addressed to enable effective use of small satellites for science applications. First, spectrum is a scarce resource, and the SmallSat science community needs to be much better educated about not only the process of obtaining spectrum allocation for their spacecraft (which can be time-consuming) but also emerging and fast-moving changes in the area. Second, export control laws of many countries inhibit scientific collaboration by putting an undue burden on scientists to ensure compliance with a complex system. Again, education of the scientific community is key here. Third, the cost of

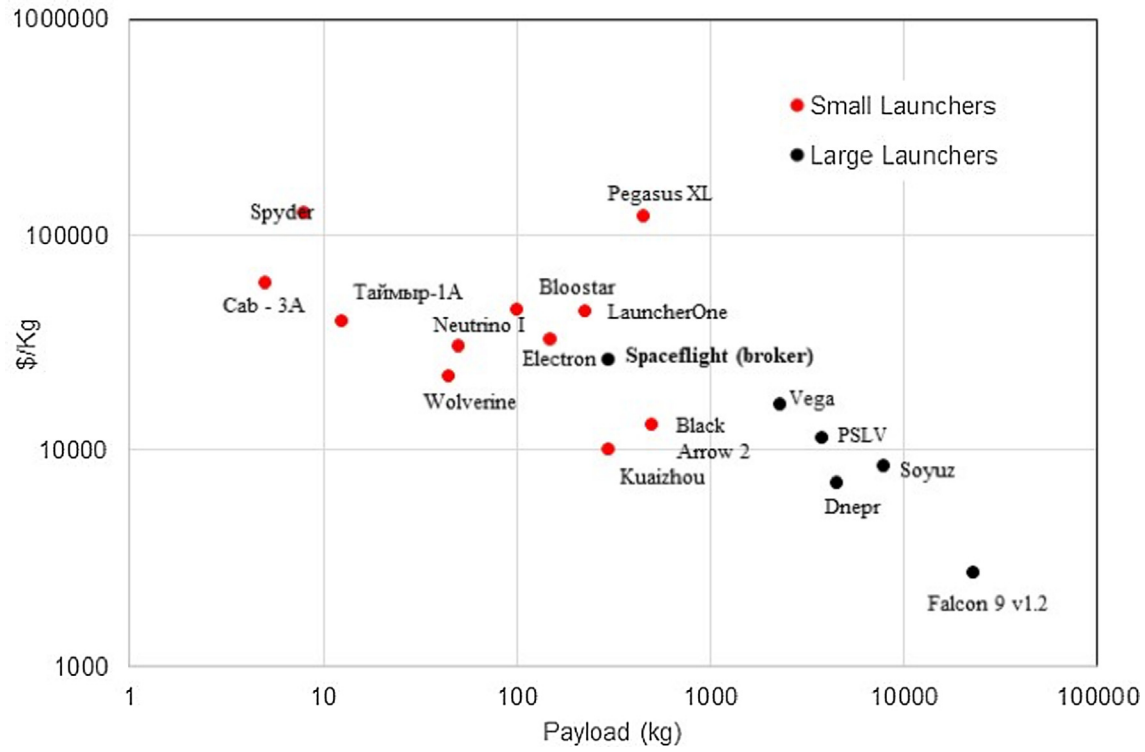

Fig. 3.2. Price per kilogram for small and large launchers. Figure reproduced from Lal et al., (2017), with permission from the Institute for Defense Analyses.

launch is a critical inhibitor of SmallSat-based science. Government agencies have typically subsidized launch, a practice that needs to continue in the near-future. It should be noted that cheap space access requires the large launchers. Small launchers dedicated for small spacecrafts have a higher per kg cost than the piggy-back launches and hence serves a market segment that requires extended control over the orbit parameters. Last not but least, as traffic in space (especially low Earth orbit) increases, there will likely be growing restrictions on satellite operators, including for science. Restrictions are likely to be related to better tracking in space, frequency interference, and stricter guidelines related to de-orbiting and debris mitigation. The science community needs to proactively address these challenges.

Finding 3.3 – Spectrum access (for data transmission to Earth as well as accessing frequencies in bands for research) is critical for any activity in space, and a scarce resource.

Finding 3.4 – The undue burden of complying with laws and regulations related to international exchange and collaboration are a deterrent to scientific collaboration.

Finding 3.5 – Low-cost launch, through easy access to rideshare options, has been a key enabler of SmallSat-driven science.

Finding 3.6 – As traffic in space (especially in low-Earth orbit) increases, growing restrictions on small satellite operators, including for science, is likely. Regulations are likely to be related to tracking in space, maneuverability, and orbital debris mitigation.

3.3. Leveraging developments in industry

Funding for science still comes primarily from government agencies, but science can potentially reduce costs or increase capabilities by taking advantage of commercial efforts, particularly the emerging industries that focus on SmallSats. If the cost of a SMEX-class mission in near-Earth orbit could be reduced to the $25 million level, a factor of ten decrease, it would open up new possibilities for science and significantly increase the number of flight opportunities. Because it offers more frequent launch opportunities, the growing SmallSat industry can also help

attract and retain talented scientists and engineers, helping to build the science and aerospace engineering workforce.

The development of the SmallSat sector was led by the private sector (including universities), and most SmallSats launched are by private or commercial organizations. As an illustration, in a database of over 650 SmallSat organizations, developed by Lal et al. (2017), over 50% of organizations globally, and over 75% in the United States are in the private sector. While in recent years, academic use of SmallSats has grown (Fig. 3.3), commercial operators continue to dominate the sector. In the last six years alone, over 475 commercial SmallSats were launched (Halt et al., 2019). Most commercial SmallSats are for remote sensing (see Fig. 1.3 and Halt et al., 2019), though it is expected that with the advent of commercial mega-constellations, more satellites will focus on broadband services from space.[64]

There are several ways in which the science community can leverage the developments in the commercial sector. Increased access to space was already discussed in Section 3.2.3 above. Here we describe ways in which science can partner with industry.

3.3.1. Commercial off-the-shelf (COTS) parts

In industry, commercial Earth observation and communications are the lucrative "killer-apps" of SmallSats, and comprise most commercial SmallSat activity occurring today. In these areas, the commercial sector is seeing not only a growing number of operators (companies such as Spire, Planet) but also a growing number of component manufacturers/suppliers (companies such as Gomspace, ISIS, and Blue Canyon, among others). This sector is focusing on mass manufacturing with the goal of decreased cost. While lower cost is important, even more important to the science community is the availability off-the-shelf flight-qualified parts. This trend is accelerating with the onset of large constellations (there are at least 16 companies focusing on use of constellations for earth observation or space-based Internet) that require at least the satellite bus (if not also the payloads) to be commoditized. Many of these companies are borrowing methods and technologies from non-space industries, for example, adapting parallax algorithms, similar to ones developed for automobile collision avoidance systems, to conduct SmallSat proximity operations. To further reduce cost, a number of manufacturers and operators are experimenting with COTS parts as inputs for their systems.

3.3.2. Commercial data buy

Private investment may also exceed (at least the unclassified publicly-available) government investment by an order of magnitude or more. As such, the scientific community should closely watch developments in the private sector, not only to procure products but also services. Commercial SmallSats may be able to collect data relevant to science. This is particularly true in Earth observation and space weather. NASA and NOAA have started small pilot programs to see if industry can produce data products to their standards. The stated hope is that this will lead to a state where the government can buy data rather than building and operating expensive satellite systems.

A developing area is weather forecasting. The value of weather prediction models that use radio occultation of Global Navigation Satellite Systems (GNSS) signals such as GPS has now been demonstrated. GPS occultation programs have been funded by Taiwan's National Space organization, NOAA, NASA and private entrepreneurs. Government funders wish to buy data to reduce cost of their forecasting operations and improve the accuracy of their forecasts (enabled by constellations because they provide a dense dataset and high revisit times). However, commercial developers may not be satisfied with just providing a data service to the government. Cooperation between government and private enterprise may allow data that are purchased and distributed openly by governments to be utilized by private industry to generate products tailored to specific customer needs. In particular, the value of near real-time customized weather data is increasing because of large computers and novel software systems. The idea of governments purchasing commercial data will thrive or not depending on whether the SmallSat developers find it more profitable to make products for commercial customers or products desired by the government agencies.

Current free and open data policies that exist for government-produced data sets are extremely valuable to the science community, leading to novel use of data for research. The open data policies also increase the data usage internationally. It should be emphasized that there is a risk of losing such open data policies if government-industry data-buy partnerships are pursued. Although commercial data opens potentially new opportunities, both the science community and government agencies must work to ensure that contracts are written in a way to preserve open data policies.

3.3.3. Hosted payloads

The Global Observations of the Limb and Disk (GOLD) mission is the first NASA science instrument to fly as a hosted payload on a commercial satellite.[65] GOLD was launched on 25 Jan 2018 aboard the SES-14 satellite that reached geostationary orbit in June. The measurements (Fig. 3.4) will improve our understanding of the uppermost reaches of Earth's atmosphere, critical for understanding space weather. Because of its location at GEO, enabled in large part because it is a hosted payload, GOLD scans the entire Western Hemisphere every 30 min, enabling us to monitor day-to-day changes in the upper atmosphere for

[64] For example, see projected small satellite launched by application at https://www.nsr.com/smallsat-growth-on-shaky-foundations/.

[65] http://gold.cs.ucf.edu/gold-will-revolutionize-our-understanding-of-space-weather/. Retrieved February 28, 2019.

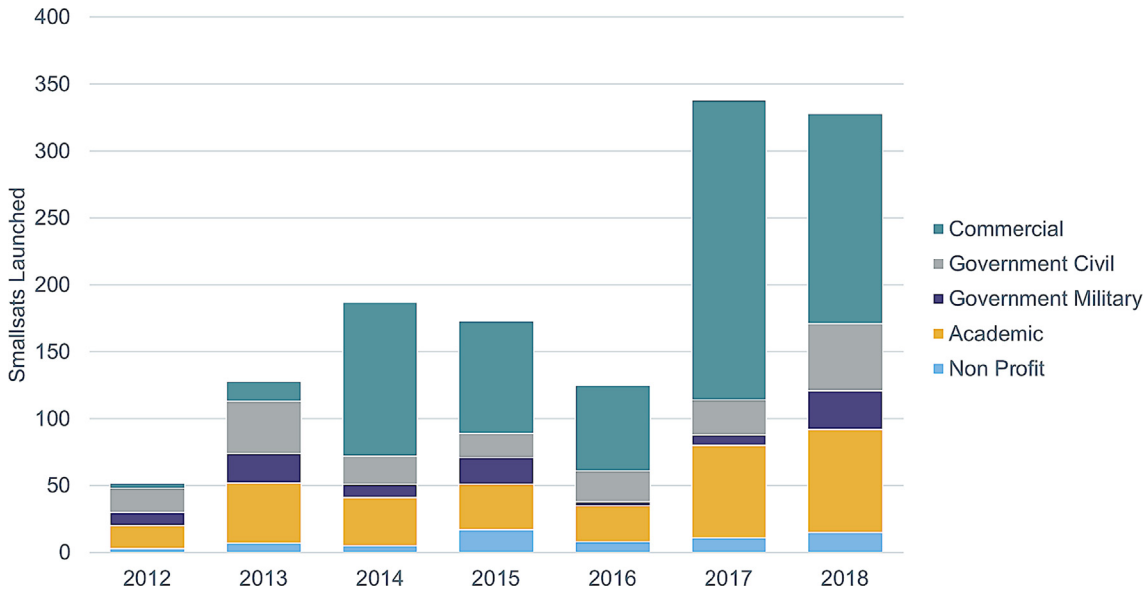

Fig. 3.3. Number of SmallSats by sector. Image Credit: Bryce Space and Technology (https://brycetech.com/reports.html).

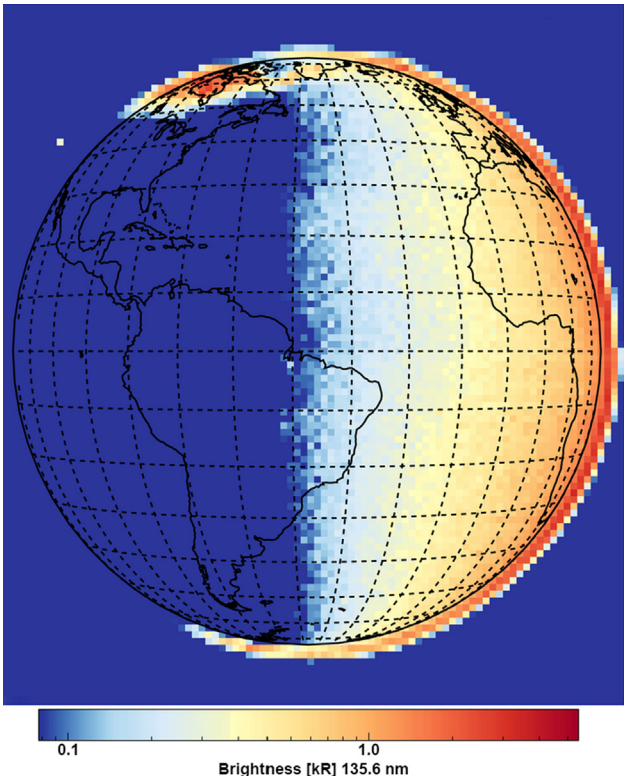

Fig. 3.4. First image of ultraviolet atomic oxygen emission at 135.6 nm from Earth's upper atmosphere captured by NASA's GOLD mission. Image credit: NASA/LASP GOLD Science team.

the first time. The increasing number of commercial constellations, especially in LEO, has the potential to provide new opportunities for hosted scientific payloads.

3.3.4. Industry-university collaboration

Finally, bringing industry to the table is an important step in creating an ecosystem of the SmallSat forces. When companies and universities collaborate to push the boundaries of knowledge, they become a powerful engine of innovation. The advantages to academia are self-evident: allowing students and researchers to work on groundbreaking research, greater potential for external funding, inputs for teaching and learning at the forefront of their disciplines, and the impact of providing solutions for pressing global challenges. Industry also benefits through workforce development and training and recruiting of potential future employees.

A recent example of such a partnership is NANOBED, a collaborative project led by the University of Strathclyde, in collaboration with Clyde Space & Bright Ascension, to develop a tool for research, innovation, and technology development. NANOBED enables rapid end-to end CubeSat mission design and technology development up to TRL6, including

- Bespoke mission & system design software
- Integrate hardware and test
- Communicate with hardware over representative radio link
- Simulate operations through day-in-the-life scenarios
- Verify hardware functionality in operational-like scenarios

The mission and system design software allows the engineer to define a mission including orbit, ground station and spacecraft design, operational modes and switching conditions, and sub-system definitions from library or user-defined (XML) functions. The engineer can then simulate mission segments through orbital & attitude dynamics and control, ground track visualisation, power profile for each solar array and associated battery levels, ground station visibility, and data collection and downlink.

The software integrates with a hardware platform enabling an interface with flight hardware, including data acquisition units to check voltages, etc. The outputs of the mission & system design software can be used to drive power profiles to reflect solar arrays, and to invoke actions on hardware, including triggering ground station passes where GNU radio modules interface with radios for up- and downlink. An image of the core hardware setup is shown in Fig. 3.5, with space slots available for additional hardware such as payload units.

NANOBED has been deployed into a number of university and research institutes around the world, including in Mexico, the USA, and the UK, with others due for deployment into other countries, including South Africa, creating a global network of collaborators who can work together and share lessons learnt, both informally and formally through provided training courses. NANOBED provides a natural collaborative platform both within academia, but also between academia and industry.

The most fruitful form of cooperation is one that allows the participants to do new things that are hard or impossible to do themselves, can be built around a common research vision, and can continue for a decade or more, creating deep professional ties, trust and shared benefits that bridge the cultural gap between academia and industry. Long-term alliances build the human capital needed to make academia-industry cooperation work. Over time, a well-managed partnership produces an increasing number of professors and graduate students who can think and act across the cultural gap, connect with the main research areas of the company and work in harmony to set joint strategic objectives.

Finding 3.7 – The availability of components off the shelf adds resilience and offers a fundamentally different way of building and operating scientific SmallSats. An approach with mass production techniques allows fast, innovative, and cheaper new space systems to be created.

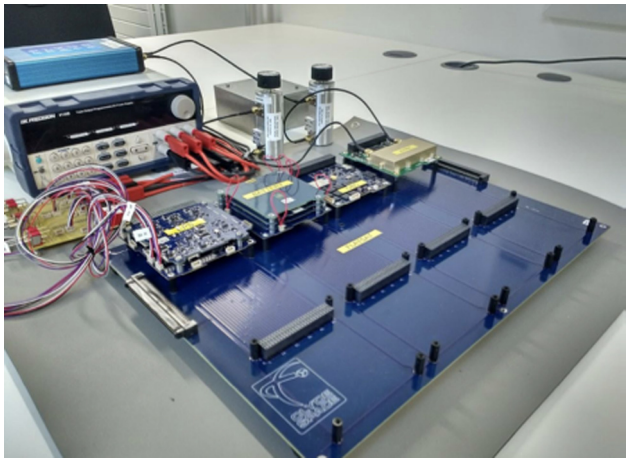

Fig. 3.5. Core NANOBED hardware setup with flight hardware in laboratory at University of Strathclyde. Image credit: Malcolm Macdonald.

Finding 3.8 – An increased number of commercial small satellite constellations may provide new opportunities for science through commercial data buy, hosted payloads, and ride shares. However, this comes with a risk that current open data policies could be in jeopardy.

Finding 3.9 – The SmallSat industry provides useful training grounds for students interested in aerospace science careers. Industry-academia partnerships, in particular, can help ensure a strong aerospace and space science workforce for the future.

3.4. Supporting innovation

The recent developments in the small satellite sector offer enormous opportunity for science. Realizing this potential to its fullest extent will require scientists and funding agencies to recognize that small satellites aren't just a miniature version of larger satellites. SmallSats can provide new kinds of measurements, be developed with a "fly-learn-refly" model, and can be lower cost. Indeed, it is not the satellite's mass that is its defining feature. The defining feature of a SmallSat is the unique culture that it engenders. This culture has more in common with a technology start-up that encourages risk-taking and rapid innovation, even at the expense of mission assurance, than with a traditional organization that emphasizes exquisite capability, long lifetimes, and high-reliability systems. New approaches that are specific to this organization are being embraced by industry, but there are cultural differences between these smaller and more nimble organizations and large space agencies[66] who, for the most part, still employ traditional approaches. For SmallSat-driven science to be at the forefront, a new paradigm will be required.

In "The Three Box Solution", Govindarajan (2016) emphasizes that different methodologies are required for addressing the three competing challenges faced by any organization: maintaining excellence in the present, identifying and letting go of outdated practices, and generating breakthrough ideas that can lead to future products or directions. In short, organizations that successfully manage all of these simultaneously do so by devoting entirely separate resources to each area. Innovation requires different skills, metrics, methods, and different management strategies.

Government agencies differ from start-ups, but the same principles apply. A report of the US National Research

[66] And also traditional space companies such as Lockheed which operate more like a space agency.

Council (2010) states, "...experience within DOD[67] has shown that actively managing basic research types of activities often requires different processes, metrics, and management techniques from those associated with managing advanced technology development and system prototyping activities." The same report points out that much of NASA's activities focus on risk mitigation which is necessary for large, expensive missions. On the other hand, mission-enabling activities and innovation require a different strategy.

Given the unique culture in which SmallSats are likely to thrive, it might be useful to emulate organizational models where high-risk research—where failure is valued—is done. Several organizations, in the United States and other countries, have attempted to create a structure to conduct R&D that might be higher risk (with the likelihood of higher scientific payoff). These organizations could be models on how to nurture small satellites—by definition a higher risk proposition compared to traditional platforms—in larger organizations.

The Advanced Research Projects Agency (ARPA) organizations (e.g., DARPA, IARPA, ARPA-E) in the United States have managed to create organizations where leadership prioritizes programs and projects that are high risk and not necessarily well-defined, seeking to maintain the integrity of the organization's high-risk culture (Peña et al., 2017).[68] Similarly in the United Kingdom, the Engineering and Physical Sciences Research Council sponsors approaches within the larger organization (called IDEAS Factory) which aim to "stimulate highly innovative and more risk-accepting research activities that would be difficult to conceive under normal circumstances".[69]

One particular organizational construct to nurture the use of SmallSats in large organizations that will typically be resistant to the SmallSat culture is that of an island + bridge model that ARPAs use (Bennis and Biederman, 1997; Sen, 2014). In this model, the island is the refuge for experimentation and failure, and the bridge is the conduit for the transfer of knowledge and technology [to the user]. New technological capabilities make their way out, requirements and other sorts of influence must make their way in. Research is neither entirely shut off from real-world interests, as with a traditional laboratory setting, nor is it beholden to the interests of operational incumbents. The island + bridge model applies a "connected science" approach to research, combining and integrating the forces of technology push and pull, balancing the need for isolation and connectivity, and providing just the right types of structure for processes that are necessarily chaotic (Sen, 2015).

Using this model, a SmallSat-specific sub-organization, created within the larger space organization, can make sure that SmallSats don't get short shrift, while ensuring connection with the larger organization (to make sure new technological capabilities make their way out and requirements make their way in). This model is neither new nor limited to the government. In industry, Lockheed Martin's Skunk Works and IBM's PC Project have shown the success of the island + bridge model.

Finding 3.10 – The culture in which SmallSats will thrive is one that allows for experimentation, risk-taking, and failure. Traditional space organizations tend to emphasize low risk and high reliability space systems, and it will take a difficult cultural change for such organizations to nurture SmallSats. There exist successful models in industry and even in government that can be emulated to ensure such a change.

3.5. Collaboration

The larger and more complex the project, the more critical it is to generate collaborative R&D to accomplish the goals of the project, for example in constellations with complex architectures or multiple means of measurement such as the EU QB50 or the TIM international projects described below. Although current consortia such as the QB50 are unlikely to survive the end of program funding, universities participating in a joint research program are much more likely to work together in the future. Increased engagement in multi-national scientific collaborations would also support the entry of new actors, connecting them with mission developers, demonstration missions, and institutional users. Such collaboration increases the chances of making a significant contribution to science while sharing resources and risks. It could also help to ensure that research tasks are dealt with by researchers with the most appropriate experience or with complementary interests and needs.

3.5.1. Models of collaboration

3.5.1.1. The TIM case study. TIM – Telematics International Mission – is an example for which partners contribute individual satellites to a formation in order to benefit from the larger database generated. The low cost of very small satellites enabled, in this case, seven partner states of the Regional Leaders' Summit (RLS, e.g. the partner regions Bavaria, Georgia, Upper Austria, Quebec, São Paulo, Shandong, and Capetown) to realize together a spacecraft formation for innovative joint Earth observation.[70] TIM addresses a cooperating pico-satellite formation to generate 3D images for Earth observation by photogrammetric methods, taking advantage of the different viewing directions (Fig. 3.6). The obtained data will be fused for monitoring of environmental pollution, harvest-

[67] Department of Defense.
[68] https://www.ida.org/idamedia/Corporate/Files/Publications/STPIPubs/2017/D-8481.ashx.
[69] https://epsrc.ukri.org/funding/applicationprocess/routes/network/ideas/experience/.
[70] https://www.rls-sciences.org/small-satellites.html.

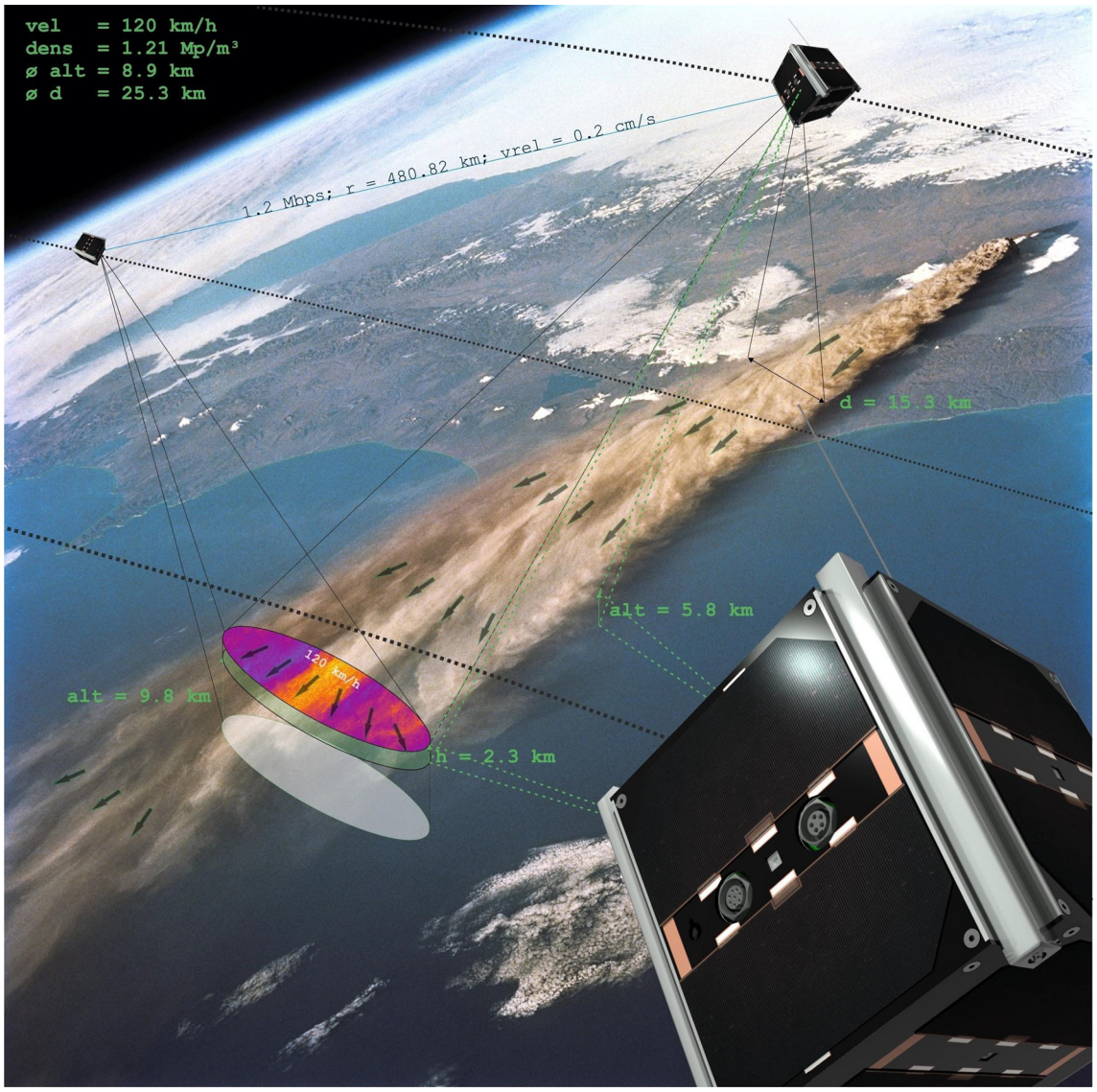

Fig. 3.6. The three TIM satellites focus on the same target area for 3D-imaging by photogrammetric methods. Image Credit: Zentrum für Telematik (https://www.telematik-zentrum.de/).

ing status, critical infrastructures, and natural disasters (like forest fires, volcanic activity, earthquakes).

The mission is currently in implementation stage with a planned launch in 2019. The scientific challenge relates to spacecraft engineering as well as to science data processing:

- Developing, in international partnership, modular, robust small satellites for a formation of networked, cooperating, "smart" small satellites, operating autonomously with minimum ground station interaction;
- Photogrammetric data processing for generation of 3D images, taking advantage of the large baseline distance between the instruments on different satellites and obtaining improved resolution by sensor data fusion methods.

Essential subsystems needed for a formation are: the attitude and orbit determination and control system, the communications system capable of inter-satellite communication and satellite-to-ground communication, as well as electrical propulsion for orbit control and maintaining formation. The core components are the 3 Bavarian satellites named TOM (Telematics earth Observation Mission). Each further contribution increases the formation capabilities and additional instruments provide complementary data. Precursor missions of the partners in this international team laid the groundwork of expertise in the relevant areas to enable this challenging pico-satellite formation flying application. Thus, through international cooperation, a challenging and innovative Earth Observation Mission is realized.

3.5.1.2. The QB50 case study. The QB50 mission demonstrated the potential of international university collaboration supported by the "new space" industry (start-up companies that grew up in academia), by launching a network of CubeSats built by university teams from 23 different countries around the world to achieve scientific

objectives. The key objectives of the mission include facilitating access to space for universities and research centers, performing measurements in the thermosphere, demonstrating new technologies in orbit and promoting space collaboration and science education.

The QB50 network conducts coordinated measurements on a poorly studied and previously inaccessible zone of the lower thermosphere. The project monitors different gaseous molecules and electrical properties to better understand space weather and its long-term trends and relations to climate change. QB50 provides data that enhances atmospheric models and improves understanding of how space weather can disrupt radio communications and GNSS signals. This research contributes to risk assessment of strong solar events that can damage power grids and space assets (i.e. military, commercial and civil satellites).

The project, coordinated by the QB50 Consortium, received funding from the European Union's Seventh Framework Programme for Research and Technological Development. Space agencies are not pursuing a multi-spacecraft network for in-situ measurements in the lower thermosphere because the cost of a network built to industrial standards would be extremely high and not justifiable in view of the limited orbital lifetime. Studying the physics and chemistry of the middle and lower thermosphere can only be realized by using a network of very low-cost satellites, and CubeSats built by universities were the only realistic option.

To accomplish the science mission, 44 highly miniaturized instruments were developed by a consortium of three Universities (UCL-MSSL, the University of Dresden and the University of Oslo) (Fig. 3.7). Thus, QB50 also furthers understanding of how to manufacture, deploy and use small, distributed sensor technologies of the sort that are becoming more common in space.

A large portion of the QB50 constellation (28 out of 36 CubeSats) lifted off on April 18th, 2017, from the launch Pad at Cape Canaveral to the ISS and were deployed into space a month later (Fig. 3.8). A second launch was made in June 2017 with the remaining eight CubeSats taking measurements along a polar orbit. Among the 36 CubeSats deployed, 9 were dead on arrival or went silent immediately after launch. For most of the 27 "survivors", commissioning proved to be challenging and only 16 were producing valuable science data on a daily basis. One IOD CubeSat successfully completed its mission within 2 months after launch: InflateSail deployed a dragsail and reentered in the atmosphere. The CubeSats orbited around the Earth, dropping gradually in altitude before completely burning up in the atmosphere, with an estimated lifetime between 1 and 2 years. As of May 2018 (one year after deployment) only 6 CubeSats were still fully operational. During their long descent, the satellites took a large number of measurements using a widely-distributed network of sensors. The last QB50 CubeSats reentered the atmosphere in December 2018, nineteen months after deployment.

QB50 was extremely successful in achieving its educational goals. The QB50 CubeSats were designed, built and operated by a great number of young engineers, supervised by experienced staff at their universities and guided by the QB50 project through reviews and feedback. Those young engineers will leave their universities with valuable hands-on experience. Although the scientific objectives were met with mixed success, this model of international partnership serves as an important pathfinder for future large constellation missions. When backed by adequate resources from national space agencies, such a model could provide enormous potential for science.

3.5.2. Higher education and sharing lessons learned

CubeSat science missions provide hands-on training opportunities to develop principal investigator leadership, scientific, engineering, and project management skills among both students and early career professionals. Due to the complex nature of the development process that spreads over multiple scientific and engineering domains, teams of students and researchers must be actively involved in the process, potentially over a number of years and take part in all development stages, achieving a level of skill necessary for achieving significant contribution to science.

SmallSat projects are a good example of a pedagogical process known as Project Based Learning (PBL), where science students are actively studying and gaining experience while working on real-world problems. Active learning methods in the fields of science, technology, engineering and mathematics (STEM) show improved learning outcomes in comparison with traditional teaching methodologies.

Lessons can be shared between universities and other organizations in a number of areas.

3.5.2.1. Common curriculum development and training methods. The curricular context of CubeSat design activities at universities varies from case to case and many universities do not have a formal CubeSat course curriculum. Instead, the CubeSat projects tend to be integrated as student projects within system engineering or spacecraft design courses (NASEM, 2016). Therefore, there is a clear need to develop a common curriculum where students follow comparable courses in different universities, to facilitate project activities and work at an international level.

A global educational network in academia is addressed by UNISEC[71] (University Spacecraft Engineering Consortium), where worldwide activities of Universities with spacecraft design activities are integrated. Here educational materials related to CanSats and CubeSats are shared, joint workshops and conferences are organized, spacecraft design competitions are organized and standardization efforts to support exchange of subsystems/components are promoted.[72]

[71] http://www.unisec-global.org.
[72] http://unisec-europe.eu/standards/bus/.

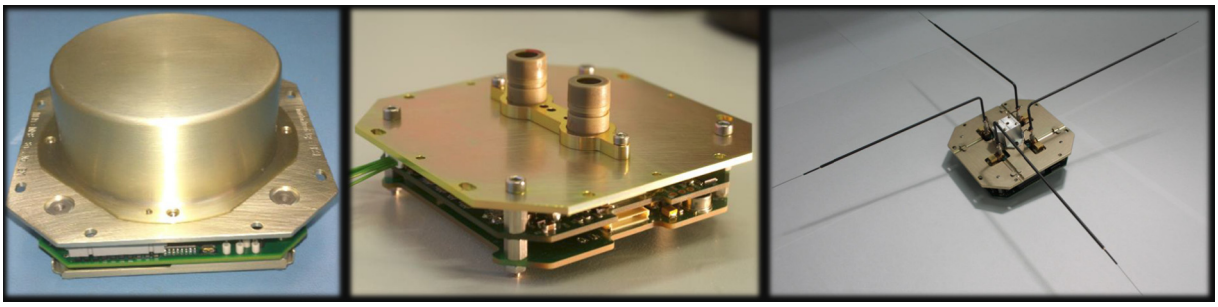

Fig. 3.7. Three types of QB50 science sensors (from left to right): the Ion-Neutral Mass Spectrometer (INMS), the Flux-Φ-Probe Experiment (FIPEX) and the multi-Needle Langmuir Probe (m-NLP). Image Credit: The QB50 Consortium (https://www.qb50.eu/).

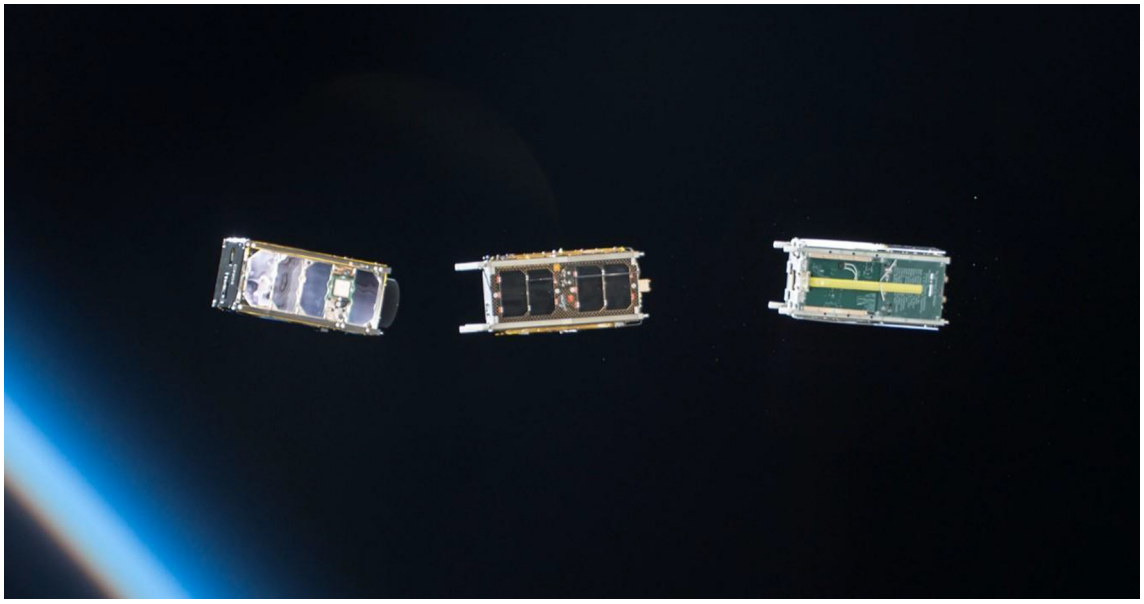

Fig. 3.8. QB50 satellites after deployment. Image Credit: The QB50 Consortium, von Karman Institute.

3.5.2.2. The SpaceMaster case study. The EU Erasmus Mundus "SpaceMaster – Master in Space Science and Engineering" is a joint international MSc program initiated in 2005 and supported by six European Universities. In this integrated program the students can study in three countries, taking advantage of a very broad spectrum for specialization in space science and engineering disciplines.[73] The universities contribute their special expertise to the courses in order to cover the broad interdisciplinary area of spacecraft design and space environment. In particular, system design techniques are emphasized, which are of interest for a broad spectrum of industrial applications well beyond aerospace. The students follow either the more scientific tracks on space physics (with an emphasis on instrumentation and astronomy, or atmospheric and planetary physics) or an engineering track emphasizing design of spacecraft and mission realization.

The international dimension of this space education is reflected by study in different locations: first semester in Würzburg (Germany) and second semester in Kiruna (Sweden), second year according to the desired specialization in one of the six partner European Universities. The successful students will receive double diplomas from the two European Universities where most credits were received. The student population is also very international: typically, from about 600 applications 50 students are selected, half of them from Europe, the other half from outside Europe.

A specific highlight is the opportunity to participate in small satellite design activities for the MSc thesis. In the UWE program (University Würzburg's Experimental satellite), so far the student-built pico-satellites UWE-1 [1] studying "internet in space" (launched 2005), UWE-2 devoted to attitude determination (launched 2009), and UWE-3 addressing attitude control (launched 2013) have been successfully operated in orbit. The objective of the UWE-program is a step-by-step development of all relevant technologies for formation flying with pico-satellites.

3.5.2.3. Sharing lessons learned from SmallSat missions. In the National Academies study (NASEM, 2016) it was established that the failure rate of a university's first CubeSat was typically higher than that of the third or fourth, and that these lessons learnt helped them build better spacecraft. International space conferences (such as

[73] http://www.spacemaster.uni-wuerzburg.de, http://spacemaster.eu/.

COSPAR and IAC), where students and researchers can meet their counterparts from other universities and high-level representatives from space agencies and space industry, provide an opportunity for groups to learn from the experience of others and share lessons learnt. Informal exchanges over lectures or seminars can spark conversations and lead to new initiatives and collaborations.

3.5.2.4. Collaborative research requiring complex architectures or constellations. Collaborative university constellations are a low-cost alternative to constellations built by industry to industrial standards. University constellations are also suited to science missions with limited orbital lifetime, or having no commercial interest in the industry.

3.5.2.5. Sharing resources and standards. International cooperation between universities in the SmallSat field offers significant advantages in cost sharing and thus potential to attract new sponsors to the space science field beyond the classical space agencies. In order to further promote this, electrical interface standards (such as UNISEC-Europe) for a broad application range need to be further developed and extended in order to support exchange of components between scientific institutions. According to the National Academies report (NASEM, 2016), subsystems such as power boards and communication systems standardized to the CubeSat form factor can now be purchased off the shelf. Advances in purchased spacecraft subsystems and common software now permit a science-driven CubeSat mission to focus primarily on developement of the science instrumentation and focus on the science mission. SmallSat projects provide an opportunity to share resources and define standards in the following fields:

- *Use of frequencies allocated to Amateur Radio users (VHF, UHF and S-Band).* University ground stations are capable of communication with more than one spacecraft on the same Amateur Radio frequency bands.
- *Shared spectrum and common interface for applying for frequency allocation and coordination.*

Adequate spectrum allocation is not only a technical issue but also a regulatory one. A common interface for applying for frequency allocation will facilitate the process for universities and ensure a more effective usage of spectrum. In fact, a single ground station can reuse the same frequency to communicate with many satellites at different time slots.

- Global flexible standard for GS SW and on-board SW based on open source.
- University GS are usually in communications footprint less than 3% of the mission time. For 97% of the time the GS is idle. As an example, for the FIREBIRD mission, only 0.5 percent of the high-rate data was received due to the limitations of the telemetry system. A standard GS and spacecraft SW allows for existing ground stations at universities worldwide to link together, communicate with satellites of other universities, and stream the mission data to research centers via the Internet. The model can be expanded to global networks of university GS providing global coverage for all participating universities and access to a larger amount of data from space at low cost. Many critical operations and science missions would benefit from having uninterrupted coverage allowing for a dramatic increase in mission return.
- Standard low-power transmitters.

These can operate under the power constraints of SmallSats while having the benefit of reducing interference to other satellites, thereby increasing the total throughput from space.

- Standard deployers and shared launches.

Most CubeSats are deployed as secondary payloads on large rockets. CubeSats use launch adapters designed to accommodate them on these launch vehicles. These devices can be used for both dedicated CubeSat launches (usually up to 3U in length) and for shared launches consisting of combinations of smaller-sized CubeSats (e.g., 1U and 2U). Today, there is still no uniform standard for CubeSat deployers which essentially means that many times the S/C design is dependent on the choice of launch broker. For example, in the ISIS QuadPack CubeSat deployer, access to the S/C is made from the top panel whereas the NanoRacks CubeSat deployer provides access to the S/C from a side panel. Accordingly, the position of the S/C access hatch to charge the batteries or connect to the on-board computer also changes. A standard deployer that can accommodate any CubeSat up to 12U and integrated to any launcher will not only be cost-effective but also increase the variety of orbits available for science CubeSats.

- Centralized systems engineering.

One of the most challenging concepts to teach in aerospace engineering is the interdependent subsystems and systems that make a successful space mission (NASEM, 2016). Proper systems engineering ensures that all likely aspects of a project are considered and integrated into a whole. Unfortunately, unlike the aerospace industry, much of academia does not have a well-established discipline of systems engineering nor a legacy of knowledge and experience in this field. As a result, systems engineering is often the weakest link in the university project and may lead to failure of the scientific mission in space. A project involving several universities requires centralized systems engineering managed by experts who will set a uniform and high standard of implementation for all the partners.

- Centralized management of international projects.

Universities collaborating in an international project should create a joint steering group to reduce duplication

in common science and technology areas, targeting resources to the most appropriate partner in each field, creating easier interfaces for investigators, provide more consistency to the integration, testing, and launch efforts and provide a common interface to vendors and launch providers.

3.5.2.6. The GENSO case study. GENSO (Global Educational Network for Satellite Operation), supported by educational programs of several space agencies under the lead of ESA 2007, was an early attempt to share ground station resources between universities. Currently most active is UNISEC (University Space Engineering Consortium),[74] where about 100 international universities with spacecraft engineering courses participate. Here not only a global ground station network is supported, but also electrical interface standards[75] are developed (Fig. 3.9), which were already successfully implemented on several European and Japanese CubeSat missions, and form an excellent basis for exchange of subsystems and components in joint international missions.

More recently, a similar project was started in 2014: SatNOGS[76] is an open source global network of satellite ground stations focused on observing and receiving the signal of satellites, particularly low earth orbit (LEO) CubeSats.

3.5.3. Secondary education

As democratization of space expands, so does the demand for skilled personnel to accomplish simple and complex industrial tasks. Whereas higher scientific education at University and graduate levels is recognized and promoted, a particular effort should be envisaged oriented towards promoting scientific as well as technical careers in secondary level education. A large variety of skilled jobs will be offered in the manufacturing and assembly of SmallSats, not necessarily requiring Msc or PhD level education. "Not only rocket scientists build rockets!"

The secondary education level is well-suited to orient young women and men towards vocational schools and/or technical universities. This means that scientists and industry must define their requirements and, whenever possible, take the time to explain the fascinating field of Space to teachers and students. This would allow schools to set up corresponding curricula and industry to have access to the required work-force. A clear societal benefit of such an approach is the early creation of production jobs providing salaries, taxes and experience.

This approach is implemented, e.g., in Switzerland's National Centre for Competence in Research in Robotics.[77] The center provides spin funds that allow scientists or engineers to take work that they have produced in an academic environment and create a spin-off company with it. They are supported in developing their project that has practical applications for the public or companies, thus acquiring the vision and wide range of skills necessary to take something to market. Outside of the academic work, roboticists are required in many organisations such as hospitals, manufacturing plants, environmental services, as well as in space agencies and industry.

One of the problems that educators face today is how to create a teaching environment that provides a meaningful and effective learning experience in the fields of science and technology. Project-based learning (PBL) is also successfully used at the secondary level. PBL is a dynamic classroom approach, where high-school students acquire a deeper knowledge through active research of real-world problems. PBL has been shown to be effective in enhancing both student learning and excitement. CubeSat projects are PBL magnets for science studies. They are using the appeal of space to the younger generation, attracting them to STEM, and training and preparing them to become the scientists and engineers of tomorrow.

3.5.3.1. Encouraging young women to engage in science and technology. Women make up nearly half of the US workforce but only 24% of STEM workers, the US Census Bureau reports. SmallSat programs can be used as platforms to encourage young women to engage in aerospace and STEM. In fact, the Israeli CubeSat program had a very successful program working with state religious schools where boys and girls are separated into single-sex classrooms. R&D teams were formed consisting entirely of female students. Not surprisingly, it turned out that girls not only had excellent R&D capabilities but also leadership and entrepreneurial abilities, and the quality of their tech project was generally better than that of male students of the same age.

3.5.3.2. Agency support of teachers and students. In recent years, ESA has been supporting the European Space Education Resource Office (ESERO) project, which envisages the establishment of contact/resource centers which are staffed by education experts and integrated into national educational systems and networks. The centers share inspirational materials that assist teachers and students with the learning process, and supports educational outreach activities that bridge between projects, students and teachers. Several programs exist where high-school students participate in R&D of affordable science experiments that can be flown on various microgravity platforms, such as balloons, or sent to the ISS (Fig. 3.10).

3.5.3.3. The Duchifat case study. Duchifat is a CubeSat-based program in the Israeli secondary education system that involves students aged 12–18 years. They start their training as early as the seventh grade with basic science courses. At the ninth grade, students who excel in their studies and show increased motivation, continue to a third year

[74] http://www.unisec-global.org/.
[75] http://unisec-europe.eu/standards/bus/.
[76] https://satnogs.org/.
[77] https://nccr-robotics.ch/kids-teachers-parents/how-to-be-a-roboticist/.

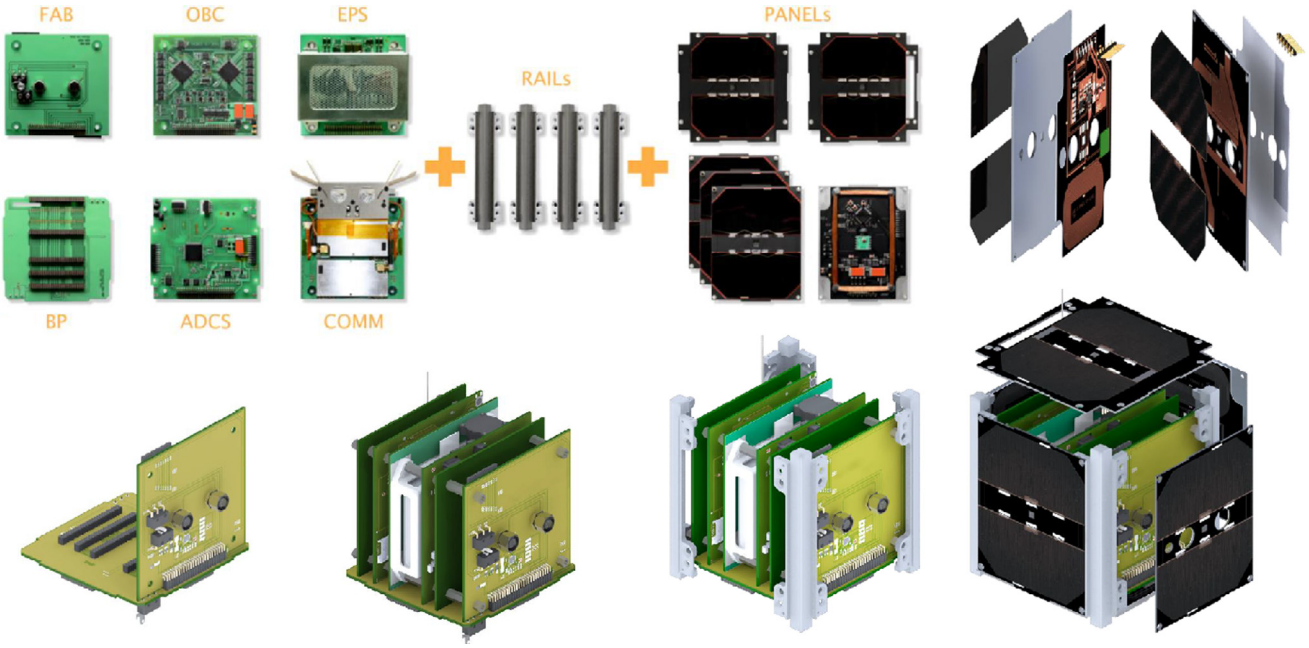

Fig. 3.9. The flexible composition of a complete satellite through the modular building blocks at subsystem level according to the UNISEC-Europe electrical interface standard, where the harness is replaced by a backplane. Image Credit: Zentrum für Telematik.

of a more advanced course focused on CubeSat design and become members of a "Satellite and Space Lab" in school. Each team of students is led by an experienced engineer from the aerospace industry and assumes responsibility on one of the satellite's subsystems. The team's task is usually fairly narrow and well defined, allowing the students to deal with it successfully even though they lack formal engineering education. System engineering, integration and testing issues are also the responsibility of the students but are presented at a later stage (usually the 12th grade) when the students are more experienced and become themselves mentors and leaders to the younger students. This program has already resulted in two CubeSats in space ("Duchifat 1" launched in June 2014, and "Duchifat 2", AKA Hoopoe, launched in May 2017 as part of the QB50 project, both are still fully operational as of May 2018).

Ten additional CubeSats in this series, Duchifat 3 to 12, for ecological applications and space weather monitoring, are now under various stages of development throughout Israel and will be launched by 2020.

Another step forward in creating a new ecosystem that combines academia, industry, government and the education system, is the INDIA/ISRAEL@75 program, a joint venture by India and Israel to develop, build, and launch into space 75 satellites by 2022, celebrating 75 years of Independence in both countries. The satellites will be built by 75 Israeli and Indian high schools and universities to form a constellation that will cover the face of the planet. These rather basic CubeSats (sized between 1U and 3U) will be capable of uploading algorithms from the ground and will serve as a platform for scientific experiments as well as for testing future technologies. The constellation will be controlled and commanded by ground control stations to be set up in schools and universities in both countries. In this novel ecosystem (Academia-Industry-Education-Governments) the teaching staff will be based primarily on science teachers (math, physics and computer sciences) as well as researchers from engineering and exact sciences faculties, but will also include experienced engineers and experts in relevant disciplines from the Israeli and Indian aerospace industries. The staff will guide students in mixed teams of all ages and levels, from high school students to doctoral students. The program is based on the heritage and experience gained in building CubeSats in both countries and is supported by both governments.

3.5.4. Fostering international collaboration

There are several other existing frameworks of collaboration between countries. The BIRDS satellite project[78] is a cross-border interdisciplinary project for non-space faring countries supported by Japan (participating countries are; Ghana, Mongolia, Nigeria and Bangladesh). During this two-years project students design, develop and operate five units of identical 1U CubeSats. The International Partnership Program (IPP)[79] was launched by the UK in 2015 to deliver a sustainable, economic or societal benefit to undeveloped nations and developing economies.

The current model for selection of large spacecraft that involve international collaborations is not well suited for small satellites. Historical examples such as Solar C and the International Solar Polar Mission (ISPM) illustrate this difficulty due to differences in programmatic frameworks of

[78] http://www.birds-project.com.
[79] https://www.gov.uk/government/collections/international-partnership-programme.

Fig. 3.10. A trio of CubeSats from Spain, Greece and Israel as seen from the ISS. Image Credit: NASA.

the involved partners. The process by which QB50 was incepted was a step in the right direction.

COSPAR has a long tradition of Capacity Building Workshops[80] with various partners in order to convey practical knowledge in areas of interest to COSPAR and to build lasting bridges between scientists. This could be developed further into a process equivalent to the decadal surveys but at the international or global level. COSPAR could possibly fill a leading role in such a process.

Finding 3.11 – COSPAR as the first and most authoritative international space organization is in a good position to support the international community in the creation and coordination of infrastructure or tools for a global and even deep-space network of small satellites to which anyone can contribute in a well-defined format and interface, thus creating a virtual constellation from all contributors that will by far exceed what the individual parts could do by themselves.

4. Recommendations

Based on the findings distributed throughout the text above, we conclude by making five recommendations; one each to the science community, to space industry, to space agencies, to policy makers, and finally, to COSPAR.

[80] https://cosparhq.cnes.fr/events/cb-workshops/.

4.1. Recommendation 1 – To the science community

The science community as a whole should acknowledge the usefulness of small satellites and look for opportunities to leverage developments in the small satellite industry. All branches of space science can potentially benefit from the smaller envelope, the associated lower cost, and higher repeat rate. Scientific communities from small countries in particular may benefit from investing their budgets in small satellites.

4.2. Recommendation 2 – To space industry

Satellite developers should seek out opportunities to partner with individual scientists and universities as well as larger government agencies. This might include data sharing arrangements, selling space on commercial spacecraft for scientific instruments, etc. Currently, publicly available operational data is very valuable for achieving science objectives. Commercial entities should be open to agreements that would continue to make such data available under a free, full, and open data policy for scientific use. Such partnerships can also contribute to workforce development.

4.3. Recommendation 3 – To space agencies

Large space agencies should adopt procedures and processes that are appropriate to the scale of the project. Agencies should find new ways to provide opportunities for

science, applications, and technology demonstrations based on small satellites and with ambitious time to launch. Agencies should additionally take advantage of commercial data or commercial infrastructure for doing science in a manner that preserves open data policies. Finally, space agencies should work together to create long-term roadmaps that outline priorities for future international missions involving small satellites.

4.4. Recommendation 4 – To policy makers

In order for scientific small satellites to succeed, the scientific community needs support from policy makers to: (1) ensure adequate access to spectrum, orbital debris mitigation and remediation options, and affordable launch and other infrastructure services; (2) ensure that export control guidelines are easier to understand and interpret, and establish a balance between national security and scientific interests; (3) provide education and guidance on national and international regulations related to access to spectrum, maneuverability, trackability, and end-of-life disposal of small satellites.

4.5. Recommendation 5 – To COSPAR

COSPAR should facilitate a process whereby International Teams can come together to define science goals and rules for a QB50-like, modular, international small satellite constellation. Through an activity like e.g. the International Geophysical Year in 1957–1958 (IGY), participants would agree on the ground rules. Agency or national representatives should be involved from the beginning. The funding would come from the individual participating member states for their individual contributions, or even from private entities or foundations. The role of COSPAR is one of an honest broker, coordinating, not funding. COSPAR should define criteria that must be met by these international teams for proposing.

The results of such an international effort would be valuable for all of the participants, and be more valuable than the individual parts. COSPAR would create a precedent for setting up community science in a very open way. The incentive for participants would be to be part of a worldwide project with access to data of the entire consortium. This recommendation is a means to facilitate progress towards really big ideas such as our four Visions for the Future or similar ideas.

5. Epilogue: Then and now

In the first years of the space age decisions were made quickly and programs started and completed just as quickly: The Soviet Union launched the first satellite on 4 October 1957; NASA was formed less than a year later in July 1958; and Project Apollo started in 1961. In the next year, 1962, the NASA Advisory Council asked the Space Studies Board of the National Academy of Sciences (NAS) to produce a set of high-priority objectives for space science. The first Orbiting Solar Observatory (OSO 1) was launched in March 1962.

The unmanned test flight of the huge Saturn V rocket occurred on 9 November 1967; the first manned Saturn V flight occurred on 11 October 1968; the first flight to the Moon started on 21 December 1968; and then the Moon landing quickly followed on 20 July 1969. During the Apollo Project OSO 3, 4, 5, 6, and Skylab were launched.

Project Apollo was accomplished without e-mail, Excel, PowerPoint or computers with anywhere near the capacity of a low-end smartphone today. Communications occurred by letters, phone, or Fax. To be fair we should recall that the fiscal environment was also very different back then, with cost much less of an issue in the cold war era. Moreover, accountability rules are much stronger today than they were back then.

That was then, but now... The NASA Parker Solar Probe was launched recently (August 2018) and the ESA/NASA Solar Orbiter is in final testing and will follow in 2020. The Solar Probe was recommended by the 2002 Decadal Survey for the Sun and Heliosphere. Before that recommendation, there had been a number of years of project planning. The ESA Orbiter had its origins in 1994. Both of these programs have had at least 20 years of active development, about twice as long as the time to decide to go to the Moon and land a man there.

Both probes approach close to the Sun, so they are complex technical tasks, but it would be hard to argue that they even approach the technical challenges of Project Apollo. Further, the two spacecraft of the Helios Mission in the seventies approached as close to the Sun as Solar Orbiter. Orbiter and Probe are just machines that do not require the oversight of manned mission.

Orbiter and Probe are not isolated examples. The James Webb Telescope was recommended a few years before them and its current earliest launch date is in March 2021, if final testing goes as planned.

Both NASA and ESA have recognized that their science missions take a long time and have developed programs designed to shorten development cycles. NASA has the SMEX and Earth Ventures programs, and ESA has created Class S missions. These programs operate on a schedule of about 7 years until the first science data are received. The planned schedules also require that the planned rate of development funding is maintained.

A mission's capabilities depend on integrated circuit computers and memory. For several decades the number of components and hence the capabilities of integrated circuits have been doubling every 18 months. This has resulted in a situation where a mission now in orbit is limited by its computers to execute modern software systems that require fast processors and large memory. A few clicks on the web and a few hundred dollars can get you two terabytes of solid state memory, which is much more than is flying on current SMEX missions.

The fact that the current generation of missions are technologically outdated at launch represents an inefficiency in both the usage of funds and human technical and scientific resources. Advances made during the development phase can even make some of the missions science goals obsolete. Understandably, because the missions are so infrequent only those with the lowest perceived technological and scientific risk pass through the long sequence of previews and selection gates.

But things are changing. A new generation of commercial rockets can launch missions at lower cost, thus reducing one of the largest fractions of mission cost. One may therefore expect that in the near future more nations will play a significant role in space science. At present the national governments in China, India, Australia, Korea, and the United Arab Emirates are vigorously developing space science programs to join the four large space agencies, NASA, ESA, Roskosmos, and JAXA/ISAS.

In 1999 two professors, one at California Polytechnic State University and the other at Stanford University, wrote a specification for small satellites used for student experiments in space. The spacecraft was a modular design based on 10 cm cubes – CubeSats. Their plan was to create projects that would encourage students to become involved in space experiments. CubeSats have evolved over the last decade. They now carry significant scientific payloads. The change has occurred because of the combination of new, lower-cost access to space and light-weight, low-power CPUs in combination with large-capacity memory chips that have been demonstrated to survive in Low Earth Orbit. The CubeSats, and their larger brothers the NanoSats and SmallSats, are providing new opportunities for doing science in space both faster and cheaper. This, together with the fact that they can interact in constellations, could create a new era in space science.

The large space agencies are no longer the only players in space operations. In the last years venture capitalists have increasingly recognized that monitoring the Earth from space can yield marketable data. Commercial projects have launched hundreds of CubeSats and SmallSats. The cost of a SmallSat program, while significant, is not too large for Universities to have their own space programs. This is already occurring in Japan, Germany, Israel, Italy, France, the UK, Switzerland, Korea, and others. In 2016 the National Academies published a report on "Achieving Science with CubeSats" (NASEM, 2016). This 2019 COSPAR roadmap reports on the prospects for scientific uses of SmallSats now and in the future.

As stated at the outset, the ultimate destination is a world in which international teams of scientists pursue novel and far-reaching goals. This roadmap provides some possible paths to reach such goals using small satellites. Science missions with masses of tens or a few hundred kilograms instead of tons, development times of a few years instead of decades, and total costs of tens of millions instead of billions may become the norm. The potential of such missions will be amplified further by building constellations of small satellites, thus not only providing multiple observation vantage points but also adding fault tolerance as failure of single network nodes little affect the entire network. A fleet of thousands of networked Earth observation satellites could allow uses and applications of enormous scientific and societal impact. A swarm of small satellites sent to a unique solar system body such as 1P/Halley, each making different observations and built by a different agency, has the potential to outperform any monolithic mission. This is even more apparent for astronomy in space as obviously nothing bigger than the JWST can possibly be launched. And when thinking about reaching any other star within a human lifetime small satellites will have to grow significantly smaller still before such a mission will come within reach even remotely. For all of these and similar visionary goals there are formidable technological challenges to master, but equally importantly, new ways and means of international collaborations between all participating entities – the scientific community in universities and research institutions, space agencies, space industry, policy makers such as governments and international organizations – will need to be established, and we hope that COSPAR can play an active and vital role in this process.

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Appendix A. List of acronyms

4S	Small Satellites for Space Science
5G	Fifth Generation (standard for mobile internet and telephony)
AAReST	Autonomous Assembly of a Reconfigurable Space Telescope
ADCS	Attitude Determination and Control System
AIDA	Asteroid Impact and Deflection Assessment
AIM	Aeronomy of Ice in the Mesosphere
AMPTE	Active Magnetospheric Particle Tracer Explorer
ARPA	Advanced Research Projects Agency
ARPA-E	Advanced Research Projects Agency–Energy
ASI	Agenzia Spaziale Italiana
ASTERIA	Arcsecond Space Telescope Enabling Research in Astrophysics
AU	Astronomical Unit
CAS	Chinese Academy of Sciences

CERN	Conseil Européen pour la Recherche Nucléaire
CHARA	Center for High Angular Resolution Astronomy
CHEOPS	CHaracterising ExOPlanets Satellite
CNES	Centre National d'Etudes Spatiales
COBE	Cosmic Background Explorer
COSPAR	Committee on Space Research
COTS	Commercial Off-The-Shelf
CSLI	CubeSat Launch Initiative
CSSWE	Colorado Student Space Weather Experiment
CYGNSS	Cyclone Global Navigation Satellite System
DARPA	Defense Advanced Research Projects Agency
DDOR	Delta Differential One-way Ranging
DISCUS	Deep Interior Scanning CubeSat
DOD	Department of Defense
DSCOVR	Deep Space Climate Observatory
DTUSat	Danmarks Tekniske Universitet Satellite
EELV	Evolved Expendable Launch Vehicle
ELaNa	Educational Launch of Nanosatellites
ELT	Extremely Large Telescope
EM-1	Exploration Mission 1
Envisat	Environmental Satellite
EO	Earth Observation
EQUULEUS	EQUilibriUm Lunar-Earth point 6U Spacecraft
ESA	European Space Agency
ESERO	European Space Education Resource Office
ESO	European Southern Observatory
ESPA	EELV Secondary Payload Adapter
EU	European Union
FAST	Fast Auroral Snapshot Explorer
FCC	Federal Communications Commission
FDIR	Fault Detection, Identification and Recovery
FIPEX	Flux-Φ-Probe Experiment
FIREBIRD	Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics
FLEX	Fluorescent Explorer
FP7	Framework Programme 7 (of the EU)
GALEX	Galaxy Evolution Explorer
GENSO	Global Educational Network for Satellite Operations
GEO	Geosynchronous Equatorial Orbit
GNSS	Global Navigation Satellite Systems
GOLD	Global-scale Observations of the Limb and Disk mission
GPS	Global Positioning System
GS SW	Ground System SoftWare
GSTP	General Support Technology Programme
GTO	Geostationary Transfer Orbit
GTOSat	Geostationary Transfer Orbit Satellite
HERMES	High Energy Rapid Modular Ensemble of Satellites
HG	High Gain
I&T	Innovation and Technology
IAC	International Astronautical Congress
IARPA	Intelligence Advanced Research Projects Activity
IBEX	Interstellar Boundary Explorer
ICE	International Cometary Explorer
ICON	Ionospheric Connection Explorer
IDA	Institute for Defense Analyses
IGRF	International Geomagnetic Reference Field
IGY	International Geophysical Year
IIST	Indian Institute of Space Science and Technology
IKAROS	Interplanetary Kite-craft Accelerated by Radiation Of the Sun
INMS	Ion-Neutral Mass Spectrometer
INSPIRE	Interplanetary Nano-Spacecraft Pathfinder in Relevant Environment
IOD	In-Orbit Demonstration
IPP	International Partnership Program
IRIS	InfraRed Imaging Surveyor
ISA	Israeli Space Agency
ISAS	Institute of Space and Astronautical Science
ISIS	Innovative Solutions in Space company
ISO	InterStellar Object
ISPM	International Solar Polar Mission
ISRO	Indian Space Research Organisation
ISS	International Space Station
ITAR	International Traffic in Arms Regulations
ITU	International Telecommunications Union
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
KRIS	Ka-band Interferometry Swarm
KSAT	Kongsberg Satellite Services
LASP	Laboratory for Atmospheric and Space Physics
LEO	Low Earth Orbit
LHC	Large Hadron Collider
LIGO	Laser Interferometer Gravitational-Wave Observatory
LISA	Laser Interferometer Space Antenna
LPO	Long Period Object
LSST	Large Synoptic Survey Telescope
MarCO	Mars Cube One

M-ARGO	Miniaturised Asteroid Remote Geophysical Observer
MICROSCOPE	A microsatellite to challenge the universality of free fall
MIDEX	Medium Explorer (line of NASA satellites)
MIRO	Microwave Instrument for the Rosetta Orbiter
MIT	Massachusetts Institute of Technology
MMS	Magnetospheric Multiscale Mission
m-NLP	multi-Needle Langmuir Probe
NANOBED	Nanosatellite Applications aNd Operations Bench for Engineering and Demonstration
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NCLE	Chinese Low Frequency Explorer
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NTIA	National Telecommunications and Information Administration
NuSTAR	Nuclear Spectroscopic Telescope Array
OCSD	Optical Communications and Sensor Demonstration
OLFAR	Orbital Low Frequency ARray
OSCAR-1	Orbiting Satellite Carrying Amateur Radio 1
Pan-STARRS	Panoramic Survey Telescope And Rapid Response System
PBL	Project Based Learning
PROBA	Project for On-Board Autonomy
PROCYON	Proximate Object Close flyby with Optical Navigation
PSLV	Polar Satellite Launch Vehicle
QB50	EU project, a network of 50 small satellites in space
R&D	Research and Development
REPT	The Relativistic Electron-Proton Telescope
RHESSI	Ramaty High Energy Solar Spectroscopic Imager
SAMPEX	Solar Anomalous and Magnetospheric Particle Explorer
SAOCOM	Satélite Argentino de Observación COn Microondas
SAR	Synthetic Aperture Radar
SatNOGS	Satellite Networked Open Ground Station
SEU	Single Event Upset
SHALOM	Spaceborne Hyperspectral Applicative Land and Ocean Mission
SIM	Space Interferometry Mission
SLS	Space Launch System
SMEX	Small Explorer (line of NASA satellites)
SMILE	Solar wind Magnetosphere Ionosphere Link Explorer
SPARC	Star-Planet Activity Research CubeSat
STEM	Science, Technology, Engineering and Mathematics
SWAS	Submillimeter Wave Astronomy Satellite
TESS	Transiting Exoplanet Survey Satellite
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TIM	Telematics International Mission
TOM	Telematics earth Observation Mission
TRACE	Transition Region and Coronal Explorer
TRL	Technology Readiness Level
TROPICS	Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats
UHF	Ultra High Frequency (300–3000 MHz)
ULA	United Launch Alliance
UNEX	University Explorer (line of NASA satellites)
UNISEC	University Space Engineering Consortium
UV	Ultraviolet
UWE	Universität Würzburg Experimentalsatellit
VCLS	Venture Class Launch Services
VENμS	Vegetation and Environment monitoring on a New Micro-Satellite
VHF	Very High Frequency (30–300 MHz)
VLTI	Very Large Telescope Interferometer
XML	Extensible Markup Language

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