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Achieving Science with CubeSats

Thinking Inside the Box

Committee on Achieving Science Goals with CubeSats

Space Studies Board

Division on Engineering and Physical Sciences

The National Academies of
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Preface

Small satellites called CubeSats (i.e., satellites built in increments of 10 cm cubes—1 cube is called 1U or "unit," two cubes together are 2U, and so on) historically have been used mostly as teaching tools and technology demonstrations. However, recently proposed and selected flight projects are showing that technologies have matured enough so that CubeSats can potentially address important science goals as well. CubeSats are now part of a trend toward an increasingly diverse set of platforms for pursuing space and Earth sciences. In recognition of this trend, the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF) requested in 2014 that the National Academies of Sciences, Engineering, and Medicine conduct an ad hoc review of the scientific potential of the CubeSat platform and make recommendations to improve the capabilities of the platform to enable its use by the scientific community. The Committee on Achieving Science Goals with CubeSats was formed and began work on its task (see Appendix A for the full statement of task).

Particular challenges for the committee were the relative newness of use of the CubeSat platform for science and the rapid pace of change in the relevant technologies, potential CubeSat missions, and the increasing interest from a variety of potential users within the research, educational, and commercial communities. As of the end of 2015, 425 CubeSats had been launched; more than 100 of those were during the course of this study. Therefore, the input processes for the committee were designed to be as inclusive as possible of new ideas and results. The committee also requested that each of NSF's CubeSat project teams, as well as the GeneSat and O/OREOS project teams, provide a list of their publications, including conference presentations, to ensure that the committee was aware of current results and also those that were not yet published. The committee would like to thank NASA and NSF and the members of their CubeSat teams for their responsiveness to these requests. All CubeSat launch and mission data analyzed for the report were up to date on December 31, 2015. Publication analyses were performed by January 15, 2016.

The committee held its first meeting on June 22-23, 2015, in Washington, D.C., followed by a writing meeting on October 22-23 and a policy-focused meeting on October 30, both in Washington, D.C. At the policy-focused meeting, the committee heard perspectives from the Office of Science and Technology Policy and discussed orbital debris and space situation awareness, spectrum availability, and current issues regarding the International Traffic in Arms Regulations (ITAR). Panelists and speakers were present from NASA, NSF, the Department of Defense, the Federal Communications Commission, the Joint Space Operations Center, the Federal Aviation Administration, the National Telecommunications and Information Administration, the Universities Space Research Association, the Secure World Foundation, and Analytical Graphics, Inc.'s Center for Space Standards and Innovation.

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The committee also sought to understand this rapidly changing environment via three focused input events. As part of their second meeting, the committee held a community symposium on September 2-3, 2015, in Irvine, California. This meeting included a combination of keynote speakers who presented the history and current state of CubeSat science and technology and panels of scientists and engineers who discussed the future of the platform in their expertise areas. Science discipline areas included Earth science, solar and space physics (also referred to as heliophysics), planetary science, and astronomy and astrophysics. Other panels discussed technology for CubeSats, CubeSats for technology development, industry capabilities, and CubeSats in education. In addition to the invited speakers and panelists, the committee held a call for poster presentations, asking the community to bring their best ideas for science, mission concepts, and technology development. More than 125 participants attended the symposium, and 60 posters were submitted (Figure P.1). To round out the relevant science disciplines, the Space Studies Board's standing Committee on Biological and Physical Sciences in Space hosted a keynote and panel discussion for their discipline during their meeting on October 27-29, 2015, in Irvine, California. The Committee on Achieving Science Goals with CubeSats attended the session via web conference. To gain an international perspective, members of the committee were hosted by the International Space Science Institute (ISSI) at their forum on Performing High-Quality Science on CubeSats on January 19-20, 2016, in Bern, Switzerland. The committee would like to thank the staff of ISSI, and in particular, Rafael Rodrigo, Rudolf von Steiger, Maurizio Falanga, and Jennifer Fankhauser-Zaugg.

This report summarizes the history of CubeSats and reflects the rapidly changing environment of the CubeSat platform, and consequently, it focuses on recommendations for near-term actions as well as on strategies for enhancing the scientific usefulness of CubeSats without overly restraining the spirit of innovation that characterizes the broad community of CubeSat users.

FIGURE P.1 Attendees at the committee's community input symposium on September 2-3, 2015, in Irvine, California, at the poster session (*left*) and during a keynote presentation (*right*). SOURCE: Courtesy of Abigail Sheffer.

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Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Michael Bartone, Intelligence Advance Research Projects Activity,
Claude Canizares, Massachusetts Institute of Technology,
Elizabeth Cantwell, Arizona State University,
David Klumpar, Montana State University,
Michael Ladisch, Purdue University,
Stephen Mackwell, Universities Space Research Association, and
Marcia McNutt, American Association for the Advancement of Science.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Marcia Rieke, University of Arizona, who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Contents

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Summary

This report examines the current state and science potential of CubeSats—defined by the committee as a spacecraft sized in units, or U's, typically up to 12U (a unit is defined as a volume of about 10 cm × 10 cm × 10 cm) that is launched fully enclosed in a container. Although the concept of launching a "canisterized" secondary payload has existed since the space shuttle program, two university groups formally introduced the concept of CubeSats in 1999 as an educational platform, seeking to give students hands-on experience building, launching, and operating spacecraft. Over the 15 years since their introduction, CubeSats have been shown to share many characteristics of disruptive innovations, such as rapid improvement of capabilities and finding niche uses in research, commercial, and homeland and national security communities. Accordingly, the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF) asked the National Academies of Sciences, Engineering, and Medicine to establish an ad hoc committee to explore the current state of CubeSats and examine the potential of the use of CubeSats to obtain high-priority science data. The full statement of task for the Committee on Achieving Science Goals with CubeSats is reprinted in Appendix A.

The rapid speed of CubeSat development has been enabled, in part, by fast "fly-learn-refly" cycles—in which two flight models are developed and the second model is modified and launched if issues arise during the first flight—comparatively low development costs, miniaturized electronics, and timely availability of affordable launch opportunities. A pioneering CubeSat-based research program launched in 2008 within NSF's Division of Atmospheric and Geospace Sciences was responsible for the first systematic support of CubeSat-based science investigations and led to a growing engagement with universities. Furthermore, a growing commercial sector for the use of CubeSats for Earth observations and remote sensing has also helped to spur rapid technology development. Commercial demand has given rise to a fast-growing component-supplier industry. These commercial users and suppliers are now major drivers of technology development for CubeSats, and many technologies or subsystems can be purchased "off the shelf" by groups that seek to use CubeSats to address science objectives.

Since 2010, the use of CubeSats for science has grown especially rapidly due to NSF's program and because of an increase of interest within various NASA programs. More than 80 percent of all science-focused CubeSats have been launched from 2012 to 2016. Similarly, more than 80 percent of peer-reviewed papers describing new science based on CubeSat data have been published in the past 5 years. The committee's review of a subset of these papers is discussed in Chapter 4 and Appendix B.

The committee concluded that CubeSats have already produced high-value science. CubeSats are useful as instruments of targeted investigations to augment the capabilities of large missions and ground-based facilities,

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and they enable new kinds of measurements and have the potential to mitigate gaps in measurements where continuity is critical.

The committee developed a list of sample science goals for CubeSats (Chapters 4 and 7). Many of these goals address targeted science, often in coordination with other spacecraft, or use “sacrificial,” or high-risk, orbits that lead to the demise of the satellite after critical data have been collected. Other goals relate to the use of CubeSats as constellations or swarms deploying tens to hundreds of CubeSats that function as one distributed array of measurements.

The committee also concluded that although all space science disciplines can benefit from innovative CubeSat missions, CubeSats cannot address all science objectives and are not a low-cost substitute for all platforms. Activities such as those needing large apertures, high-power instruments, or very-high-precision pointing most likely will always require larger platforms because of the fundamental and practical constraints of small spacecraft. Also, large spacecraft excel at large-scale investigations when, for example, several instruments need to be collocated. CubeSats excel at simple, focused, or short-duration missions and missions that need to be comparatively low cost or that require multipoint measurements.

The set of science goals where the use of CubeSats would be enabling is evolving too quickly for the committee to create a comprehensive list, and the committee was not tasked with prioritizing CubeSat missions. However, the following examples, from those listed in Chapter 4, provide a sampling of high-priority science goals that could potentially be pursued using CubeSats:

- *Solar and space physics, Earth science and applications from space—Exploration of Earth’s atmospheric boundary region*. CubeSats are uniquely suited because of their expendability to explore the scientific processes that shape the upper atmospheric boundary using short-lifetime, low-altitude orbits.
- *Earth science and applications from space—Multipoint, high temporal resolution of Earth processes*. Satellite constellations in low Earth orbit could provide both global and diurnal observations of Earth processes that vary throughout the day, such as severe storms, and are currently under-sampled by Sun-synchronous observatories.
- *Planetary science—In situ investigation of the physical and chemical properties of planetary surfaces or atmospheres*. Deployable (daughter-ship) CubeSats could expand the scope of the motherships with complementary science or site exploration.
- *Astronomy and astrophysics, solar and space physics—Low-frequency radio science*. Interferometers made of CubeSats could explore the local space environment and also galactic and extragalactic sources with spatial resolution in ways not accessible from Earth.
- *Biological and physical sciences in space—Investigate the survival and adaptation of organisms to space*. CubeSats offer a platform to understand the effects of the environment encountered in deep space, such as microgravity and high levels of radiation.

To unlock the science potential of CubeSats or missions relying on CubeSat technology, federal investments continue to be crucial, especially in areas that will not see commercial investment. Both NSF and NASA have active CubeSat programs. NSF’s program has the dual goals of supporting small satellite missions to advance space weather-related research and of providing opportunities to train the next generation of experimental space scientists and aerospace engineers. As of 2015, NSF had launched 8 science-based CubeSat missions (consisting of 13 CubeSat spacecraft) and has 7 missions (11 CubeSat spacecraft) in development. The committee believes that the program has been successful with regard to both goals and that NSF’s current program continues to be valuable. The program is particularly well aligned with the goals and recommendations of the 2013 decadal survey for solar and space physics, *Solar and Space Physics: A Science for a Technological Society* (National Research Council, The National Academies Press, Washington, D.C.); however, other disciplines at NSF, such as Earth science and astronomy and astrophysics, could also benefit from the scientific and educational opportunities that CubeSats provide.

Recommendation: The National Science Foundation (NSF) should continue to support the existing CubeSat program, provide secure funding on a multiyear basis, and continue to focus on high-priority science and the training of the next generation of scientists and engineers. In particular, NSF should consider ways to

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increase CubeSat opportunities for a broad range of science disciplines going beyond solar and space physics, with financial support from those participating disciplines.

Although most CubeSat science results published today have come from NSF-sponsored investigations, that is expected to change. NASA's programs, which are distributed throughout the agency, thus far have placed greater emphasis on maturing new technologies. However, NASA provided a large increase in opportunities to propose science-based CubeSat missions in 2013. As of 2015, NASA had launched a total of 18 CubeSat missions (34 spacecraft) with science and technology objectives. Each of the four NASA Science Mission Directorate science divisions, at least two other directorates, and at least five NASA centers are developing CubeSat missions. Additionally, some of the science divisions and centers may have more than one funding opportunity for CubeSats.

The committee observed that CubeSat activities within NASA programs have remained largely independent—perhaps, not surprisingly, as a result of rapid growth in the use of CubeSats—and a lack of coordination has impacted NASA's ability to communicate a clear strategic plan and vision on the role of CubeSats for scientific exploration internally within NASA and to the community. The explosion of interest in the deployment of CubeSats has led to some management challenges that have the potential to stifle the impact that CubeSats can have for science. Newcomers seeking NASA support for CubeSat missions have difficulty navigating the rapidly evolving and varied programs, technologies, and funding opportunities at the agency. Interested partners in academia, government, and industry may have difficulty finding and creating collaborations. In addition, because of the disaggregated nature of CubeSat programs at NASA, programs have begun to duplicate efforts in some areas—for example, communication and propulsion technology development—and are not systematically sharing lessons learned. Technology development by industry is evolving equally rapidly and is underleveraged in many government programs, including at NASA.

CubeSats have proven their usefulness in the pursuit of science, most notably demonstrated by the increase in the publication of scientific papers. Thus, it is now time for NASA to respond by increasing coordination of their CubeSat programs for science and science-enabling technology, with the goal of further increasing the overall scientific return and advancing sophisticated uses of CubeSats, such as large constellations. An additional level of management is needed that can continue to encourage innovation—in all of the science disciplines and at different costs—but also can reduce duplication in common technology areas by targeting resources to the most promising developments.

Recommendation: NASA should develop centralized management of the agency's CubeSat programs for science and science-enabling technology that is in coordination with all directorates involved in CubeSat missions and programs, to allow for more efficient and tailored development processes to create easier interfaces for CubeSat science investigators; provide more consistency to the integration, test, and launch efforts; and provide a clearinghouse for CubeSat technology, vendor information, and lessons learned. The management structure should use a lower-cost and streamlined oversight approach that is also agile for diverse science observation requirements and evolutionary technology advances.

The goal of this increased management focus is to leverage NASA's investments to maximize scientific output. However, it is equally important to encourage innovation by maintaining a variety of programs.

Recommendation: NASA should develop and maintain a variety of CubeSat programs with cost and risk postures appropriate for each science goal and relevant science division and justified by the anticipated science return. A variety of programs are important to allow CubeSats to be used for rapid responses to newly recognized needs and to realize the potential from recently developed technology.

For example, a solar and space physics-focused CubeSat with a short development cycle and lower cost might be able to take rapid advantage of a technological breakthrough. On the other hand, a CubeSat flying as part of a planetary science mission might be developed on the same timescale as the larger spacecraft of the mission and require higher reliability, which is typically associated with higher cost.

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One critical benefit of NASA's engagement in CubeSats is the role of CubeSats in training students, early career project scientists, engineering teams, and project managers. Care must be taken to not inadvertently stifle such training opportunities as CubeSats evolve toward more capable science missions and as the proposed new management structure is implemented.

Recommendation: NASA should use CubeSat-enabled science missions as hands-on training opportunities to develop principal investigator leadership, scientific, engineering, and project management skills among both students and early career professionals. NASA should accept the risk that is associated with this approach.

There is one type of mission class that is of high priority for multiple disciplines and that deserves focused investment and development—the creation of swarms and constellations of CubeSats. Many high-priority science investigations of the future will require data from constellations or swarms of 10 to 100 spacecraft that, for the first time, would have the spatial and temporal coverage to map out and characterize the physical processes that shape the near Earth space environment. Historically, the cost associated with large constellations has been prohibitive, but the time is ripe to develop this capacity.

Recommendation: Constellations of 10 to 100 science spacecraft have the potential to enable critical measurements for space science and related space weather, weather and climate, as well as some astrophysics and planetary science topics. Therefore, NASA should develop the capability to implement large-scale constellation missions taking advantage of CubeSats or CubeSat-derived technology and a philosophy of evolutionary development.

The capacity to do science with CubeSats strongly depends on the technological capabilities available to the investigators. These capabilities, which have the most impact on the ability of CubeSats to enable high-priority science and are currently limiting the use of CubeSats in some science applications, are the subject of the next recommendation.

Recommendation: NASA and other relevant agencies should invest in technology development programs in four areas that the committee believes will have the largest impact on science missions: high-bandwidth communications, precision attitude control, propulsion, and the development of miniaturized instrument technology. To maximize their impact, such investments should be competitively awarded across the community and take into account coordination across different agencies and directorates, including NASA's Science Mission Directorate and Space Technology Mission Directorate, and between different NASA and Department of Defense centers.

An additional area of technology development that is important to several disciplines is thermal control, a much broader topic than those recommended above. Aspects of thermal control vary from maintaining low temperatures for imaging spectrometers to creating a stable payload environment for biology experiments with live specimens.

Recommendation: As part of a CubeSat management structure, NASA should analyze private capabilities on an ongoing basis and ensure that its own activities are well coordinated with private developments and determine if there are areas to leverage or that would benefit from strategic partnerships with the private sector.

The committee also examined the challenges regarding policy—in particular, the regulatory framework—that could constrain the expansion of CubeSats for science applications. The following three challenges stand out: (1) the reality and perception of science CubeSats as an orbital debris hazard, (2) the complexities and constraints of radio spectrum availability, and (3) the availability of affordable launch opportunities. Chapter 6 of this report quantifies and discusses these issues and recommends that they be addressed more comprehensively.

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Recommendation: NASA, with the National Science Foundation, and in coordination with other relevant federal agencies, should consider conducting a review and developing a plan to address CubeSat-related policies to maximize the potential of CubeSats as a science tool. Topics may include, but are not limited to, the following: guidelines and regulations regarding CubeSat maneuverability, tracking, and end-of-mission deorbit; the education of the growing CubeSat community about orbital debris and spectrum-licensing regulatory requirements; and the continued availability of low-cost CubeSat launch capabilities. It is important to consider that current and new guidelines promote innovation, rather than inadvertently stifling it, and ensure that new guidelines are science-based, equitable, and affordable for emerging players within the United States and internationally.

In Chapter 2, the committee discusses the theory of disruptive innovation with respect to CubeSats and revisits historic instances of disruptive innovations that originated in the federal research and development space. CubeSats share many of the characteristics of disruptive innovations. History has shown that the likelihood of success and economic impact of potentially disruptive innovations is difficult to predict in the early days of the disruption. Currently, it seems that CubeSats will become an effective tool for a specific and eventually well-defined performance envelope, similar to balloons or sounding rockets. However, it is possible that CubeSats will have a much bigger impact and lead to new types of missions and scientific data and, perhaps, even lead to a more macroscopic realignment of the space industry. The principles of disruptive innovations informed the above recommendations and also led the committee to suggest the following best practices to guide the ongoing development of CubeSats:

- *Avoid premature focus*. Although the committee recommends a NASA-wide management structure to create opportunities for new investigators and provide a clearinghouse for information and lessons learned, premature top-down direction that eliminates the experimental, risk-taking programs would slow progress and limit potential breakthroughs.
- *Maintain low-cost approaches as the cornerstone of CubeSat development*. It is critical to resist the creep toward larger and more expensive CubeSat missions. Low-cost options for CubeSats are important because more constrained platforms and standardization, coupled with higher risk tolerance, tend to create more technology innovation in the long run.
- *Manage appropriately*. As missions grow more capable and expensive, management and mission assurance processes will have to evolve. Yet, it is critical to manage appropriately, without burdening low-cost missions with such enhanced processes, by actively involving CubeSat experts in policy changes and discussions as well as in proposal reviews.

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1

Introduction

WHAT ARE CUBESATS?

Space-based observations have transformed our understanding of Earth, its environment, the solar system, and the universe at large. During past decades, driven by increasingly advanced science questions, space observatories have become more sophisticated and more complex, with costs often growing to billions of dollars. Although these kinds of ever-more-sophisticated missions will continue into the future, small satellites ranging in mass between 500 kg to 0.1 kg—from microsatellites (10 kg-100 kg), nanosatellites (1-10 kg), and even picosatellites (0.1-1 kg)—are gaining momentum as an additional means to address targeted science questions in a rapid, and possibly more affordable, manner. Within the category of small satellites, CubeSats have emerged as a space-platform defined in terms of $(10\ \text{cm})^3$-sized units of approximately 1.3 kg each called "U's." Historically, CubeSats were developed as training projects to expose students to the challenges of real-world engineering practices and system design. Yet, their use has rapidly spread within academia, industry, and government agencies both nationally and internationally (see Figure 1.1 for examples of CubeSats).

In particular, CubeSats have caught the attention of parts of the U.S. space science community, which sees this platform, despite its inherent constraints, as a way to affordably access space and perform unique measurements of scientific value. The first science results from such CubeSats have only recently become available; however, questions remain regarding the scientific potential and technological promise of CubeSats in the future.

> For the purpose of this study, the committee defines a *CubeSat* as a spacecraft sized in units, or U's, typically up to 12U (a unit is defined as a volume of about 10 cm × 10 cm × 10 cm) that is launched fully enclosed in a container, enabling ease of launch vehicle system integration, thus easing access to space.

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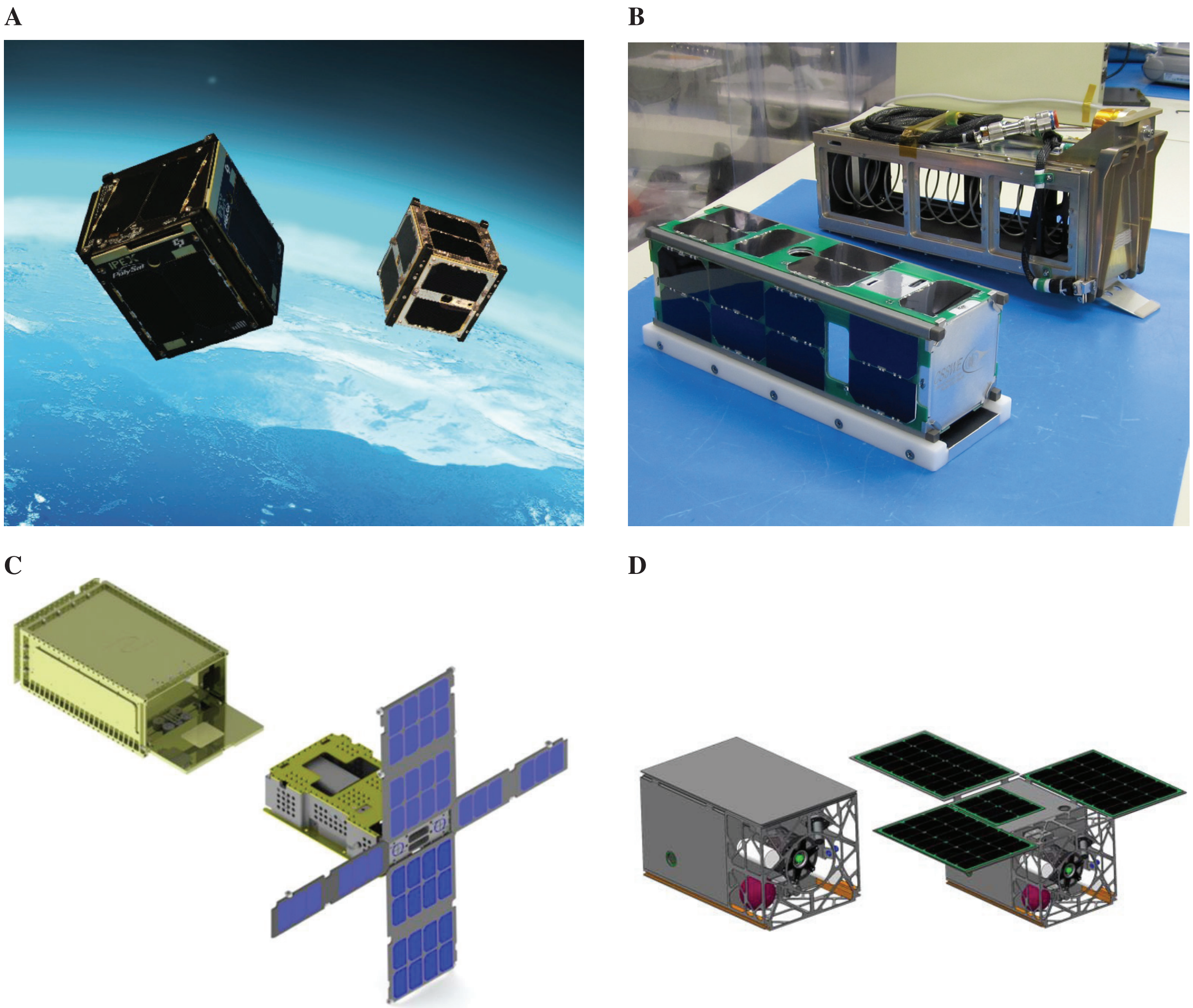

FIGURE 1.1 CubeSat examples: (a) NASA-sponsored MCubed and IPEX 1U onboard flight processing technology demonstration CubeSats (10 cm on a side). (b) The NSF-sponsored CSSWE 3U CubeSat designed to measure solar energetic protons and Earth's radiation belt electrons. (c) Containerized deployment systems, 6U shown, enable launch integration and access to space. (d) The NASA-sponsored Iodine Satellite (iSAT) is a 12U technology demonstration mission to mature new propulsion technologies. SOURCE: (a) Courtesy of NASA/JPL-Caltech. (b) Courtesy of X. Li, S. Palo, R. Kohnert, D. Gerhardt, L. Blum, Q. Schiller, D. Turner, W. Tu, N. Sheiko, and C. S. Cooper, 2012, Colorado student space weather experiment: Differential flux measurements of energetic particles in a highly inclined low Earth orbit, pp. 385-404 in *Dynamics of the Earth's Radiation Belts and Inner Magnetosphere*, Geophysical Monograph Series, Vol. 199 (D. Summers et al., ed.), American Geophysical Union, Washington, D.C., doi:10.1029/2012GM001313, copyright 2013 John Wiley and Sons. (c) Courtesy of the Planetary Systems Corporation. (d) Courtesy of NASA Marshall Space Flight Center.

RATIONALE FOR THE CREATION OF THE COMMITTEE ON ACHIEVING SCIENCE GOALS WITH CUBESATS

This committee, under the auspices of the National Academies of Sciences, Engineering, and Medicine and called for by the National Aeronautics and Space Administration (NASA) and National Science Foundation (NSF), was charged to review the current state of the scientific potential and technological promise of CubeSats. This

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Achieving Science with CubeSats: Thinking Inside the Box

assessment focuses on the platform's promise to obtain high-priority science data, as defined in recent decadal surveys[1] in astronomy and astrophysics,[2] Earth science and applications from space,[3] planetary science,[4] and solar and space physics (heliophysics)[5]; the science priorities identified in the 2014 NASA Science Plan; and the potential for CubeSats to advance biology and microgravity research. Using the study objectives from the committee's statement of task (provided in Appendix A), the specific actions to the committee are listed below. Table 1.1 provides a "map" of the report.

1. Develop a brief summary overview of the status, capability, availability, and accomplishments of a selection of existing CubeSat programs in the government, academic, and industrial sectors.
2. Recommend any potential near-term investments that could be made (a) to improve the capabilities that have a high impact on the increased science and technology return—thereby increasing the value of CubeSats to the science community—and (b) to enable the science communities' use of CubeSats.
3. Identify a set of sample priority science goals that describe near-term science opportunities—such as providing continuity of key measurements to mitigate potential gaps in measurements of key parameters—and that can be accomplished given the current state of CubeSat capabilities.

HISTORY AND GROWTH OF CUBESATS

An Educational Beginning

The promise of CubeSats for education and training (formal, informal, and early career development) is that they are relatively affordable and that they provide easy access to space. This is achieved through standardized interfaces and, especially, picosatellite deployment mechanisms that can be added to launch vehicles as secondary payloads. The initial development of such a mechanism in the 1990s by Aerospace Corporation (i.e., the Orbiting Picosatellite Automated Launcher (OPAL)) led Robert Twiggs (then at Stanford University) to develop the initial CubeSat concept in early 1999. Jordi Puig-Suari from California Polytechnic State University (Cal Poly) at San Luis Obispo helped refine this concept and created the specifications for the Poly Picosatellite Orbital Deployer (P-POD, canister) (Figure 1.2). Eight OPAL-based picosatellites were launched in 2000-2001 on U.S. Minotaur-1 rockets.[6] Six CubeSats were first launched using the P-POD in 2003 aboard a Russian Rokot launch vehicle, with three more CubeSats aboard a Kosmos-3M rocket in 2005. The larger P-POD displaced the smaller OPAL deployer, and most of the CubeSats launched in 2006 to the present time have utilized the 3U P-POD or similar form-factor 3U and 6U deployers.

During the same time, CubeSat-specific technology developments began within universities, government agencies, and industry with funding primarily from various agencies within the United States. In 2008, university groups led nearly three-quarters of all CubeSats launched. Educational institutions that were focused both on engineering of space systems and on space sciences were engaging preferentially in this novel activity. A partnership between NASA and Santa Clara University led to the first science-based NASA CubeSat, a bacterial life support experiment called GeneSat that was launched in December 2006. As technology has matured, the focus for CubeSats has increasingly turned toward high-value commercial and science-focused missions.

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[1] The National Research Council (NRC) has conducted 11 decadal surveys in the Earth and space sciences since 1964 and released the latest four surveys in the past 8 years. Through a rigorous process, a primary survey committee and thematic panels of community members construct a prioritized program of science goals and objectives and define an executable strategy for achieving them. These reports play a critical role in defining the nation's agenda in that science area for the following 10 years, and often beyond (National Academies of Sciences, Engineering and Medicine, 2015, *The Space Science Decadal Surveys: Lessons Learned and Best Practices*, The National Academies Press, Washington, D.C.).

[2] NRC, 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C.

[3] NRC, 2007, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, The National Academies Press, Washington, D.C.

[4] NRC, 2011, *Vision and Voyages for Planetary Science in the Decade 2013-2022,* The National Academies Press, Washington, D.C.

[5] NRC, 2013, *Solar and Space Physics: A Science for a Technological Society*, The National Academies Press, Washington, D.C.

[6] The OPAL picosatellites—characteristic of the CubeSat standard that was developed later—are included in all statistics given they represent the early development of the field.

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Achieving Science with CubeSats: Thinking Inside the Box

TABLE 1.1 Report Map of Objectives as They Are Addressed in Chapters 1-7

	Objective 1: Summary of Status	Objective 2: Recommend Investments	Objective 3: Identify Sample Priority Science Goals
Chapter 1	Accomplishments and status, NASA and NSF programs, mission success		
Chapter 2	Interpretation of development as disruptive innovation		
Chapter 3	Educational role		
Chapter 4	Publication overview, ongoing science programs and planned missions	Identify technology gaps for high-priority science missions	Sample priority science goals in each discipline
Chapter 5	Technological progress & growth of industrial sector		
Chapter 6	Policy relevant data such as orbital debris, communications, and launch rates	Identify policy challenges to future growth of CubeSats	
Chapter 7		Recommend near-term investments for NSF, NASA	Sample science priorities and constellation focus

Growth of an Industry

The pace of CubeSat development accelerated rapidly in the mid-2000s with an expansion of both the number and the type of organizations beyond those focused on education or technology development, as illustrated in Figure 1.3. During this time, NASA was increasing its investments in CubeSats primarily for technology development (such as technology maturations toward higher technology readiness levels (TRLs)) and training objectives. In 2007, the Geospace Science Section at NSF pioneered the role CubeSats could fulfill for space weather research by establishing a funded program in 2008 that was focused on science and education. After 2010, new commercial players were emerging as technology providers and also as companies developing and launching entire CubeSat systems (for discussion of the commercial sector, see Chapter 6). In 2013 through 2015, the commercial CubeSat launches provided approximately 55 percent of all CubeSats, university-led launches consisted of approximately 21 percent, and government (military, NASA, and NSF) provided the remaining 24 percent. By the end of 2015, 425 CubeSats had been launched, bolstered significantly by the growth of commercial applications for CubeSats in Earth observation and communications. For example, 71 percent of the CubeSat launches in 2014 were commercial Earth-imaging CubeSats for the U.S. firm Planet Labs, carried in NanoRacks or ISIPOD deployers. Another factor contributing to the increasing number of CubeSat launches is the opportunity for CubeSats to fly as secondary payloads on the frequent re-supply missions to the International Space Station (ISS). For example, 72 percent of the CubeSat launches in 2014 were to the ISS using the NanoRacks canister.[7,8] Of the 425 CubeSats launched, NASA and NSF have launched 19 CubeSats focused explicitly on science objectives, as discussed in the section "The Current NSF and NASA CubeSat Programs."

[7] This report counts CubeSats integrated into a launch vehicle with a successful liftoff, even if they failed to deploy on orbit due to a subsequent launch vehicle failure.

[8] The statistics throughout this report include all CubeSat missions and associated spacecraft through December 31, 2015, except where specifically noted. The most widely used sources are based on the following references: M. Swartwout, CubeSat Database, https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database#refs, adjusted and updated by the committee; Gunter's Space Page, http://space.skyrocket.de/doc_sat/cubesat.htm; and Earth Observation Portal Satellite Mission Database, https://directory.eoportal.org/web/eoportal/satellite-missions. Data from these public sources were adjusted and updated by the committee with assistance from NASA and NSF within this report to correct errors and to account for missing information.

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Achieving Science with CubeSats: Thinking Inside the Box

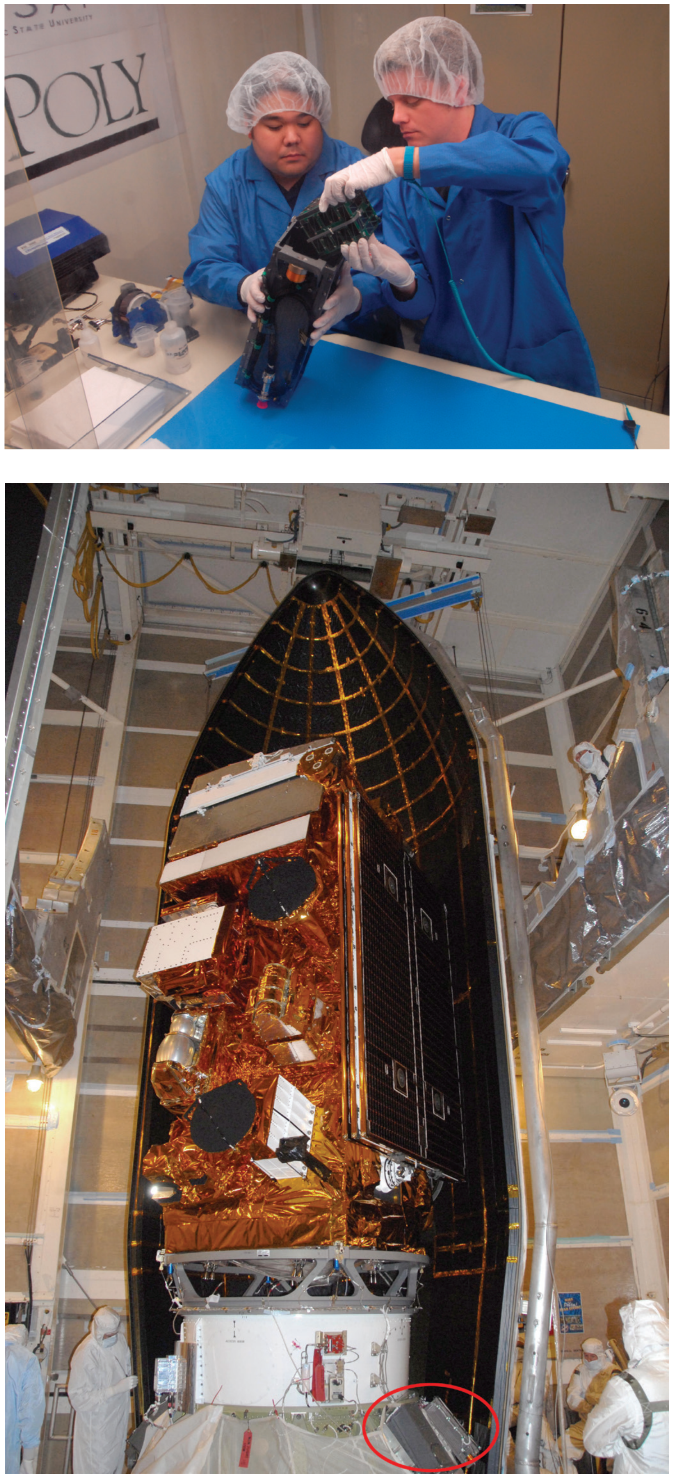

FIGURE 1.2 *Top:* CubeSats placed into P-POD deployers. *Bottom:* Delta-2 rocket fairing with the Suomi-NPP spacecraft and the integrated P-POD deployers (inside red circle) for NASA's CubeSat Launch Initiative ELaNa-3 mission (Educational Launch of Nanosatellites). A total of three deployers contain five CubeSat projects. SOURCE: *Top:* Courtesy of U.S. Air Force photo/Jerry E. Clemens, Jr. *Bottom:* Courtesy of NASA/Don Kososka, VAFB.

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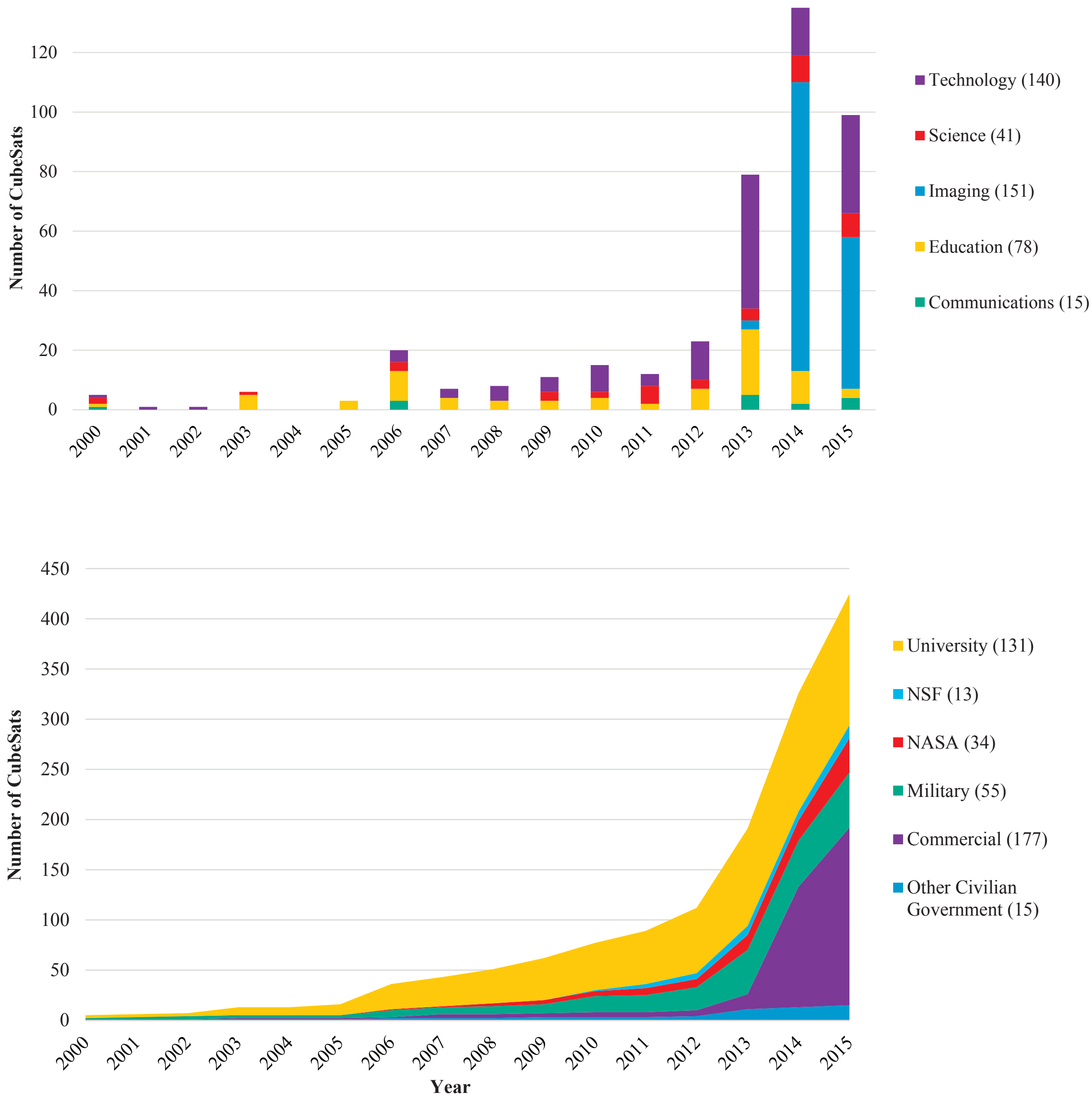

FIGURE 1.3 *Top:* The number of CubeSats launched per year by mission type. *Bottom:* The cumulative number of CubeSats launched by organization. The sudden rise of CubeSat launches in 2013 is from all mission types and provider classes, and the rises in 2014 and 2015 are primarily for the imaging CubeSat constellation by Planet Labs (commercial provider). Data include 2000-2002 OPAL picosatellites characteristic of, but developed prior to, the CubeSat standard. SOURCE: Data from M. Swartwout, St. Louis University, "CubeSat Database," PistachioTables 2.6.3, February 2016, https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database#refs, adjusted and updated by the committee.

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GROWTH OF THE COMMUNITY

The primary conferences regarding CubeSats have generally been the CubeSat Developer's Workshop, held annually in April at Cal Poly; the AIAA/USU Conference on Small Satellites; the 4S Symposium: Small Satellite Systems and Services; and the European CubeSat Symposium. Although the CubeSat Developer's Workshop and the Conference on Small Satellites will enter their 13th and 30th years, respectively, the number of new CubeSat meetings throughout the world has grown both in number and in attendance. Furthermore, specific meetings addressing ongoing and proposed CubeSat science have been introduced, such as the NSF 2011 Workshop on CubeSats for GEM and CEDAR Science, along with other GEM/CEDAR workshops, that represent important venues for the geosciences community to share their CubeSat flight results. Other meetings include the iCubeSat Workshops, Lunar Cubes Workshops, and Interplanetary Small Satellite Conferences that have been created to focus exclusively on beyond-low Earth orbit (LEO) science exploration and technology maturation with CubeSats. Furthermore, major scientific meetings have now incorporated CubeSats as part of the scientific agenda. The American Geophysical Union (AGU) had a total of 189 CubeSat-related oral and poster presentations from 2001-2015. Only 3 submissions to AGU were found from 2001-2008, and the first dedicated science session on "The Scientific Promise of Nanosatellites and CubeSats to Advance Geospace and Upper Atmospheric Science" was held in 2009 where a total of 31 topics were presented. This trend has increased with a total of 52 presentations at the 2015 AGU Fall meeting, representing the largest number to date, including a NASA-organized session under the theme of Disruptive Technologies in Space called "Taking SmallSats to the Next Level, Enabling New Science." Other science meetings, such as the Lunar and Planetary Science Conference and the American Astronomical Society have also held a growing number of CubeSat sessions with broad participation.

An illustration of the growth of the community is the attendance statistic at the Utah Conference on Small Satellites, the leading conference for CubeSats and other small satellite platforms, which has tripled from 600 prior to the launch of the first P-POD CubeSat in 2003 to more than 1,800 in 2015, as shown in Figure 1.4. While the numbers do not necessarily reflect only growth of the CubeSat community, according to the conference organizers, the rapid upticks of interest in 2003 and in 2013 were related to a broader engagement of science and engineering groups and then commercial entities, respectively.

Student interest in CubeSats has moved from a community almost entirely of undergraduate students—mostly from engineering-focused departments at U.S. universities—to nearly 50 percent graduate students who use these platforms for engineering and scientific research. In fact, the Conference on Small Satellites provides a research award for such graduate students, judged by sets of referees from private industry and federal agencies. Furthermore, the fraction of industry attendees has increased over time as well; several of the start-up entrepreneurs and investors registering as "self" are using the conference to assess technology and market trends.

Given their affordability and short development life cycles, CubeSats have attracted global interest. For many countries, such as Uruguay, CubeSats are the country's first forays into space. However, as Figure 1.5 illustrates, the United States currently is the dominant player in the community. Thirty-six different countries (led by Japan, Germany, and Denmark) have launched at least one CubeSat. For most of these countries, the numbers are in the single digits but are expected to grow. Figure 1.5 also shows the addition of countries by year (excluding the United States for clarity). The first countries outside the United States to launch a CubeSat were Canada, Denmark, and Japan (in 2003).

An interesting observation with respect to global launches of CubeSats is that although commercial actors now dominate the United States, for other countries, the launches are almost entirely led by universities.

THE CURRENT NSF AND NASA CUBESAT PROGRAMS

Pioneering CubeSats funded by NASA from 2006-2010, such as GeneSat, focused on space biology and were developed by NASA's Ames Research Center and partner organizations. Following these initial NASA-funded developments, NSF has since led the nation in the development of science-driven CubeSat programs and, to date, provides a large fraction of the flight heritage of science-driven missions. The NSF program of CubeSat-based science missions for geospace and atmospheric research issued a first call for proposals in 2008. Thus far, five

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Achieving Science with CubeSats: Thinking Inside the Box

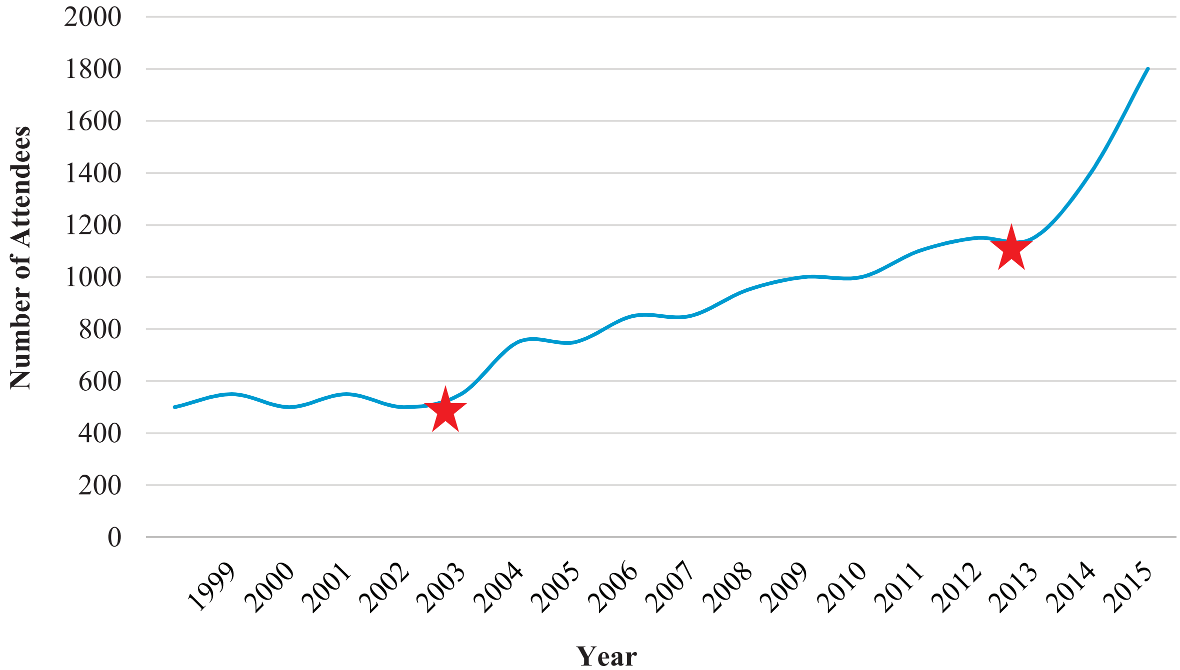

FIGURE 1.4 Attendance at the AIAA/USU Conference on Small Satellites, considered the leading conference for CubeSat and small spacecraft systems, has tripled over time. The upturn in participation in 2003 indicates when mostly university-based CubeSat-focused teams began participating; 2013 indicates the inception of CubeSat commercial players affecting the attendance. Participation from NASA and other federal agencies also increased. SOURCE: Attendance data courtesy of USU Conference on Small Satellites organizers.

such calls have been issued, and the next solicitation is expected in the summer or fall of 2016. The number of selected CubeSats is limited by the available budget, which is approximately $1.4 million/year, although supplemental funding from industry and other sources have contributed support. As of the end of 2015, NSF has launched 8 missions for a total of 13 CubeSats. According to the NSF program manager, all but one selected mission has been successful at providing science measurements so far, although three of them required a reflight to address a spacecraft anomaly. This includes Radio Aurora Explorer (RAX)-1, which was reflown as the RAX-2 mission (see Figure 1.7). NSF has 7 missions with a total of 11 CubeSats in development. It is noteworthy how well NSF's CubeSat program aligns with the first recommendation of the 2013 decadal survey *Solar and Space Physics: A Science for a Technological Society*.[9] The survey recommended the implementation of the DRIVE[10] initiative, which called out very small satellite flight opportunities, including CubeSats, as a growth area for both NSF and NASA. (See Chapter 4, "Solar and Space Physics" for details.)

The next significant increase for science-based CubeSat missions occurred in 2013, when NASA provided multiple opportunities for the space science community to propose science-based CubeSat missions. During this period, a significant increase in launches also occurred for NASA technology and NSF science CubeSats. As of the end of 2015, NASA has launched 18 missions for a total of 34 CubeSats with science and technology objectives. NASA has 39 missions for a total of 46 CubeSats in development (Table 1.2). Of the total NASA CubeSat missions, 33 percent have goals that are science-based and 67 percent have goals that are technology-based. These

[9] NRC, 2013, *Solar and Space Physics: A Science for a Technological Society*, The National Academies Press, Washington, D.C.
[10] DRIVE stands for diversify, realize, integrate, venture, and educate.

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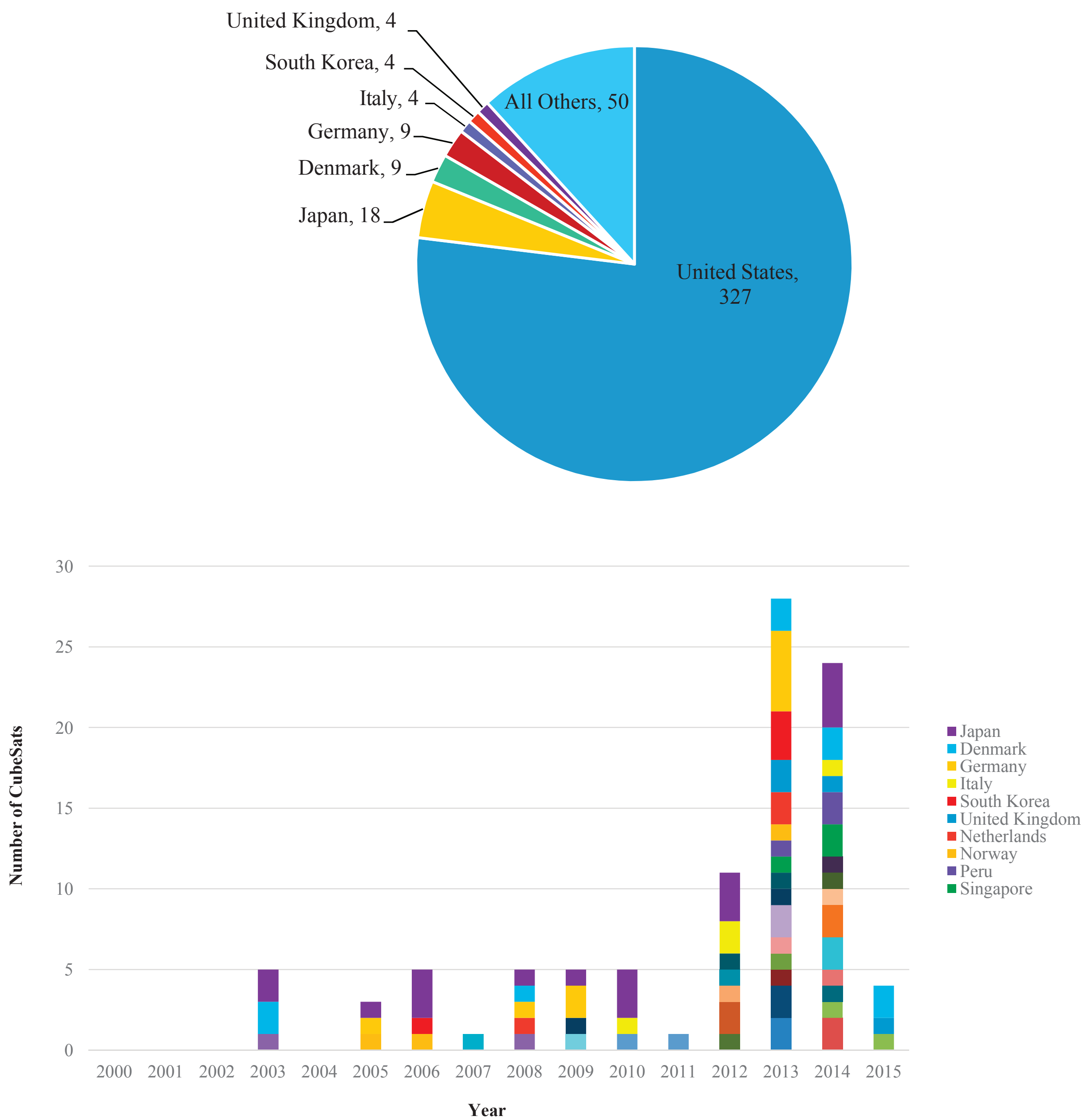

FIGURE 1.5 Number of CubeSats launched by country *(top)* and the number of CubeSats launched by year from 2000 through 2015, not including the United States *(bottom)*. Only the top 10 countries by number of CubeSats launched are shown in the key; however, all countries other than the United States (35 total) are represented in the figure. SOURCE: Data from M. Swartwout, St. Louis University, "CubeSat Database," PistachioTables 2.6.3, February 2016, https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database#refs, adjusted and updated by the committee.

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TABLE 1.2 Summary of CubeSat Statistics for NASA and NSF that Launched in 2006-2015 or are in Development for Launch 2016-2018+

Launch Dates	NASA Science	NASA Technology	NSF Science	Total
2006-2015	6 CubeSats (6 missions)	28 (12)	13 (8)	47 (26)
Planned 2016-2018+	14 (13)	32 (26)	11 (7)	57 (46)
Total	20 (19)	60 (38)	24 (15)	104 (72)

CubeSats (number of missions) by Science Category

Launch Dates	Technology	Astronomy and Astrophysics	Biological and Physical Science	Earth Science	Solar and Space Physics	Planetary Science	Total
2006-2015	28 (12)	0 (0)	4 (4)	1 (1)	14 (9)	0 (0)	47 (26)
Planned 2016-2018+	32 (26)	1 (1)	4 (3)	7 (3)	10 (10)	3 (3)	57 (46)
Total	60 (38)	1 (1)	8 (7)	8 (4)	24 (19)	3 (3)	104 (72)

NOTE: Some missions consist of more than one CubeSat, or the original single CubeSat was reflown. These CubeSat statistics include all launched missions, including those that were lost due to launch failures. Launch dates from 2016-2018 are presented as a forecast of future activities.

projects span all four NASA Science Mission Directorate (SMD) science divisions, the Space Technology Mission Directorate (STMD), the Human Exploration and Operations Mission Directorate (HEOMD), and NASA centers. A total of 104 CubeSat spacecraft have launched or are in development under NASA and NSF support through the year 2018 (see also Table 1.3 in the section "Future NASA CubeSat Programs").[11]

Figure 1.6 shows the 47 total NASA and NSF CubeSats through 2015 where, cumulatively, 19 focused explicitly on science objectives and 28 were technology-driven across both agencies. Examining these 19 science CubeSats from NASA and NSF, there were 14 that focused on solar and space physics, 4 on biological and physical science, 1 on Earth science, and none in astronomy and astrophysics or planetary science through 2015. NASA's current emphasis on technology is shown through the 28 CubeSats launched through 2015, but they were driven by SMD science themes. All of the NSF missions were science-focused. In preparation for launches from 2016 to 2018, NASA has 32 technology-focused and 14 science-focused CubeSats in development, and NSF is sponsoring 11 science-focused CubeSats. Of the 25 science CubeSats planned from 2016 to 2018 by NASA and NSF, 1 is in astronomy and astrophysics, 4 are in space/microgravity science, 7 are in Earth science, 10 are in solar and space physics, and 3 are in planetary science, where a number of these CubeSats will travel beyond LEO. Selected NASA- and NSF-funded CubeSats, shown in Figure 1.7, also illustrate some of the diversity in CubeSat science objectives.

NASA CubeSat programs are spread among STMD, SMD, and HEOMD and thus have a range of program objectives. STMD describes the objectives for its CubeSat program as "focused technology development and demonstration in relevant space environments," furthering its existing objectives to develop flight hardware for use by the other mission directorates. STMD missions are competitively selected through solicitations from the Small Spacecraft Technology Program, and the directorate has funded 8 technology CubeSat missions (23 spacecraft) to date.

SMD describes its CubeSat vision as "cutting edge science, instrument technologies, and student flight investigations." CubeSat programs are operated individually by each of SMD's science divisions and solicited by NASA Research Announcements through the Research Opportunities in Space and Earth Sciences (ROSES) system. In 2013, SMD received a new budget line item of $5 million per year as an additional means to support CubeSat sci-

[11] Science categories were decided based upon funding programs and information available in the public domain without contacting each CubeSat team.

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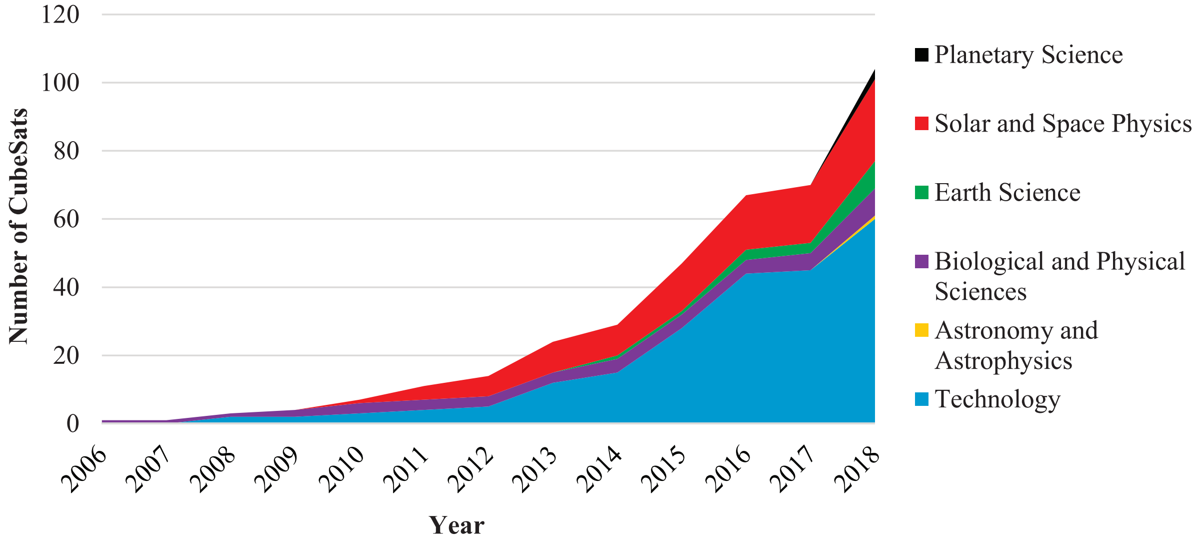

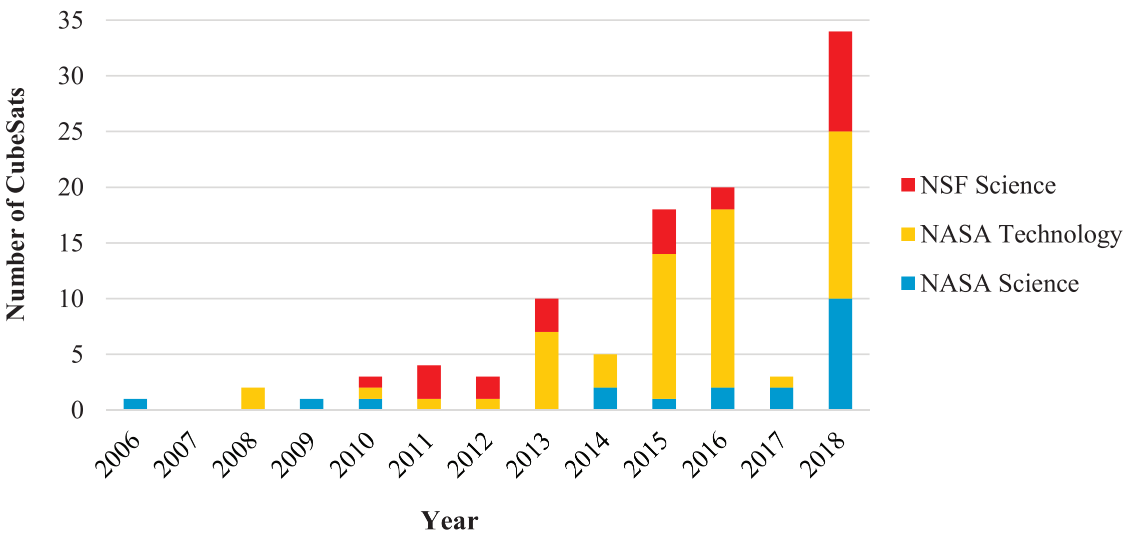

FIGURE 1.6 *Top:* Cumulative graph, by specific technology and science focus areas, of the 104 NASA- and NSF-funded CubeSat spacecraft launched and planned through 2018. As of the end of 2015, no CubeSats have been flown for planetary science or astronomy and astrophysics. *Bottom:* Distribution, by launch year, of the 20 NASA science, 60 NASA technology, and 24 NSF-funded spacecraft launched and planned through 2018. SOURCE: Data from M. Swartwout, St. Louis University, "CubeSat Database," PistachioTables 2.6.3, February 2016, https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database#refs, adjusted and updated by the committee.

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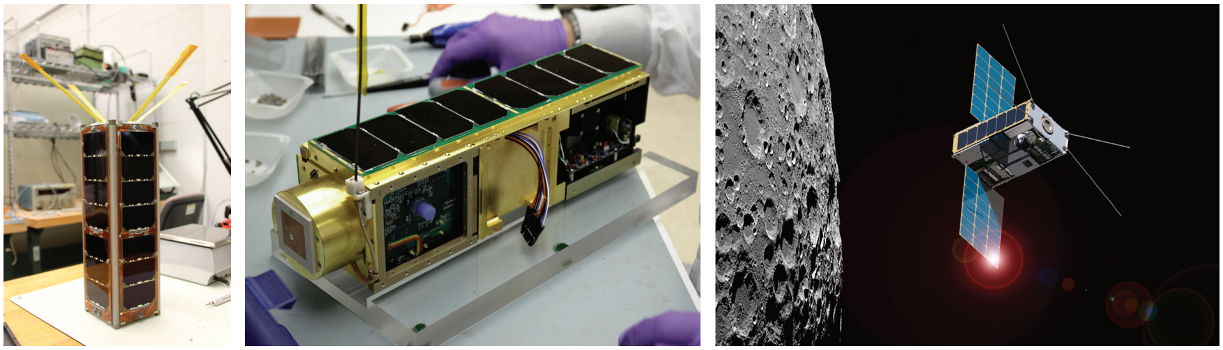

FIGURE 1.7 Various CubeSat science examples. RAX-2, the Radio Aurora Explorer project, used ground-based radar pulses to measure auroral scatter and reveal the structure of plasma in Earth's ionosphere in high resolution. O/OREOS contained two experiments to study the effects of the microgravity and radiation environment of Earth orbit on microorganisms and organic molecules. Lunar IceCube will search for water ice deposits on the lunar surface using a compact infrared spectrometer called BIRCHES. SOURCE: *RAX-2:* Courtesy of University of Michigan/Michigan Exploration Lab. *O/OREOS:* Courtesy of NASA/Dominic Hart. *Lunar IceCube:* Courtesy of Morehead State University.

ence and technology validation missions.[12] To date, the Earth Science Division has funded 13 CubeSat missions (14 spacecraft), all for technology development with the goal to enhance capabilities for future small science missions. The Heliophysics Science Division has funded 7 CubeSat missions (7 spacecraft), all for science, including ELFIN jointly with NSF.[13] The Planetary Science Division (PSD), which currently includes astrobiology within its purview, has funded 5 CubeSat missions (7 spacecraft), including two spacecraft under the SIMPLEx program and the remaining five under direct PSD support. SIMPLEx separately awarded three additional CubeSat projects for ground-based technology development. The Astrophysics Science Division only awarded one science CubeSat thus far, through the Astrophysics Research and Analysis (APRA) program.

HEOMD competitively makes launch opportunities available to institutions that are NASA centers, U.S. not-for-profit organizations, or U.S.-accredited educational institutions via the CubeSat Launch Initiative (CSLI). CSLI, which has successfully launched 43 CubeSats as of the end of 2015,[14] identifies opportunities for CubeSat launches as secondary payloads and assists with the integration of CubeSats aboard launch vehicles. HEOMD also directly sponsors CubeSats under the Advanced Exploration Systems (AES) program, which has funded 9 CubeSat missions (10 spacecraft) to date that support science in response to human exploration objectives such as BioSentinel, Lunar Flashlight, and others. HEOMD is also working with the AES program to offer the opportunity to deploy CubeSats into deep space aboard the inaugural launch of the Space Launch System planned in 2018.

NASA's STMD Centennial Challenge Program has also sponsored the Cube Quest Challenge, which offers $5.5 million to teams that can successfully design and build one or multiple CubeSats (with a total volume of 6U) that can demonstrate advanced operations near and beyond the Moon. Organized across a series of three stages (Ground Tournaments, Deep Space Derby, and Lunar Derby), the objective of the challenge is to incentivize innovation in the development of CubeSat capabilities in communication, propulsion, navigation, and durability to enable future deep space missions. Deep Space Derby and Lunar Derby prizes will be awarded based on metrics for burst data rate, largest aggregate data volume, and spacecraft longevity at a minimum range of 4 million km (Deep Space) or lunar orbit (Lunar), respectively. Deep Space Derby will also award prizes for the farthest com-

[12] This does not include the TROPICS 12 CubeSat constellation science mission awarded through the Earth Venture Instruments-3 solicitation announced in March 2016.

[13] The ELFIN (Electron Losses and Fields Investigation) mission, originally a part of the University Nanosatellite Program, is now funded jointly by NASA and NSF.

[14] CSLI has successfully integrated 49 CubeSats as of December 2015, but 6 of those were lost due to the launch vehicle failures of the 2011 Taurus XL (3), 2014 Antares/Cygnus (1), and 2015 Super Strypi (2).

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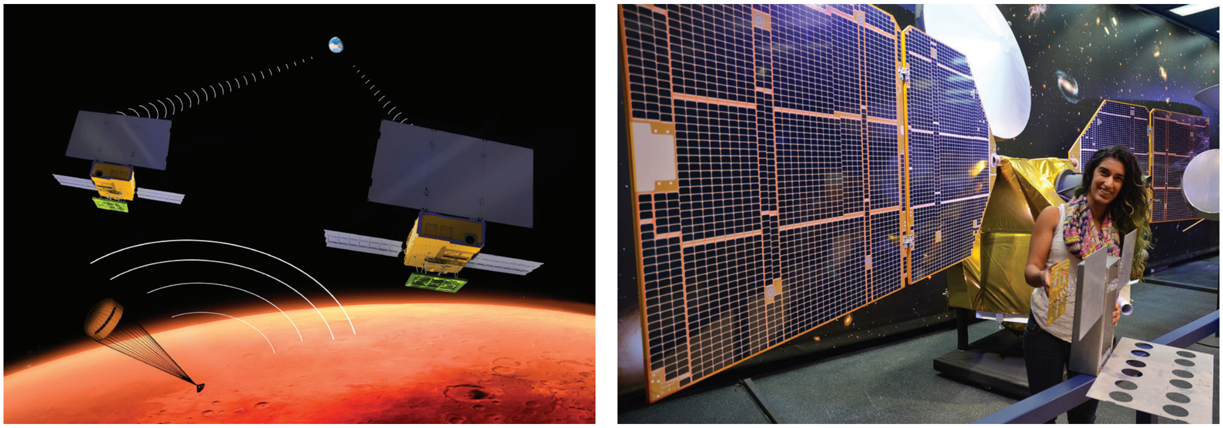

FIGURE 1.8 This illustration shows the planned MarCO CubeSats flying past Mars as they receive the UHF entry-descent-landing (EDL) telemetry from the InSight mission. MarCO will act as a bent-pipe relay to transmit the UHF signal back to Earth in the X-band. The full-scale 6U MarCO model is compared to the 1/2-scale Mars Reconnaissance Orbiter (MRO) model at the Jet Propulsion Laboratory. SOURCE: Courtesy of NASA/JPL-Caltech.

munication from Earth, while the Lunar Derby will award prizes for achieving at least one verifiable propulsive lunar orbit. Cube Quest teams may be offered launch opportunities as secondary payloads aboard the NASA Orion (EM-1) spacecraft atop the Space Launch System (planned for launch no earlier than 2018), provided a variety of conditions are satisfied as described within the Cube Quest Challenge Operations and Rules document.

FUTURE NASA CUBESAT PROGRAMS

The growth in CubeSat usage as a tool for education, technology development, and science is unlikely to abate in the near future. For example, two 6U interplanetary CubeSats, MarCO-1 and MarCO-2, are expected to launch on the same Atlas-V launch vehicle with NASA's InSight lander at the 2018 launch opportunity (Figure 1.8). These spacecraft are designed to support a real-time 8 kbps UHF to X-band bent-pipe relay of transmissions from InSight on entry-descent-landing through the Mars atmosphere, demonstrating new technologies (e.g., deep space telecom, navigation and tracking via NASA's Deep Space Network, and propulsion) and providing auxiliary communications—potentially enabling CubeSat applications beyond Earth orbit. EM-1, the maiden flight of the Space Launch System, is also expected to include a number of CubeSats as secondary payloads, lofting them to lunar and heliocentric orbits for a variety of scientific purposes and technology demonstrations. Furthermore, 10 universities are currently exploring CubeSat science mission concepts that could potentially enhance the NASA Europa Clipper mission concept under study. These, and other future opportunities, are partially enabled by accelerated industry growth, which will likely lead to enhanced technological capabilities, standards, and, ultimately, science.

Table 1.3 summarizes all known NASA and NSF CubeSat missions and associated spacecraft per mission. Although universities, industry, and NASA centers, including JPL, lead the NASA missions listed in Table 1.3, the missions are classified by the program sponsor, with a separate category for missions funded internally by NASA centers or JPL. Undoubtedly, there are many science and technology mission proposals beyond those that are represented in Table 1.3 that have not been selected for funding.

There has been a rapid growth of CubeSat programs across NASA and in several NASA centers. Each of the four Science Mission Directorate science divisions, at least two other directorates, and at least five NASA centers are developing CubeSat missions. Additionally, some of the science divisions and centers may have more than one funding opportunity for CubeSats. With the exception of the CubeSat Launch Initiative, CubeSat activities within NASA's programs have remained largely independent.

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Achieving Science with CubeSats: Thinking Inside the Box

TABLE 1.3 Known CubeSat Projects Funded by NASA or the National Science Foundation During Launch Years 2006-2018

Funding Program	CubeSat Missions Launched	CubeSat Missions Planned	Launch Years
NASA			
Heliophysics	MinXSS	CeREs, CuSP, ELFIN,[a] HeDI, SORTIE, TBEx	2015-2018
Earth Science	GRIFEX, IPEX, MCubed/COVE (2)	CIRAS, CIRiS, CubeRRT, HARP, IceCube, LMPC, MiRaTA, RainCube, RAVAN, TEMPEST-D	2011-2018
Planetary Science	O/OREOS	INSPIRE (2), LunaH-Map, MarCO (2), Q-PACE Technology Development Only: DAVID, HALO, MMO	2010-2018
Astrophysics		HaloSat	2018
Advanced Exploration Systems and Human Exploration and Operations	GeneSat, PharmaSat, SporeSat (2)	BioSentinel, EcAMSat, Lunar Flashlight, Lunar IceCube, NEA Scout, Skyfire	2006-2018
Space Technology	EDSN (8),[b] NODeS (2), OCSD-1, PhoneSat (5)	CPOD (2), CSUNSat-1, ISARA, iSAT, OCSD (2)	2013-2017
Centers (Internal)			2008-2018
Ames Research Center	PreSat,[c] TechEdSat (3)	KickSat, TechEdSat-5	
Ames Research Center and Marshall Space Flight Center	NanoSail-D (2)		
Goddard Space Flight Center		CANYVAL-X, Dellingr, ESCAPE, RBLE	
Jet Propulsion Laboratory	LMRST, RACE[d]	ASTERIA, MITEE	
Kennedy Space Center		Cryocube, StangSat	
NASA IV&V Facility		STF-1	
National Science Foundation			
	CADRE, CSSWE, CINEMA-1, DICE (2), ExoCube, FIREBIRD (4), Firefly, RAX (2)	ELFIN,[a] ISX, IT-SPINS, LAICE, OPAL, QBUS/QB50 (4), TRYAD (2)	2010-2018

NOTE: NASA has sponsored 57 missions (80 CubeSats total) and NSF has sponsored 15 missions (24 CubeSats total) for a total of 72 missions with 104 CubeSats across NASA and NSF.

CubeSats are counted by individual spacecraft, but missions are counted once even if they involve a reflight or multiple spacecraft. Numbers in parentheses after a mission name indicate the total number of CubeSat spacecraft counted in the mission. Acronyms are defined in Appendix E.

[a] The ELFIN (Electron Losses and Fields Investigation) mission, originally a part of the University Nanosatellite Program, is now funded jointly by NASA and NSF.

[b] Super Strypi launch failure.

[c] Falcon-1 launch failure.

[d] Antares launch failure.

OTHER U.S. GOVERNMENT PROGRAMS

In addition to CubeSat work within NSF, NASA, universities, and industry, other government organizations have been active in developing, sponsoring, and launching these systems. The University Nanosatellite Program (UNP) (see Chapter 4), administrated by the Air Force Office of Scientific Research (AFOSR), the Air Force Research Laboratory (AFRL), Space Missile Command (SMC), and the Department of Defense (DoD) Space Test

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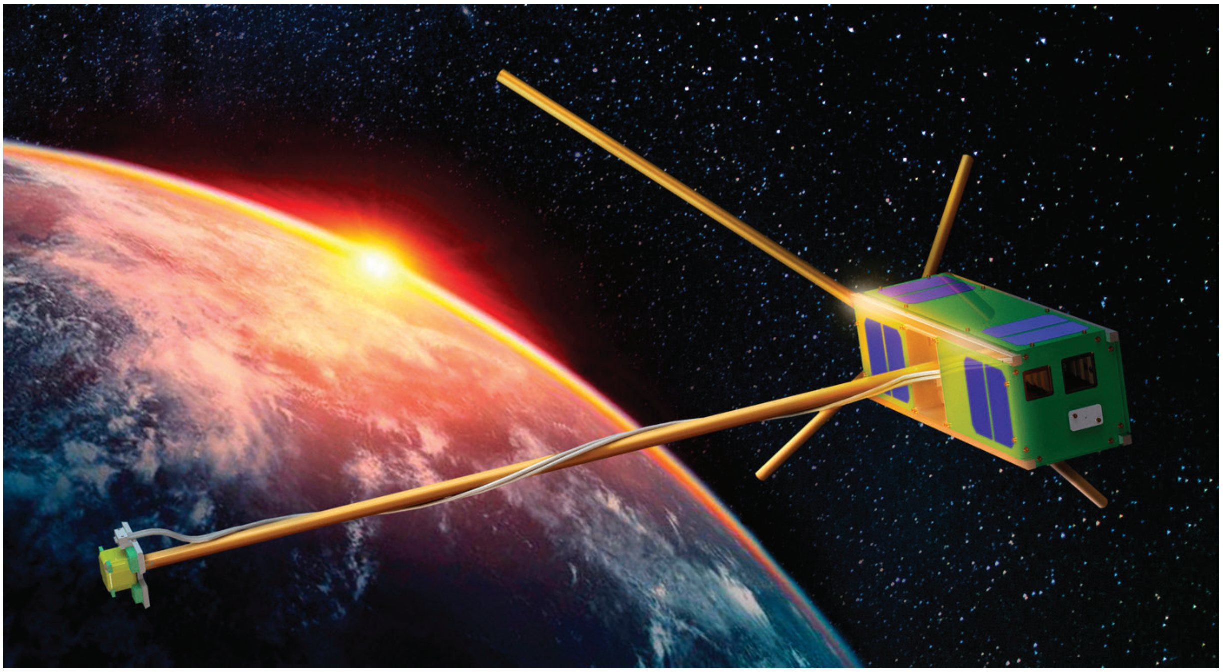

FIGURE 1.9 The ELFIN CubeSat was part of the University Nanosatellite Program. SOURCE: Courtesy of the University of California, Los Angeles.

Program (STP), provides a multiyear program for students to design, build, and fly a small satellite. Many of these STP-funded missions have focused on flying new technologies, but there have been science selections as well. The University of Colorado's PolarCube, for example, will fly a radiometer to perform tropospheric temperature soundings at 118 GHz O_2 emission resonance. Furthermore. ELFIN from the University of California, Los Angeles, will investigate the mechanisms responsible for the loss of relativistic electrons from the radiation belts (Figure 1.9).

The National Reconnaissance Office (NRO) has also been an active participant developing CubeSat buses, providing rideshare opportunities to space with NRO primary payloads, and developing CubeSat missions for NRO programs. Indeed, NASA CSLI selected CubeSats have regularly been deployed in space on NRO launches. In 2007, NRO, the Air Force, and NASA collaboratively determined that CubeSats could have a role in supporting government applications. Shortly afterward, in 2008, NRO's Advanced Systems and Technology Directorate provided funding to advance CubeSat subsystem and technology payloads. While the specifics of NRO's developments are not in the public domain, NRO has partnered with numerous organizations, indirectly enabling capabilities that have supported the work of others for technology validation and science measurements. This includes 16 government agencies, 5 major academic partners, and 6 commercial partners to date.

Additional government agencies, as discussed in Chapter 6, support CubeSat missions by providing a legal and regulatory framework. For example, CubeSat operators are required to obtain radio licenses, either from the National Telecommunications and Information Administration (NTIA) for federal government CubeSats or from the Federal Communications Commission (FCC) for nonfederal CubeSats. Under Title 51 of the United States Code, "National and Commercial Space Programs" (P.L. 111-314), private CubeSats involved in remote sensing need to apply for a license from the National Oceanic and Atmospheric Administration (NOAA). In addition, the Air Force Joint Space Operations Center (JSpOC) has provided the website spacetrack.org for the community to acquire orbital position data for identification and tracking purposes of CubeSats in low Earth orbit. This has been a valuable, free resource to ground operation teams and to the worldwide community of HAM (handheld amateur radio) radio operators that often participate in tracking and decoding telemetry beacon transmissions from

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Achieving Science with CubeSats: Thinking Inside the Box

CubeSats worldwide. Although the JSpOC capabilities were not originally designed for this purpose, their service has directly helped enable the growth of CubeSats for Earth exploration missions.

CUBESAT SUCCESS AND RELIABILITY

During the course of this study, the committee heard a wide range of impressions about the success rate for CubeSats and whether their reliability has improved since their early use as educational tools. Whether or not a CubeSat achieves success is based on meeting mission objectives that can encompass science, technology, and education. For the purposes of this analysis, a mission is defined as a full success when the CubeSat has operated in-orbit nominally and has completed its mission objectives. A mission is defined as a partial success when the CubeSat has completed commissioning, is in primary operations, and is taking actions to achieve primary mission objectives.

An analysis of all CubeSats launched through 2015 indicates that 67 percent of them have been considered successful in orbit if they achieved full success (33 percent) or partial success (34 percent) criteria (Figure 1.10). This average 67 percent success rate for all CubeSats should be considered in the context of the expected reliability design goals for NASA Class C/D missions at ~80 percent and NASA Class A/B and NOAA operational missions at ~90 percent. With concerns about the lower reliability for CubeSats, an effective design practice often adopted is a "fly-learn-refly" approach (used with Aerospace Corporation and also the NSF CubeSat program), in which two flight models are developed and the second flight model is modified and launched if any issues arise during the first flight. This CubeSat development approach may, in part, explain why CubeSat missions in the past 8 years (2008-2015) have been significantly more successful (full and partial success), at 71 percent, than in the first 8 years (2000-2007), at 35 percent.

As perhaps expected, education-only CubeSats have had a lower success rate of 45 percent for in-orbit performance compared to all CubeSats. When used as an educational tool, the science or technology objectives of CubeSat missions are not usually considered the highest priority because most of the learning objectives are achieved during the designing, building, and testing of the CubeSat. While the educational CubeSats may not be listed as successful by the above definition of success, largely based on in-orbit performance, these CubeSats are successful in meeting their educational objectives and play an important role in training the next generation of space engineers and scientists.

The fly-learn-refly approach also seems justifiable from the analysis of small satellite success rates reported by Richardson et al.[15] The overall success rate for their sample of small satellites was approximately 84 percent, as defined as the number of CubeSats to be fully successful and half the number of CubeSats that have partial success. The study showed that there was no significant difference between CubeSats and small satellites that are not consistent with the CubeSat form factor. The most important predictor for success in this study was the experience of the team. Richardson et al. also indicated that the first satellite built by a development team has a success rate of approximately 72 percent and that by the time the team had developed more than five spacecraft, mission success was achieved in an average of 93 percent of all cases.

It is worthwhile to analyze the 15 NSF CubeSat science missions separately. The NSF CubeSats launched prior to September 2015 include 8 CubeSat missions (13 spacecraft) with involvement from 14 different universities. Of these NSF CubeSat spacecraft launched so far, none have been a complete failure; that is, all of them have returned some science data. However, the RAX-1, CINEMA-1, and Firefly CubeSats have only fulfilled some of their mission objectives due to a power issue for RAX-1 and communication issues for CINEMA-1 and Firefly. The ExoCube CubeSat mission also experienced a communication problem, and while larger receiver antennas on the ground allowed for receipt of some magnetometer data, it is considered unsuccessful until the team demonstrates new science results from their mission. The RAX-2, DICE 1 and 2, CSSWE, and FIREBIRD 1, 2, 3, and 4 have had full mission success, thus representing 8 of the 12 CubeSats (66 percent) that have deployed into

[15] G. Richardson, K. Schmitt, M. Covert, and C. Rogers, 2015, "Small Satellite Trends 2009-2013," *Proceedings of the AIAA/USU Conference on Small Satellites*, Technical Session VII: Opportunities, Trends and Initiatives, SSC15-VII-3, http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3212&context=smallsat.

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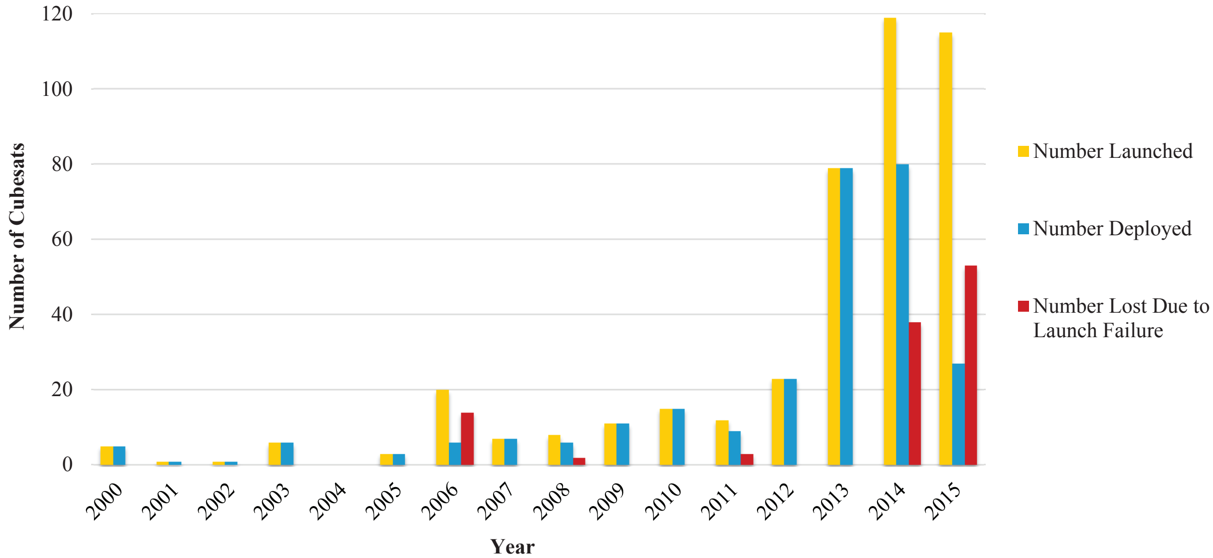

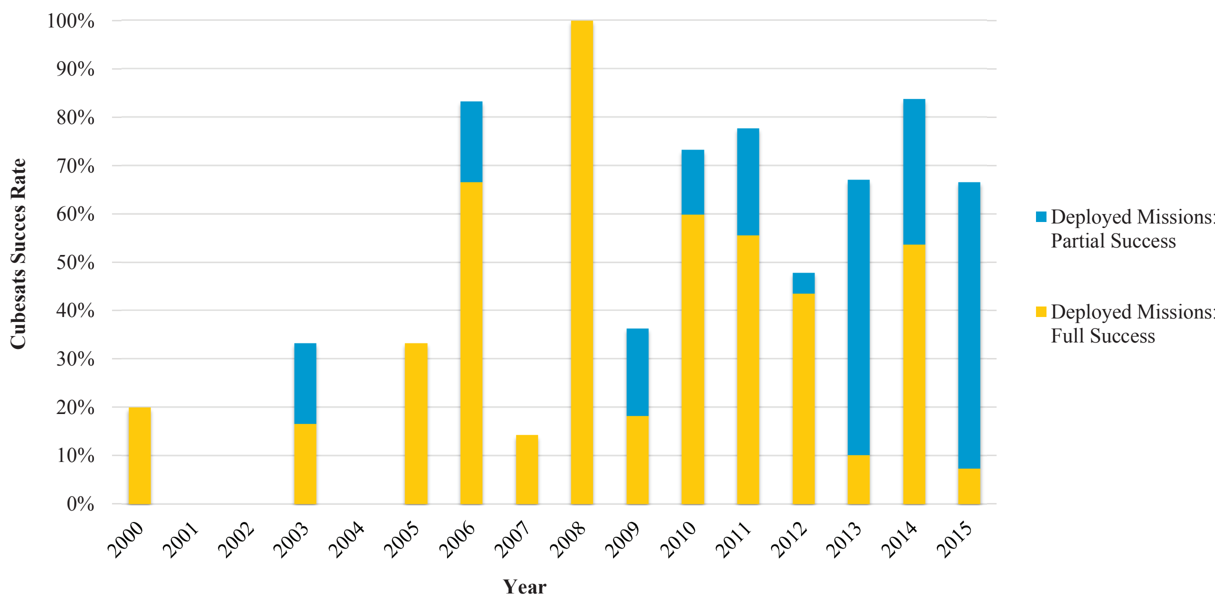

FIGURE 1.10 The number of launched CubeSats has increased steadily through 2012, followed by a significant increase in 2013 (top panel). Many CubeSats did not even have the chance of deployment in 2014 and 2015 due to launch vehicle failures those years. The success rate for the deployed CubeSats is shown in the bottom panel. A mission is defined as a full success when the CubeSat has operated in-orbit nominally and has completed its mission objectives. A mission is defined as a partial success when the CubeSat has completed commissioning, is in primary operations, and is taking actions to achieve primary mission objectives. SOURCE: Data from M. Swartwout, St. Louis University, “CubeSat Database,” PistachioTables 2.6.3, February 2016, https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database#refs, adjusted and updated by the committee.

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Achieving Science with CubeSats: Thinking Inside the Box

orbit after launch with a full success rate.[16] The success rate, which meets partial and full success criteria, for the NSF CubeSats (including reflights) is at 11 of 12 (92 percent). For NASA science CubeSats, the success rate (partial and full success criteria) is 83 percent through 2015. In the committee's judgment, the strong motivation for a successful mission—for the sake of science as well as adequate funding to address any preflight issues or risks—are likely contributing to these high success rates for the NSF and NASA CubeSat-based science missions.

[16] Note that 12 of the 13 NSF CubeSats that have launched also deployed into space, but CADRE (launched in December 2015) is awaiting deployment from the ISS in 2016.

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2

CubeSats—A Disruptive Innovation

Technological innovation and the resulting scientific impact can relate to each other in a nonobvious way. It is obvious that a better computer can solve more complicated calculations, enabling better models to be run, which hopefully leads to more scientific insights. Thus, increased science impact can directly come from improved technology. There are, however, technology innovations that create a large impact in a nonobvious way: targeted application of technology can lead to new science, even if that technology performs at a lower level than the advanced technologies available. For example, a mass-spectrometer on a chip may have only 10 percent of the resolution and mass range of traditional instruments, but it can be carried on a balloon to make targeted measurements of pollution in places that traditional instruments cannot reach, leading to new science insights. Such targeted science applications often have huge commercial potential as well. It is the purpose of this chapter to introduce the theoretical foundation of disruptive innovation from innovation theory and to create a foundation for management recommendations later on.

In 1995, Clayton Christensen introduced the idea of disruptive innovation—distinguishing it from sustaining innovation—and defined it as the "process by which a product or service takes root initially in simple applications at the bottom of a market and then relentlessly moves up market, eventually displacing established competitors."[1] Figure 2.1 introduces the idea that has been used to describe many shifts in the economy, from the introduction of personal computers (that disrupted the mainframe computer industry), to cellular phones (that disrupted fixed line telephony), to smartphones (that continue disruption of multiple sectors, inter alia, computers, digital cameras, telephones, and GPS receivers). The term "disruptive" has also been misapplied, where any innovation that shakes up an industry or upsets previously successful incumbents is incorrectly called disruptive.

CubeSats meet many of the characteristics of a disruptive innovation. In this chapter, the committee discusses how and what that might mean for the future development of the platform.

CUBESATS AS A DISRUPTIVE PLATFORM

Disruptive innovations have unique characteristics that distinguish them from other types of innovation. At their start, for example, they have poorer performance than the current standard solution does. They are also significantly cheaper than is the status quo and target underserved or new applications or users. Their performance

[1] C. Christensen, "Disruptive Innovation," http://www.claytonchristensen.com/key-concepts/, accessed March 23, 2016; C. Christensen, 1997, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*, Harvard Business Review Press, Boston, Massachusetts.

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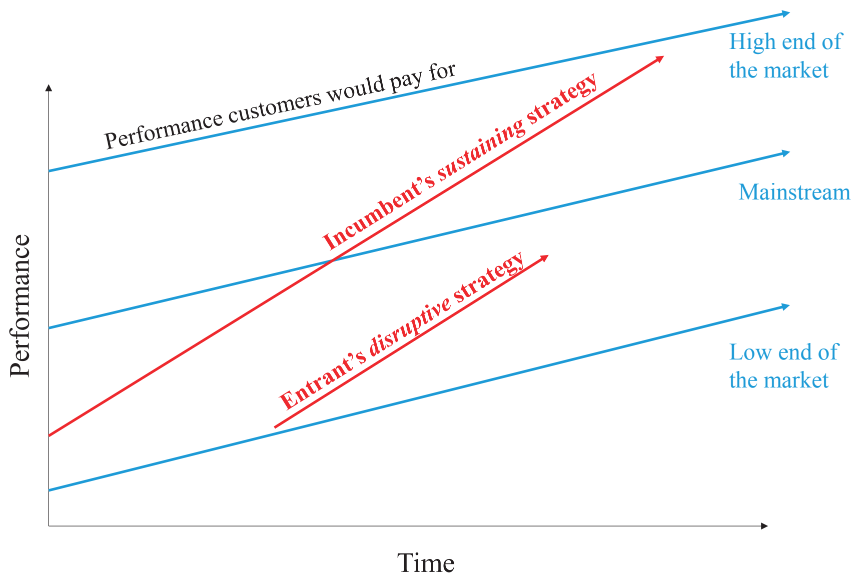

FIGURE 2.1 The theory of disruptive innovation. The natural evolution of a given technology over time is toward higher performance through sustaining innovations. Disruptive innovations start at the low end of performance, but can evolve toward higher performance over time. SOURCE: Adapted with permission from "What Is Disruptive Innovation?" by Clayton M. Christensen, Michael E. Raynor, and Rory McDonald, *Harvard Business Review*, December 2015. Copyright 2015 by Harvard Business Publishing; all rights reserved.

improves rapidly and at low cost. They are typically introduced by a nonmainstream player, are advanced by an enabling technology, and follow business models not typically followed by incumbents. Examining the CubeSat paradigm along these dimensions indicates that CubeSats may be a disruptive innovation in the satellite sector. If CubeSats are a disruptive technology, then that has implications for the best way to manage their growth.

- *At the start, has poorer performance than the status quo*. Just as the early cameras on mobile phones were inferior to digital cameras but improved over time, CubeSats began with a threadbare set of capabilities, but today those capabilities are beginning to improve as the technology matures and the number of users increases. Indeed, some of the earliest CubeSats served rather limited on-orbit functions other than "beeping" back telemetry.

Significantly cheaper than the status quo. While it has poorer performance, a mobile phone at about $500 provides users with a computing interface at a lower cost than for most computers. Similarly, although they are not as capable as traditional satellites, CubeSats are typically much cheaper than traditional satellites. Hardware for a basic Sputnik-type CubeSat can be purchased for only a few tens of thousands of dollars.

- *Targets underserved or new application/user.* Just as 3D printers are bringing in nontraditional manufacturers, such as members of the do-it-yourself "maker movement" as users, CubeSats are introducing students and other participants (e.g., information technology firms rather than aerospace firms) to space technology. TJ3Sat, for example, was the first satellite in history to be built by high school students.[2] CubeSats are also introducing new functionalities (such as the ability to "stop and stare" at one bright Sun-like star to search for transiting exoplanets) often not feasible with traditional satellites. Most of all, by virtue of being able to launch low-cost constellations and swarms comprising hundreds or even thousands of data collection platforms, CubeSats have the potential to introduce entirely new architectures and ways to conceptualize space science.

[2] Thomas Jefferson High School for Science and Technology, "CubeSat Experimental Satellite for Educational Outreach," https://www.tjhsst.edu/students/activities/tj3sat/, accessed March 23, 2016.

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Achieving Science with CubeSats: Thinking Inside the Box

- *Performance improves rapidly and at low cost*. Initially seen as a toy, 3D printers have seen speeds increase 500-fold. Another example of technologies improving rapidly is the PC company Compaq increasing its revenue more than tenfold and reaching parity with the industry leader, DEC, in only 12 years.[3] Similarly, CubeSats that began as platforms for education or technology demonstration are increasingly being sought to supplement and supplant traditional satellites and spacecraft. NASA's MarCO mission, for example, is an experimental capability designed to provide additional real-time relay communications to Earth from NASA's Mars-bound InSight mission during entry, descent, and landing.[4]
- *Typically introduced by a nonmainstream player.* Streaming video was not introduced by any of the existing players in the home video market, but by a start-up firm, Netflix. Similarly, CubeSats did not emerge from the research and development laboratories of the powerhouse space companies—Lockheed Martin, Boeing, and Northrup Grumman—or even cutting-edge government laboratories; they were first proposed by researchers at Stanford University and California Polytechnic State University (Cal Poly). Cal Poly, the institution where the CubeSat standard was created, was not a household name in the aerospace sector. All five of the winners of the first milestone of NASA's Cube Quest Challenge are entrepreneurial entities within universities or relatively unknown companies in the aerospace sector.
- *Typically advanced by an enabling technology.* Netflix streaming was propelled by ubiquitous broadband Internet service. Similarly, CubeSats are being helped along by advances in non-space-related terrestrial, commercial technology areas: software advances, processing power, data storage, camera technology, compression, and solar array efficiency.
- *Follow development models that are very different from those of incumbents*. The Apple iPhone disrupted the laptop sector by building a facilitated network connecting application developers with phone users. Similarly, CubeSat platforms are being developed by university-based and private-sector entrepreneurs using low-cost off-the-shelf components, small teams, rapid iterations, and high-risk postures. Planet Labs' CubeSats have gone through 12 generations of design since the firm was established in 2010, and the company claims that 20 percent of its CubeSats (called Doves) can fail in orbit without losing a meaningful amount of imaging capacity. This model is unprecedented in the risk-averse satellite sector.

As with other fields, the small size and standardized form factor and interfaces of CubeSats are key ingredients to accelerating innovation, rather than obstructing it.[5] Standardization, in particular, ensures that CubeSats can be easily inserted into launch vehicles, lowering the overall cost of integration and launch. Standardization also allows companies to develop subsystems, such as powerboards, that can be useful for many CubeSat missions.

It is important to note that disruptive innovation often does not and need not replace the mainstream technology. Laptops today do not replace high-performance computers at the Department of Energy (DOE), for example. Large DOE computers excel at complex computations and speed, while laptops excel at affordability and ease of use. Similarly, large spacecraft excel at large-scale investigations, when, for example, several instruments need to be collocated. CubeSats excel at simple, focused, or short-duration missions and missions that need to be low cost or that require multipoint measurements.

There are lessons to be drawn from the literature on managing disruptive innovations.[6] It can be difficult to manage disruptive innovations and traditional approaches in the same organization. Disruptive ideas prosper if

[3] C. Christensen, M. Raynor, and R. McDonald, What is disruptive innovation?, *Harvard Business Review*, December 2015, https://hbr.org/2015/12/what-is-disruptive-innovation.

[4] Jet Propulsion Laboratory, "Mars Cube One (MarCO)," http://www.jpl.nasa.gov/cubesat/missions/marco.php, accessed April 15, 2016.

[5] It is often believed that standards obstruct innovation. The literature on the topic, however, points to the opposite. See P. Swann, 2010, "The Economics of Standardization: An Update," https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/461419/The_Economics_of_Standardization_-_an_update_.pdf; K. Blind, 2013, "The Impact of Standardization and Standards on Innovation," https://www.nesta.org.uk/sites/default/files/the_impact_of_standardization_and_standards_on_innovation.pdf; K. Blind and S. Gauch, 2009, Research and standardization in nanotechnology: Evidence from Germany, *Journal of Technology Transfer* 34(3):320-342.

[6] Deloitte, 2013, *Public Sector, Disrupted: How Disruptive Innovation Can Help Government Achieve More for Less*, http://www2.deloitte.com/content/dam/Deloitte/global/Documents/Public-Sector/dttl-ps-publicsectordisrupted-08082013.pdf.

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there are champions within such organizations who allow for experimentation and risk-taking but, at the same time can also focus resources on promising applications, once their value becomes clear.[7]

IMPLICATIONS

CubeSats share many characteristics of disruptive innovations similar to innovations in other sectors (PCs in computing, 3D printing) in that they are initially more inexpensive than are traditional satellites, emerged outside the mainstream industry, target new capabilities or new users, and initially showed poor (but growing) performance.

The theory of disruptive innovation, therefore, provides some best practices with respect to enabling CubeSat innovations in support of science. A key element of disruptive innovation, and the principal reason for an often-unexpected evolutionary path, lies in the cultural tensions that arise from its development. A novel and innovative technology that is cheaper than are current systems is not always welcomed in organizations that are responsible for these status quo systems. For such innovations to live up to their potential, the management of disruptive innovations needs to be deliberate and cognizant of the issues that arise. Thus,

- CubeSat programs are likely to be best managed with a focus on decentralized development that enables innovation via a wide variety of approaches. At the same time, this management needs to identify and focus resources onto promising applications.
- At government agencies such as NASA, CubeSats may need a high-level champion who understands their potential importance as they evolve in capability and scope, recognizing that major breakthroughs can also emerge from outside of the government, especially if one or several CubeSat-based companies become commercially successful.
- Although investment and technological development in the commercial sector may be substantial, CubeSats may benefit from government support in areas such as standards development, deorbiting technologies, or other areas of research and development that may not be supported by mainstream satellite actors, creating clarity and growth for the entire sector.
- There are opportunities for the government to leverage commercial progress through the creation of public-private partnerships, such as data-buys, and joint developments.
- CubeSats are likely to evolve in more than one way, depending on specific applications and value to stakeholders. For CubeSats to achieve their potential, these evolutionary trajectories need to be recognized and addressed. Prematurely limiting what CubeSats can become will likely limit their impact.

The balance of this report, especially the conclusions and recommendations proposed by the committee, follow these principles and try to strike the balance between enabling where CubeSats are promising while also remaining cognizant of the fact that these developments have to fit into the funding systems of NASA and NSF and have to be balanced with other value systems and priorities.

[7] Additional references: Z. Szajnfarber, M.G. Richards, and A.L. Weigel, 2011, *Challenges to Innovation in the Government Space Sector*, Defense Acquisition University, July, http://www.dau.mil/pubscats/PubsCats/ AR%20Journal/arj59/Szajnfarber_ARJ59.pdf; C. O'Reilly III and M. Tushman, 2013, Organizational ambidexterity: Past, present, and future, *Academy of Management Perspectives* 27(4):324-338; C. Markides and W. Chu, 2009, Innovation through ambidexterity: How to achieve the ambidextrous organization, Chapter 19 in *Handbook of Research on Strategy and Foresight* (L.A. Costanzo and R.B. MacKay, eds.), Edward Elgar Publishing, Cheltenham, U.K., http://www.elgaronline.com/view/9781845429638.xml; D. Wood, S. Pfotenhauer, W. Glover, and D. Newman, 2013, Disruptive innovation in public service sectors: Ambidexterity and the role of incumbents, pp. 669-676 in *Proceedings of the 8th European Conference on Innovation and Entrepreneurship*, Volume 2, Academic Conferences and Publishing International, Reading, U.K.

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3

CubeSats as a Tool for Education and Hands-on Training

WHY CUBESATS FOR EDUCATION AND TRAINING?

As discussed previously, CubeSats were first conceived as a hands-on education tool allowing students to design and test small satellites and develop space missions. This teaching tool has now spread to many different universities, especially those with aerospace and similar engineering departments.

This rapid adoption of active and hands-on learning techniques is consistent with a trend in science, technology, engineering, and mathematics (STEM) disciplines away from lecture-based teaching toward alternative teaching models that show enhanced learning outcomes. Compared to lecture-based learning, average examination scores of students with hands-on approaches are higher. According to Freeman et al. (2014), "average examination scores improved by about 6 percent in active learning sections, and . . . students in classes with traditional lecturing were 1.5 times more likely to fail [their classes] than were students in classes with active learning."[1] There has been particular focus on team-based, hands-on, active-learning techniques, which provide opportunities for students to interact with complex problems—like the design and operation of a space mission—and to do so as a multifunctional team. These engaged and team-based learning techniques have a positive impact on retention of students in STEM fields. Such a net increase of STEM graduates was one of the top recommendations of the 2010 report *Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5* and a matter of national competitiveness.[2]

One of the most challenging concepts to teach in aerospace engineering is the interdependent subsystems and systems that make a successful space mission. Even though there are textbooks[3] on the issue, active engagement in system development is essential for a young scientist or engineer to understand how their work fits into a greater whole. With few exceptions, the active development of a space system is generally beyond the range of opportunities offered by academia and can only be experienced through internship in industry. CubeSats offer an alternative that has the benefits of typically shorter development lifetimes, a reduced set of requirements due to smaller system complexity, shorter overall mission life, and typically a higher level of acceptable risk for the mission.

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[1] S. Freeman, S.L. Eddy, M. McDonough, M.K. Smith, N. Okoroafor, H. Jordt, and M.P. Wenderoth, 2014, Active learning increases student performance in science, engineering, and mathematics, *Proceedings of the National Academy of Sciences* 111(23):8410-8415.

[2] National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, 2010, *Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5*, The National Academies Press, Washington, D.C.

[3] Space Technology Library, 1999, *Space Mission Analysis and Design*, 3rd edition. Microcosm Press, El Segundo, Calif., and Kluwer Academic Publishers, The Netherlands.

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Achieving Science with CubeSats: Thinking Inside the Box

Currently, within U.S. universities more than a thousand students per year graduate with some educational experience on a CubeSat project. This number of students is an estimate by the committee that is based on self-reported numbers of nearly 50 different universities collected by the National Science Foundation (NSF) and the Department of Defense (DOD), with the assumption of approximately 30 students per university. The total number of participating students is almost certainly larger as more universities engage as part of the 52 NASA Space Grant Consortia,[4] which also includes some secondary school participation. Furthermore, elementary school students can build a simple communication system with the Robert Twiggs' CricketSat development kit, originally designed to be flown as balloon experiments.[5]

EDUCATION AND TRAINING PROGRAMS

U.S. Air Force

One of the first education-focused satellite development programs was the University Nanosatellite Program (UNP), a joint program of the Air Force Research Laboratory's Space Vehicles Directorate (AFRL/RV), the Air Force Office of Scientific Research, and the American Institute of Aeronautics and Astronautics in 1999. To date, the program has funded more than 32 small satellite and CubeSat missions. Starting primarily with micro- or nanosatellites, UNP missions have followed the trend of terrestrial-based electronics described in Chapter 2: they have shrunk in size while increasing in capability (missions have now moved from mostly 50 kg satellites to nano- and picosatellites or CubeSats). The primary objective of this program is educational, in particular in systems engineering and overall engineering workforce development. It has been described as supporting the technical development of the industrial aerospace workforce both in military schools and in a broader educational community. The secondary objective of this program is technology—the development of innovative, low-cost technologies of relevance to DOD. The tertiary objective of this program is university development: for example, through support of space hardware laboratories. During its program lifetime, approximately 5,000 students have been actively involved in educational programs offered by the nanosatellite program; a snapshot of the most recent funding round is provided in Table 3.1. The results are self-reported by 10 of the participating universities during 2013-2015 and are given as examples of the effects of the UNP. During 2013-2015, the program primarily benefited undergraduate students but has also seen impacts at the graduate level, indicated by a number of Ph.D. dissertations.

The UNP program is designed around 10 scheduled milestones mandatory for all participants, which include 6 design reviews, and 3 skill-building events with a focus on education and team development. The milestones follow the design cycle generally used for space payloads, such as system concept reviews, system requirement reviews, preliminary design review, and critical design review. Furthermore, the complete design is analyzed in a proto-qualification review and, finally, a flight competition review. A critical part of this review process is that students are present at all reviews conducted by external reviewers, and they also are the authors and owners of the design documentation and design analyses.

The UNP is currently funded at approximately $1.25 million per year through both awards to universities and the program office, which is responsible for program execution, mission assurance testing (i.e., environmental stress screening) and launch coordination. Although a large number of mission concepts are developed through UNP, the high level of competition and limited funds typically allow for only one mission to be selected to move forward throughout the entire program. However, for the latest round of competition, the program has been restructured to select as many missions as met the maturity and other criteria, resulting in 6 of the 10 schools moving into later phases of the program. Of the initial missions to reach orbit (one was lost to a launch failure), all three met minimum mission success. During 2016 and 2017, UNP is scheduled to launch eight student-built satellites through the Space Test Program (three microsats and five CubeSats).

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[4] NASA, "About the Space Grant Program," http://www.nasa.gov/offices/education/programs/national/spacegrant/about/index.html.

[5] CricketSat was developed at Stanford University, but they no longer maintain the original websites. CricketSat kits can be purchased from http://www.anasphere.com.

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Achieving Science with CubeSats: Thinking Inside the Box

TABLE 3.1 Examples of the Educational Impact of the University Nanosat Program-Funded Nanosats at 10 of the Participating Universities (2013-2015)

Undergraduate students	306	Ph.D. dissertations	3
Graduate students	34	Master theses	20
All students	340	Journal publications	7
Faculty/advisors	16	Conference papers	56
		Presentations and posters	75

SOURCE: Personal communication from David Voss, program manager, University Nanosatellite Program, to Thomas Zurbuchen, January 2016.

National Science Foundation

Since 2008, the NSF Division of Atmospheric and Geospace Sciences has funded CubeSats (Figure 3.1) focused on the advancement of science in space weather and also the educational benefits to participants. A 2013 report of the program characterizes those benefits as follows: "They allow students, through hands-on work on real, exciting, end-to-end projects, to develop the necessary skills and experience needed to succeed in STEM careers. CubeSat projects are also an effective tool to broaden the participation amongst underrepresented groups in STEM research and education. The projects stimulate widespread excitement and involve a uniquely diverse set of skills and interest. Therefore they appeal to a broader range of participants than more traditional science and engineering projects."[6]

The response of the atmospheric and geospace sciences communities has been significant. Since 2008, 5 NSF CubeSat competitions have been carried out, and 15 missions have been funded for about $900,000 per mission over a 3-year development period. Throughout its activity from 2008-2015, the program was supported by approximately $15.6 million. The program remains competitive, receiving an average of 25 proposals for each of the calls, but typically there is only enough funding to select two or three investigations per call. Besides a thorough proposal review, requirements dictated by launch acceptance, and minimal prescriptions for project management (testing, review, documentation, etc.), each team is free to implement their educational and management processes. The educational content, therefore, varies widely depending on the experience of a participating university and the availability of experienced mentors or public-private partnerships that can support university teams during the satellite design-build-test process.

According to the NSF report on the program[7] and reports from various participating universities, CubeSat developments tend to be appropriately sized for undergraduate and graduate students to work on for 1 to 3 years, with individual subsystem team sizes typically being less than 5 students and the full mission team sizes typically being less than 30. According to the report, there is particular interest among engineering students because CubeSat programs are likely the only way for students to be involved with a spacecraft that will actually fly. Anecdotally, over half of students working on CubeSats have gone on to positions focused on the aerospace industry. Some NSF-funded projects have made a deliberate effort to include minorities, thus broadening the impact of this research and educational program.

The curricular context of CubeSat design activities at universities varies from case to case. 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. Students are often part of a multidisciplinary program or are in aerospace engineering or other majors. As is common with most university CubeSat student projects, undergraduate and graduate students put into practice their classroom learning through direct participation in the challenges associated with spaceflight hardware design, fabrication, testing, and operations in space. Some individual students spend multiple years engaged in CubeSat development while being mentored by professional engineers and scientists.

[6] NSF and NASA, 2013, *National Science Foundation (NSF) CubeSat-Based Missions for Geospace and Atmospheric Research Annual Report*, NP-2013-12-097-GSFC, Arlington, Va., http://www.nsf.gov/geo/ags/uars/cubesat/nsf-nasa-annual-report-cubesat-2013.pdf.

[7] Ibid.

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FIGURE 3.1 Students are involved in all phases of CubeSat development and flight operations. *Upper left:* A student examines CubeSat hardware. *Upper middle:* A student deploys a communication test for the MEROPE CubeSat. *Upper right:* A student holds one of the DICE CubeSats. *Bottom left:* Students assemble the CADRE CubeSat. *Bottom right:* Professors and students examine the RAX-1 engineering model. SOURCE: *Upper left and middle:* Courtesy of Montana State University. *Upper right:* Courtesy of Utah State University. *Bottom left:* Courtesy of the University of Michigan and the Michigan eXploration Laboratory. *Bottom right:* Courtesy of the National Science Foundation.

NASA

Approximately 60 percent of NASA-funded CubeSat programs also involve universities, often overlapping with the set of universities funded through AFRL or NSF. Although educational objectives are most often not primary to the NASA programs, both NASA program officials as well as participating institutions often name them as an essential outcome. In addition to university student projects, NASA centers and the private sector use CubeSats to provide valuable hands-on training for the future leaders in engineering, science, and management. This experience is akin to hands-on training from working with rocket and balloon experiments, which provide

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experience with the full cycle of concept and requirement definitions that balance scientific goals and engineering constraints, detailed design, reviews, fabrication, test, launch, and data analysis. In addition to hands-on training of NASA center staff, many of the NASA technology fellowship students have the opportunity to work on a CubeSat project. On these smaller space-hardware projects, almost everyone is involved in hardware development and testing. This is in contrast with large satellite projects, where most engineers, scientists, and managers do not have the opportunity to ever touch the hardware because only NASA-certified technicians are permitted to handle flight hardware.

SUMMARY FOR CUBESATS FOR EDUCATION

Every university, industry, and agency-based team that spoke to the committee stressed the benefits of education and training using CubeSats that include, but are not limited to, providing hands-on hardware and software development experience, education about satellite system engineering and technology, and cross-disciplinary science and engineering training for students and early-career professionals. These educational programs help to attract students into STEM fields and retain them. Furthermore, CubeSat programs provide training opportunities for young scientists and engineers in NASA centers and the industrial sector, similar to balloon and rocket programs.

Conclusion: The teaching and training of satellite technology, engineering, and space science provided by CubeSat programs are of high educational and leadership training value to participating educational institutions and for early career scientists and engineers.

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4

Science Impact and Potential

OVERVIEW

This chapter discusses the scientific contributions and potential of CubeSats in the context of the science goals set in the decadal surveys from each of five space science subdisciplines: solar and space physics, Earth science and applications from space, planetary sciences, astronomy and astrophysics, and biological and physical sciences in space. As described below, CubeSat mission concepts are highly varied in terms of complexity and scale, filling a role that is distinct in each subdiscipline. For an example list of enabling technologies and potential applications by discipline, see Table 5.1 in Chapter 5. CubeSats are also a platform for demonstration of new technologies that may be used for missions of different sizes.

Before discussing each space science subdiscipline, the overall impact of CubeSats is considered, based on the committee's review of publications through the end of calendar year 2015. The number and quality of publications are important measures of scientific output. As part of this study, the committee searched for publications using a number of different sources. A detailed account of the methods and findings, including an analysis of Web of Science, Scopus, and NASA/ADS, is provided in Appendix B. Figure 4.1 shows the number of publications as a function of year using the search terms "CubeSat" or "CubeSats" in the NASA/ADS abstract service. About a quarter of the papers (160 of 536) are in refereed journals. Although the primary focus of the committee was on refereed publications, both refereed and non-refereed publications are shown in Figure 4.1. The number of refereed publications is small and often lags missions by several years, thus, the inclusion of non-refereed publications provides another measure of recent activity. The number of both non-refereed and refereed publications increased rapidly between 2008 and 2015.

Not surprisingly, considering the distribution of CubeSat programs, 74 percent (118) of the 160 refereed papers were engineering-focused, while only 26 percent (41) were science-focused, as classified by the committee. The 41 science papers were further classified by subfield (see Figure B.4 in Appendix B). The largest presence by far is in solar and space physics, which has also seen the largest number of science CubeSats launched, primarily supported by the NSF-funded CubeSat program. Science papers from NASA-funded CubeSat science missions are not expected until after they launch, starting in 2016 and later. Refereed publications in astronomy and astrophysics or planetary sciences are mostly focused on the description of new measurement techniques or data strategies enabled by CubeSats. The majority of space physics papers are published in relatively high-impact journals. One paper was published in *Nature*, and several appeared in *Geophysical Research Letters* and *Journal of Geophysical Research: Space Physics*.

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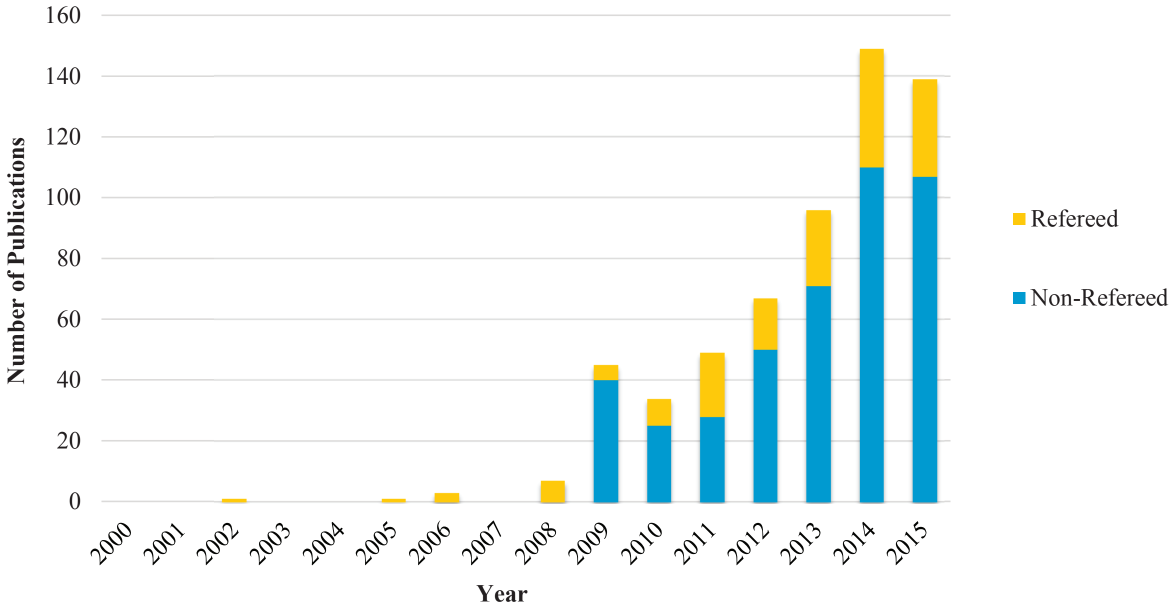

FIGURE 4.1 Number of papers published, by year, 2000-2015, with the keyword "CubeSat" or "CubeSats" in both the title and abstract in the Smithsonian Astrophysical Observatory (SAO)/NASA Astrophysics Data System (ADS). NOTE: For details and limitations, refer to Appendix B. The count for 2015 may be incomplete because the search was conducted in January 2016, and the databases sometimes lag the actual publication numbers. SOURCE: SAO/NASA ADS, http://www.adsabs.harvard.edu/, accessed January 2016.

In reviewing the scientific literature, the committee found the following:

Finding: The research interest in CubeSats is increasing with time, as demonstrated by the growing number of publications. The majority of CubeSat-related publications are in non-refereed journals, but the number of refereed papers is also increasing with time.

Finding: The majority (74 percent) of refereed papers is engineering-focused, but the number of science-related papers is increasing over time. The majority of science papers is in the field of space physics and is based on NSF-funded CubeSats.

Conclusion: CubeSats have already produced high-value science, as demonstrated by peer-reviewed publications in high-impact journals.

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Achieving Science with CubeSats: Thinking Inside the Box

SOLAR AND SPACE PHYSICS

Science Priorities in Solar and Space Physics—Decadal Survey Highlights

The most recent solar and space physics decadal survey, *Solar and Space Physics: A Science for a Technological Society,*[1] was published in 2013 and emphasized that the Sun-Earth system has to be understood as a coupled system. The decadal survey outlined the following four key science goals:

- Determine the origins of the Sun's activity and predict the variations of the space environment.
- Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.
- Determine the interaction of the Sun with the solar system and the interstellar medium.
- Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

The decadal survey also focused on the importance of the scientific foundations that improve the ability to forecast the Earth's space environment.

In addition to the baseline recommendation of completing the ongoing science program, the first recommendation of the decadal survey was to implement the DRIVE initiative to "diversify" observing platforms in solar and space physics, "realize" the scientific potential of already existing assets, "integrate" observing platforms into successful investigations, "venture" forward with technology development, and "educate" the next generation. CubeSats diversify by providing stand-alone, unique measurements and measurements that increase the science-return of larger facilities; venture forward by driving technology development; and educate, as discussed in Chapters 1 and 3. The DRIVE recommendation from the decadal survey identified flight opportunities for very small satellites, including CubeSats, as a key growth area for both NASA and NSF.

The decadal survey also highlighted the importance of NASA's Explorer program and proposed an expansion of this program, again recognizing the importance of diversified observing platforms in space physics. With regard to new strategic (larger) mission concepts, the review focused on an Interstellar Mapping and Acceleration Probe (IMAP) to follow up on the Interstellar Boundary Explorer (IBEX) and take advantage of the overlap with the historic Voyager missions; the DYNAMIC mission concept to focus on the variability of space weather driven by the lower atmosphere weather on Earth; and MEDICI, which focuses on the magnetosphere-ionosphere-thermosphere system and its coupling under heliospheric forcing. Both DYNAMIC and MEDICI concepts are multi-spacecraft missions of the scale that has been demonstrated previously with missions such as THEMIS, Van Allen Probes, and Magnetospheric Multiscale (MMS) (two to five spacecraft with masses ranging from approximately 100 to 1,000 kg).

The final recommendation for new mission concepts in the decadal survey was Geospace Dynamics Constellation (GDC), which has been a high-priority science recommendation in space physics for many years. GDC would be a constellation of at least six identical satellites in low Earth orbit providing simultaneous global observations of the coupled atmosphere-ionosphere-magnetosphere system. GDC would make measurements critical for understanding how the ionosphere-thermosphere system of Earth responds to driving from above by the solar wind and driving from below by the atmosphere. The notional GDC design presented in the decadal survey does not employ CubeSats. However, a constellation mission on the scale of GDC is expensive to achieve using the current mission paradigm and NASA Heliophysics projected funding profile. CubeSat-derived technology can benefit missions of this scale, as demonstrated by the CYGNSS Earth science mission, a constellation of eight small spacecraft (not CubeSats) measuring ocean surface winds associated with tropical cyclones (see Figure 4.4 below).

The decadal survey also described two future mission concepts that are not achievable within the next decade because significant technology development is required. The Magnetospheric Constellation (MagCon) mission, consisting of several tens of spacecraft measuring particles and fields, would provide a global view of how the magnetosphere stores and releases energy in the magnetotail and accelerates particles that supply the radiation

[1] National Research Council (NRC), 2013, *Solar and Space Physics: A Science for a Technological Society*, The National Academies Press, Washington, D.C.

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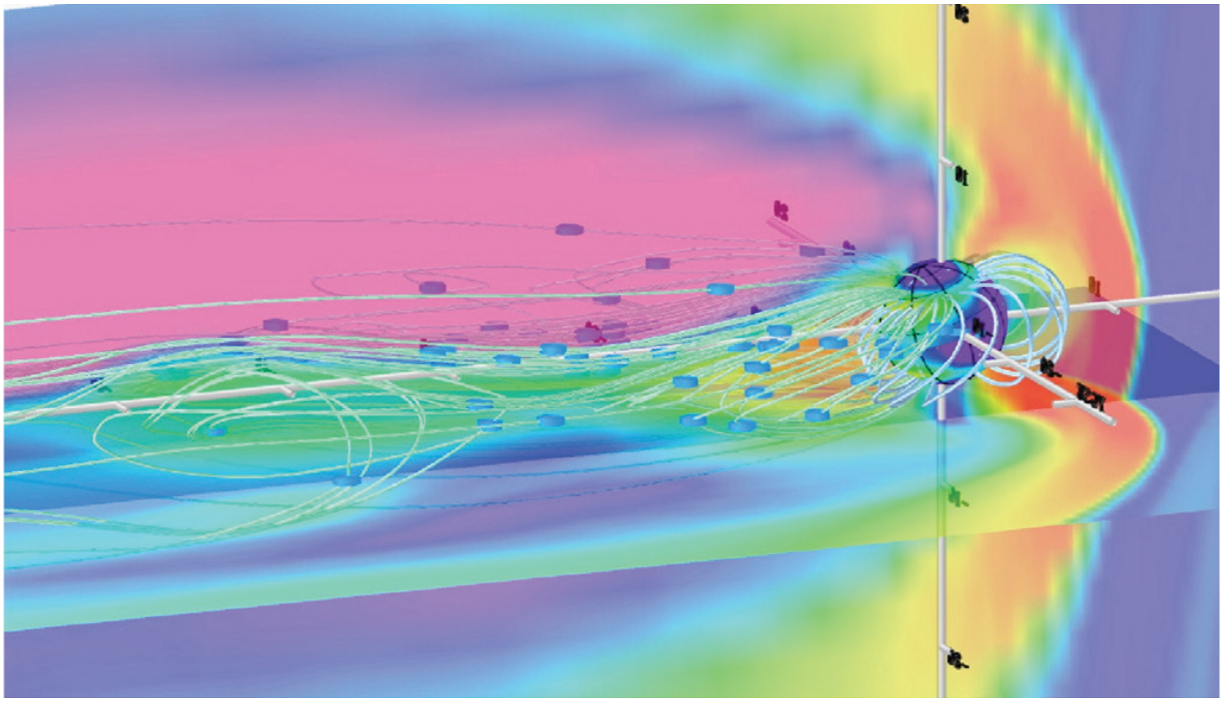

FIGURE 4.2 The Magnetospheric Constellation (MagCon) mission concept showing 36 spacecraft superimposed on a magnetohydrodynamic (MHD) simulation of Earth's magnetosphere. Constellation missions of this scale require a new paradigm. SOURCE: NASA Science and Technology Definition Team, 2004, *Global Dynamics of the Structured Magnetotail: Updated Synopsis of the Report of the NASA Science and Technology Definition Team for the Magnetospheric Constellation Mission*, http://www.phy6.org/MagCON.pdf.

belts. It would also provide the first set of space weather buoys, making space weather measurements much like those at terrestrial weather stations (Figure 4.2). Magnetospheric Constellation and Tomography (MagCat) would provide global imaging of the magnetosphere for the first time. Although the decadal survey did not specify the size or geometry of spacecraft required to implement these concepts, missions such as MagCat and MagCon, which require tens to hundreds of spacecraft, will never be achievable without a new development approach.

The History and Current Role of CubeSats in Solar and Space Physics

CubeSats have shown their ability to produce high-priority science in space physics. For example, Radio Aurora Explorer (RAX)-2 worked with ground-based radar to measure ionospheric irregularities[2] (Chapter 1, Figure 1.8); CSSWE has contributed to the understanding of radiation belt variability (Figure 4.3). A number of other missions are inflight and returning science data or in development. Thus far, most of these successes come from the NSF CubeSat program.

There are two general categories where CubeSats have the most potential to contribute to space physics research: targeted science investigations with either unique orbits or new instruments and constellation missions. Both CSSWE and RAX addressed targeted science questions that are part of the broad science goals outlined

[2] H. Bahcivan, J.W. Cutler, J.C. Springmann, R. Doe, and M.J. Nicolls, 2014, Magnetic aspect sensitivity of high-latitude E region irregularities measured by the RAX-2 CubeSat, *Journal of Geophysical Research: Space Physics* 119(2):1233-1249.

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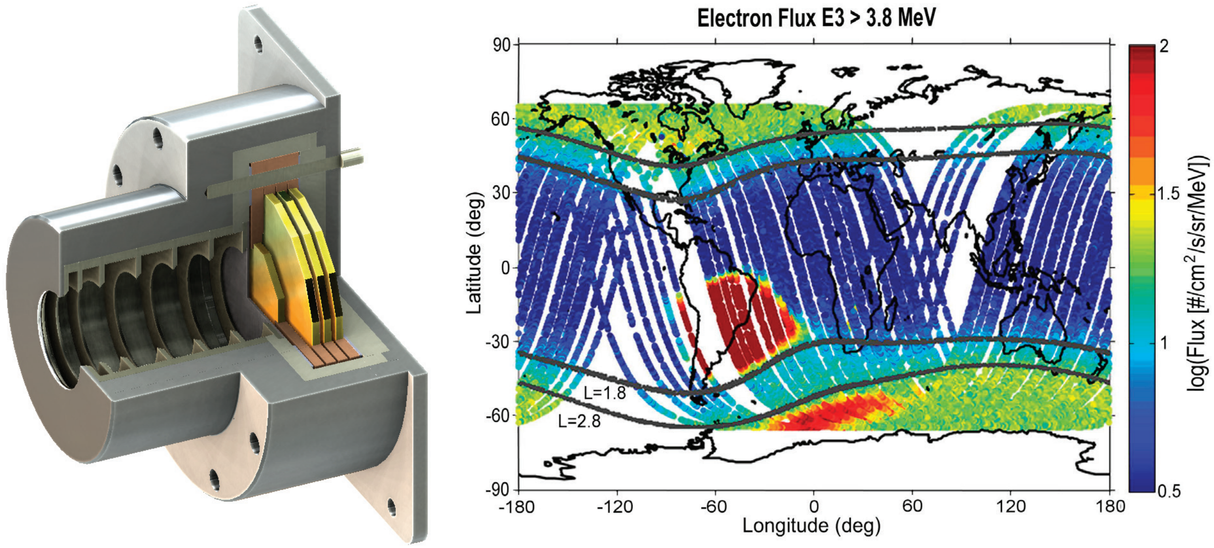

FIGURE 4.3 The Colorado Student Space Weather Experiment (CSSWE) was launched in 2012. CSSWE has been used in tandem with the Van Allen Probes satellites and BARREL balloons to further understanding of the space environment, one of the four decadal survey science goals. CSSWE has so far resulted in eight peer-reviewed publications. *Left*: Miniaturized particle detector developed for CSSWE. *Right*: CSSWE >3.8 MeV electron data shown in a latitude–longitude Mercator projection, illustrating the sharp inner boundary of high energy electrons in Earth's radiation belts. SOURCE: *Left:* Courtesy of the Laboratory for Atmospheric and Space Physics/University of Colorado, Boulder. *Right:* Reprinted by permission from Macmillan Publishers Ltd: Nature, D.N. Baker, A.N. Jaynes, V.C. Hoxie, R.M. Thorne, J.C. Foster, and X. Li, An impenetrable barrier to ultrarelativistic electrons in the Van Allen radiation belts, *Nature* 515:7528, copyright 2014, http://www.nature.com/index.html.

in the decadal survey. These missions augmented larger missions (Van Allen Probes in the case of CSSWE) or ground-based instrumentation (PFISR in the case of RAX), increasing the return on investment for large facilities.

Large constellations of CubeSats have not yet flown, even though they appear to be a natural application of this disruptive technology to magnetospheric research. Traditional approaches for gathering multipoint data often have cost estimates well beyond typical budgetary constraints for missions. The Edison Demonstration of Smallsat Networks (EDSN) mission,[3] consisting of eight CubeSats operating in a swarm configuration, was a first attempt toward demonstrating larger constellations and inter-spacecraft network operations. The spacecraft were successfully built but were lost when the launch vehicle failed in November 2015. There are several examples of successful missions employing two CubeSats. Both FIREBIRD[4] and Aerocube-6[5] used closely separated spacecraft to study radiation belt losses. Aerocube-6 has successfully demonstrated the use of differential drag for controlling spacecraft separation in low Earth orbit. These and other CubeSat missions under development may be viewed as pathfinders to future space physics missions that will use many spacecraft to carry out critical multipoint measurements necessary for understanding the coupled Sun-Earth system. CubeSats, or the technology they enable, may be the most effective path toward large constellation missions. Future space physics constella-

[3] J. Cockrell, R. Alena, D. Mayer, H. Sanchez, T. Luzod, B. Yost, and D.M. Klumpar, 2012, "EDSN: A Large Swarm of Advanced Yet Very Affordable, COTS-based NanoSats that Enable Multipoint Physics and Open Source Apps," *Proceedings of the 26th Annual AIAA/USU Conference on Small Satellites*, Technical Session I: The Horizon, SSC12-I-5, http://digitalcommons.usu.edu/smallsat/2012/all2012/89/.

[4] A.B. Crew, B.A. Larsen, D.M. Klumpar, E. Mosleh, H.E. Spence, J. Legere, J.B. Blake, L. Springer, M. Widholm, S. Driscoll, S. Longworth, et al., 2012, Focusing on size and energy dependence of electron microbursts from the Van Allen radiation belts, *Space Weather* 10(11):1-3.

[5] J.B. Blake, and T.P. O'Brien, 2016, Observations of small-scale latitudinal structure in energetic electron precipitation, *Journal of Geophysical Research: Space Physics*, accepted. doi:10.1002/2015JA021815.

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tions such as MagCon may require spacecraft of a different form factor or size than traditional CubeSats require, but CubeSat-derived technology can play an important role in their development.

In addition to technology development that will enable constellation missions, CubeSats have already been instrumental in demonstrating miniaturized sensors for use in space physics. For example, the energetic particle detector flown on CSSWE is a miniaturized version of the REPT instrument on Van Allen Probes.

The Future of CubeSats in Solar and Space Physics

In the future, better and more capable miniaturized instruments will continue to enable targeted science. Concepts are being developed that not only provide in situ measurements of energetic particles, plasmas, and fields but also key observations of the Sun. For example, a scaled-down HMI (Helioseismic and Magnetic Imager), which provides key insights into the evolution of the solar magnetic field, could be packaged to fit into a CubeSat, as could the Polarimetric and Helioseismic Imager (SO/PHI) developed for the European Space Agency's (ESA's) Solar Orbiter mission. Coronagraphs, ultraviolet (UV), and extreme ultraviolet (EUV) imagers could also be implemented as CubeSats. These imaging applications will require developments in high-rate communication and pointing capability.

CubeSats can have short development cycles that allow for rapid response to targeted opportunities—for example, augmenting larger missions such as CSSWE did for the Van Allen Probes. They can also be used in hazardous orbits not accessible to traditional large observatories—for example, probing the atmospheric boundary region and lower ionosphere (a few hundred kilometers in altitude) where orbital lifetimes are short.

As mentioned previously, constellations can enable transformational understanding of the dynamics and coupling of the Earth's magnetosphere, ionosphere, and atmosphere. Constellations of tens to hundreds of spacecraft would provide significant advancements over missions like the MMS mission and the Van Allen Probes, allowing for separation of temporal and spatial variation on fast enough timescales to resolve physical mechanisms. A constellation of CubeSats or other small satellites could make fundamental discoveries about how the magnetosphere stores, processes, and releases energy in response to the solar wind, as illustrated by the MagCon concept.[6] Another example is a constellation of magnetographs spaced throughout Earth's orbit that could provide magnetic maps of the entire Sun, enhancing the forecast accuracy for solar outbursts.

In addition to constellations where multiple satellites are in different orbits, a swarm utilizes multiple satellites flying in formation near each other in similar orbits. Formation flying with a positional knowledge of a meter or less is now possible with CubeSats. Swarms could be used to study small-scale structure in the auroral acceleration region, for example. Both constellations and swarms would require propulsion for placing the satellites into their science orbits and for station keeping.

Summary: CubeSats in Solar and Space Physics

CubeSats and platforms taking advantage of CubeSat-derived technology have the potential to make a unique contribution to the field of solar and space physics (heliophysics) and have already proven their value in obtaining breakthrough science. The recommendations in the solar and space physics decadal survey emphasized diversification and integration of platforms of different sizes. It also emphasized that the coupled Sun-Earth system must be investigated using a system-science approach and highlighted the importance of multipoint measurements to accomplish this. Advances in pointing, high-rate communication, sensor technology, and propulsion will enable CubeSats and other small satellites to address a wide array of space physics science goals.

Conclusion: CubeSats have proven their ability to address the high-priority science goals outlined in the solar and space physics decadal survey and are specifically mentioned there. In the area of solar and space physics, CubeSats are particularly useful for achieving targeted science provided by novel measurements or augmentation of larger facilities and for enabling constellation and swarm missions.

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[6] NASA Science and Technology Definition Team, 2004, *Global Dynamics of the Structured Magnetotail: Updated Synopsis of the Report of the NASA Science and Technology Definition Team for the Magnetospheric Constellation Mission*, http://www.phy6.org/MagCON.pdf.

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Achieving Science with CubeSats: Thinking Inside the Box

EARTH SCIENCE AND APPLICATIONS FROM SPACE

Science Priorities in Earth Science and Applications from Space—Decadal Survey Highlights

The first Earth science and applications from space decadal survey[7] (hereafter ESAS 2007) was published nearly a decade ago, followed by a midterm review.[8] The decadal survey was organized primarily around the following questions central to Earth system science:

- How is the global Earth system changing?
- What are the sources of change in the Earth system and their magnitude and trends?
- How will the Earth system change in the future?
- How can Earth system science improve mitigation of and adaptation to global change?

Many of the recommendations of the Earth science decadal survey present rather well-defined missions and investigations, many which have not yet flown, focusing on a range of science problems, including the Earth radiation budget, surface and ice sheet deformation, land surface composition and vegetation type and structure, atmospheric gas/aerosol composition, and ocean color. The decadal survey also recommended the creation of an innovative, principal-investigator (PI)-led line of missions, the Earth Venture Class.

The second decadal survey in Earth science and applications from space, sponsored by NASA, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey (USGS), was initiated in fall 2015; a final report is anticipated in summer 2017 (ESAS 2017[9]). The survey occurs against a backdrop of highly constrained federal and agency budgets. In addition, for NASA, the survey context includes a backlog of missions recommended by the 2007 survey report, increased responsibility—without commensurate budget increases—for sustained or "continuity" measurements, and growing demands for the information products derived from Earth observations. For NOAA, the survey context includes challenges in ensuring continuity of service from critical operational systems, especially the polar-orbiting spacecraft that feed numerical weather prediction models. USGS looks to ensure continuity of data from its Landsat series of spacecraft.

To meet current and future needs, the relevant agencies are challenged with the need to "accomplish more with less." Thus, for example, language in the survey's task statement asks the steering committee to make their recommendations to NASA cognizant of the likely emergence of new technologies; for NOAA and USGS, recommendations are to be made "with the expectation that the capabilities of non-traditional providers of Earth observations continue to increase in scope and quality."[10]

The History and Current Role of CubeSats in Earth Science and Applications from Space

CubeSats launched to date have primarily focused on education, technology development, solar and space physics science (see "Solar and Space Physics" above), and commercial Earth imaging. Despite the fact that all of the CubeSats that have flown thus far have done so in low Earth orbit (LEO), the Earth science community has not yet exploited the potential that CubeSats have to offer either in terms of lower-cost, faster science return, or unique observations that are made feasible by the platform (e.g., constellation measurements).

NASA's Earth Science Technology Office (ESTO) has used CubeSats for Earth science technology development with more than a dozen active CubeSat instrument subsystem development and technology flight maturation

[7] NRC, 2007, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, The National Academies Press, Washington, D.C.

[8] NRC, 2012, *Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey*, The National Academies Press, Washington, D.C.

[9] For more information, go to the 2017 Decadal Survey for Earth Science and Applications from Space website at http://www.nas.edu/esas2017, accessed April 29, 2016.

[10] The statement of task of the 2017 Decadal Survey for Earth Science and Applications from Space is available at http://sites.nationalacademies.org/DEPS/esas2017/DEPS_169443, accessed April 29, 2016.

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Achieving Science with CubeSats: Thinking Inside the Box

projects.[11] CubeSat technology development has also been funded internally at individual NASA centers. At the same time, there has been significant commercial development of CubeSats for observations that have some overlap with Earth science objectives—namely, Earth surface imaging (e.g., Planet Labs, Skybox) and more recently atmospheric sounding (e.g., PlanetIQ, Spire). The applicability of commercial Earth observations for Earth science (e.g., purchase of science data as a service from commercial firms) depends on many factors, including duration of data record, data resolution, and quality of calibrations.

Current technology CubeSat projects funded by NASA fall into two categories. The first is the use of the platform to demonstrate technology destined for use on larger missions. The objective of the 3U CubeSat GRIFEX, for example, was to verify the spaceborne performance of a state-of-the-art readout integrated circuit/focal plane array that specifically targets the requirements of the Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission concept in ESAS 2007.[12] Increasingly, however, a second category of technology CubeSats is being used to prove technology intended for use in science payloads on future targeted CubeSat science missions themselves or as constellation precursors. The Temporal Experiment for Storms and Tropical Systems Demonstration (TEMPEST-D) is a 6U mission currently developing a millimeter-wave radiometer for cloud precipitation that could fly as a part of the TEMPEST CubeSat constellation as an Earth Venture mission concept.[13] Another example is the Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN) 3U CubeSat that will demonstrate a payload that could be incorporated into a CubeSat or hosted payload constellation for measuring Earth's radiation budget.[14]

In March 2016, while the present report was being written, NASA, through its Earth Venture program, selected the Time-Resolved Observations of Precipitation Structure and Storm Intensity with a Constellation of Smallsats (TROPICS) investigation, which will be a constellation of 12 3U CubeSats studying the development of tropical cyclones. This CubeSat constellation will be able to make rapid revisits, allowing its microwave radiometers to measure temperature, humidity, precipitation, and cloud properties as frequently as every 21 minutes.[15]

CubeSat-derived technology is also enabling missions using platforms larger than the 12U CubeSat size limit considered in this report. This is manifested in the Cyclone Global Navigation Satellite System (CYGNSS) Earth Venture mission (Figure 4.4).[16] CYGNSS is complementary to traditional spacecraft that measure winds. By going from active to passive technology using GPS, CYGNSS requires significantly less power than does a spacecraft using the traditional technique. This results in smaller, less costly spacecraft that are CubeSat derived, are larger than 12U, and do not have standardized CubeSat dimensions, making a constellation feasible. The combined measurements from multiple spacecraft provide higher time resolution, returning data on timescales relevant for the development of storms.

Near-Term Future Science Opportunities for CubeSats in Earth Science and Applications from Space

Even though not yet proven in flight, it is likely that CubeSats and missions derived from CubeSat technology have the potential to address decadal survey Earth science goals through targeted investigations (e.g., CubeSats

[11] NASA, "Earth Science Technology Office Portfolio," http://www.estotechnology.us/techportfolio/, accessed April 8, 2016.

[12] Jet Propulsion Laboratory, "GEO-CAPE ROIC In-Flight Performance Experiment (GRIFEX)," http://www.jpl.nasa.gov/cubesat/grifex.php, accessed April 8, 2016.

[13] S.C. Reising, T.C. Gaier, C.D. Kummerow, V. Chandrasekar, S.T. Brown, S. Padmanabhan, B.H. Lim, S.C. van den Heever, T.S. L'Ecuyer, C.S. Ruf, Z.S. Haddad, et al., 2015, Overview of Temporal Experiment for Storms and Tropical Systems (TEMPEST) CubeSat constellation mission, paper presented at IEEE MTT-S International Microwave Symposium, Phoenix, Arizona, http://ieeexplore.ieee.org/xpls/icp.jsp?arnumber=7167136&tag=1.

[14] John Hopkins Applied Physics Laboratory, "Johns Hopkins APL Will Launch RAVAN to Help Solve an Earth Science Mystery," release date December 10, 2013, http://www.jhuapl.edu/newscenter/pressreleases/2013/131210.asp.

[15] NASA, "NASA Selects Instruments to Study Air Pollution, Tropical Cyclones," release date March 10, 2016, http://www.nasa.gov/press-release/nasa-selects-instruments-to-study-air-pollution-tropical-cyclones.

[16] University of Michigan, "Cyclone Global Navigation Satellite System Mission," updated August 3, 2015, http://clasp-research.engin.umich.edu/missions/cygnss/.

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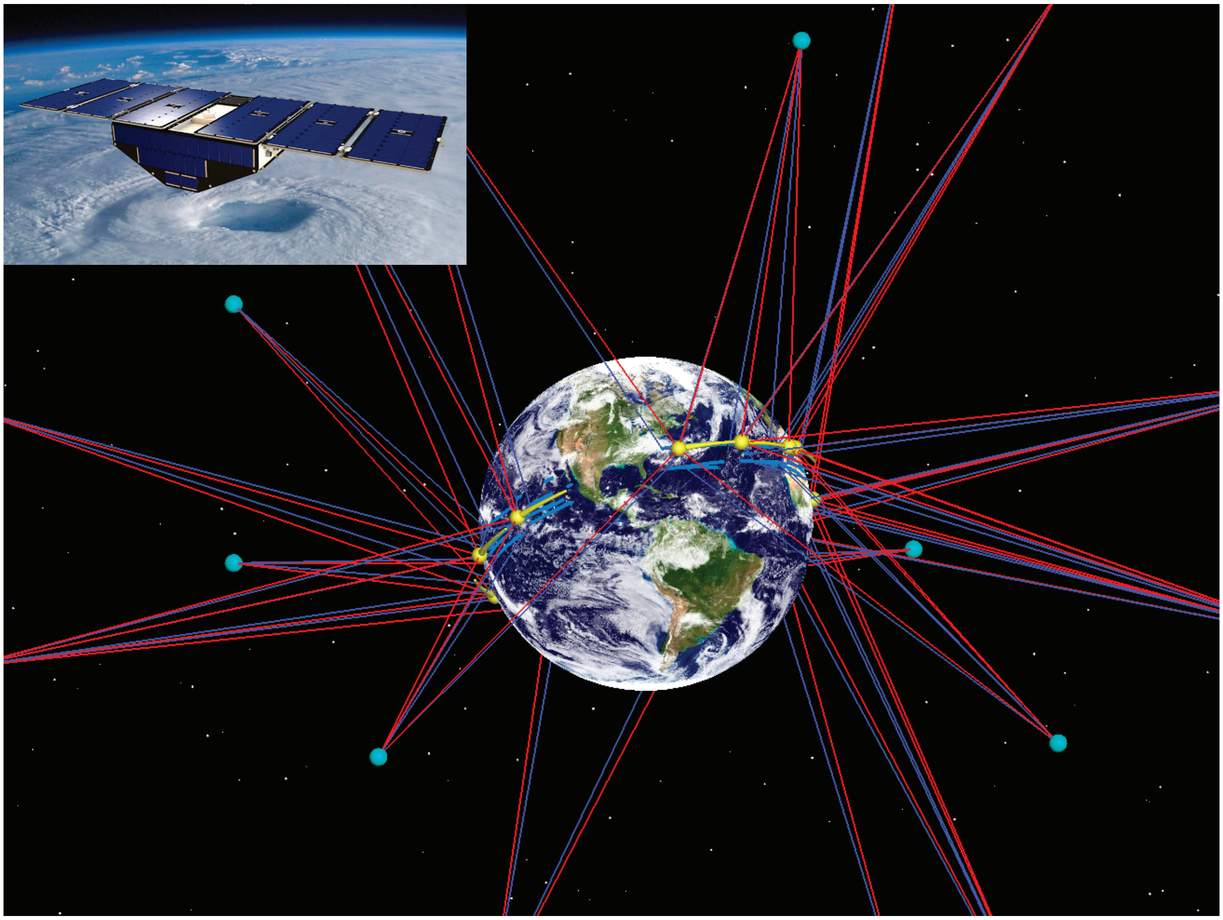

FIGURE 4.4 CYGNSS is a CubeSat-enabled mission scheduled to launch in 2016 as a constellation of 8 low Earth-orbiting spacecraft (yellow dots) that analyze reflected GPS signals (dark blue lines) from water surfaces shaped by hurricane-associated winds. Red lines indicate signals directly between the CYGNSS satellites and the GPS satellites (light blue dots further from Earth). Each CYGNSS spacecraft, weighing about 25 kg (inset), will carry a delay-Doppler mapping instrument consisting of a multi-channel GPS receiver, low-gain zenith antennas, and high-gain nadir antenna. CYGNSS measures the ocean surface wind field associated with tropical cyclones by combining the all-weather performance of GPS-based bistatic scatterometry. Blue lines on the Earth's surface represent measurements of the wind speed that CYGNSS derives from the reflected GPS signal. CYGNSS will measure GPS reflectivity during their entire orbit and new applications focused on hydrology and tsunami detection are currently being investigated. SOURCE: Courtesy of NASA/University of Michigan; inset courtesy of NASA/Southwest Research Institute.

are being developed to measure solar irradiance and Earth's energy budget) and by enabling new kinds of Earth science observations.

Perhaps chief among these are multipoint or constellation-type Earth measurements, which provide much greater temporal coverage than that possible with single, large spacecraft. A single spacecraft in LEO provides high-spatial-resolution imaging, but poor temporal coverage; a single geostationary Earth orbit (GEO) spacecraft provides diurnal temporal coverage, but at the expense of spatial resolution. A LEO constellation comprising several or dozens of individual small spacecraft could provide both global spatial and high temporal resolution. The understanding of many Earth processes benefit from this kind of observation, including severe weather, cloud formation and evolutionary processes, aerosols or air quality related measurements, atmospheric photochemistry, vegetation,

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ocean color, and Earth outgoing radiation. Constellations of lower-cost spacecraft also can provide for replenishment over time, allowing technology updates or replacement of failed spacecraft or instruments. To enable such missions, a number of technological advances are required. These include the need for high-rate communication and accurate pointing for high-resolution applications and propulsion needed for station keeping and establishment of constellations.

As an example, CubeSats could offer valuable data for weather and climate forecasting and projections. Global navigation satellite system-radio occultation (GNSS-RO) is a precise, cost-effective technique for measuring Earth's atmosphere from space, leveraging existing global navigation satellite systems,[17] and providing atmospheric measurements similar to those obtained from weather balloons, on a global scale. There are commercial efforts under way utilizing CubeSat technology with the potential of making GNSS-RO measurements analogous to the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission, a constellation of six 70-kg microsatellites that has been making atmospheric soundings of temperature, moisture, and pressure in the troposphere and stratosphere using GNSS-RO for nearly a decade.[18] CubeSat-enabled constellations could deliver tens of thousands of occultations daily and make them available in near real time.

An area that is challenging for Earth science satellite observations is both absolute and relative calibration between data sets, especially if the data are used for long-term data analysis for climate-related questions. Some Earth science problems require determination of trends at the percent level per decade. It is not clear whether this can be done inexpensively, but comparative measurements with enough lower-accuracy sensors may be possible.

Mitigation of Data Gaps with CubeSats

An application of CubeSats in Earth science is the potential to make observations that mitigate the gaps in operational data from critical satellite systems, in part because of their lower cost and shorter development cycles.

Gaps in Weather Forecasting Data

Perhaps the most significant gap in satellite data is in observations critical for routine weather forecasting and climate monitoring, the prediction of extreme weather, military operations, and the emergency response to wildfires and other natural disasters. There will likely be a gap in data of 1 to 4 years between the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP) spacecraft and the next-generation Joint Polar Satellite System (JPSS). There are also potential gaps in Department of Defense (DOD) and European polar satellite programs that provide data for NOAA forecasts. Further, NOAA's Geostationary Operational Environmental Satellite (GOES) program faces a period of more than 1 year without a backup satellite on orbit.

A number of commercial efforts are developing CubeSat or small satellite constellations seeking to address these gaps using the GNSS-RO sounding technique pioneered by the COSMIC mission. For example, Spire, GeoOptics, and PlanetIQ are developing CubeSat-based GNSS-RO constellations.[19]

Surface Imagery

Landsat 8 has been operating since 2013, and Landsat 9 is not planned for launch until 2021. To help mitigate a possible loss of the thermal infrared sensor on L8 before L9 flies, the Class D Thermal Infrared Free Flyer (TIR-FF) was considered as a possibility for launch in 2019. TIR-FF was part of the President's fiscal year 2016 budget request for USGS, but it was not funded by Congress. TIR-FF would have been a low-cost thermal infrared (TIR) free-flying small satellite—not a CubeSat—possibly larger than 12U, designed to ensure data continuity by flying in formation with L8 and would have carried a microbolometer TIR sensor and cloud camera. If suc-

[17] NRC, 1995, *The Global Positioning System: A Shared National Asset*, National Academy Press, Washington, D.C.

[18] C.-J. Fong, D. Whiteley, E. Yang, K. Cook, V. Chu, B. Schreiner, D. Ector, P. Wilczynski, T.-Y. Liu, and N. Yen, 2011, Space and ground segment performance of the FORMOSAT-3/COSMIC mission: Four years in orbit, *Atmospheric Measurement Techniques Discussions* 4:599-638; University Corporation for Atmospheric Research, "COSMIC Program Office," updated April 19, 2016, http://www.cosmic.ucar.edu/.

[19] E. Hand, 2012, Microsatellites aim to fill weather-data gap, *Nature* 491(7426):650-651.

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Achieving Science with CubeSats: Thinking Inside the Box

cessful at providing data with sufficient quality, TIR-FF would have had the potential to fill this gap and lay the groundwork for filling future gaps in imaging data using a targeted small spacecraft mission.

Solar Irradiance

The solar irradiance reaching Earth is an essential climate variable. The total solar irradiance (TSI) has been measured continuously since the late 1970s. The SORCE mission is near the end of its mission life, and with the loss of the Total Irradiance Monitor (TIM) on the Glory mission and the descope of the Total and Spectral Solar Irradiance Sensor (TSIS) from JPSS-1, the Total Solar Irradiance Calibration Transfer Experiment (TCTE) mission is bridging the gap for TSI. The TCTE mission is expected to end operations after an overlap period with another TSIS, to be installed on the International Space Station (ISS) in 2017. Continuity of the solar irradiance record, however, is precarious. Miniaturized total and spectral irradiance sensors are under development, suitable for flight on CubeSats, and plans exist to use small spacecraft to enable a robust, overlapping solar irradiance record into the future at a lower average operating cost than traditional measurements.

Summary: CubeSats in Earth Science and Applications from Space

Most CubeSats in LEO today are commercial satellites that focus on remote sensing, imagery, and Earth observation. The majority of NASA-funded CubeSats in Earth science to date are technology demonstrations. The Earth science community is just starting to exploit CubeSats and CubeSat-derived small satellites as a platform for doing science—for example, with the TROPICS and CYGNSS missions. CubeSats have the potential to provide high-temporal-resolution measurements through constellations and to mitigate data gaps. To realize this potential, technology developments in sensors and instruments—in particular in their calibration, high-rate communications, and propulsion to set up and maintain constellations—are needed.

Conclusion: CubeSats provide technology demonstration for Earth science missions, but the Earth science community is just starting to exploit CubeSats and CubeSat-derived small satellites for science. CubeSats hold promise for Earth science in several ways:

- CubeSats and CubeSat-associated technologies can enable targeted science and can augment existing capabilities by providing particular Earth science measurements that take advantage of the CubeSat platform.
- CubeSats and CubeSat-associated technologies can provide unique science opportunities as constellations or swarms by providing distributed, multipoint measurements for high-temporal-resolution, global-scale measurements.
- CubeSats or related systems have the potential to mitigate data gaps (e.g., JPSS, Landsat, TSIS) and provide sustained measurements (including monitoring).
- CubeSats are potentially more responsive to observation needs and in the employment of new technologies, owing to their shorter development cycles.

PLANETARY SCIENCE

Science Priorities in Planetary Science—Decadal Survey Highlights

The 2011 planetary science decadal survey, *Vision and Voyages for Planetary Science in the Decade 2013-2022*,[20] revolved around the following three major themes:

- *Building new worlds*—understanding solar system origins,
- *Planetary habitats*—searching for the requirements for life, and
- *Workings of solar system*—revealing planetary processes through time.

[20] NRC, 2011, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, The National Academies Press, Washington, D.C.

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Achieving Science with CubeSats: Thinking Inside the Box

Many of the objectives require close proximity observations with sophisticated instruments for elemental and mineralogy measurements. Some observations pertaining to origin science and habitability may be obtained only from in situ investigations and sampling. Some of these observations and targets are also of interest to human exploration, planetary defense, and reconnaissance for in situ resource utilization.

The high-priority flagship missions recommended by the decadal survey include the first mission in a Mars sample-return campaign, a mission to Europa addressing the planetary habitat goals, and a Uranus orbiter and probe. The decadal survey's highest recommendations included increasing the research and analysis (R&A) program and the establishment of a technology development program, as well as strengthening the Discovery program, which has produced significant and cost-effective science return operating in a PI mode. Priorities for the next PI-led New Frontiers missions include a comet surface sample return, a Lunar South Pole-Aitken Basin sample return mission, as well as three other missions.

The History and Current Role of Deep Space CubeSats for Planetary Science

There are currently no deep space CubeSats in flight launched by NASA or NSF, hence no track record of success, no heritage hardware, and no lessons learned. However, there are eight planetary CubeSat missions and three non-flight planetary technology systems under development by NASA. Classification based on the committee's databases, referenced in Chapter 1, are as follows: two technology and instrument demonstration missions (INSPIRE, MarCO) at and beyond lunar orbit; three science (LunaH-Map, Q-PACE, Lunar Flashlight) and two technology missions (Lunar IceCube, Skyfire) at or near the Moon; and one exploration science mission at a Near Earth Asteroid (NEA) Scout—all to be launched in the 2016-2018 time frame. The three non-flight planetary technology demonstrations are DAVID, HALO, and MMO.

Significant progress in electronics miniaturization in the past decade has led to increased interest for small platforms, including CubeSats. JAXA's Hayabusa mission carried the Minerva hopper (~1U in size, although with a different geometrical shape) for in situ imaging of an NEA. Despite a failed deployment, Minerva demonstrated its functionality by transmitting images of the mothership.[21] In 2005, the CubeSat form factor was introduced into planetary exploration concepts with the Planetary Hitchhiker,[22] which would use an Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) as the main vehicle and telecom relay, dropping CubeSats at multiple asteroids (this concept was not funded to move forward). Since then, a large number of CubeSat concepts have been proposed and presented at conferences (e.g., Interplanetary SmallSat Conference, iCubeSat, LunarCubes), based on the premise that enabling technologies and launch opportunities will soon become available. Interest for developing efficient, long-range propulsion systems that could fit within the CubeSat form factor began during the same period with the demonstration of solar sail deployment from the 3U NanoSail-D2 CubeSat in 2008.

Interest in deep space exploration concepts using independent CubeSats expanded in 2011 after Staehle et al. published results from a NASA Innovative Advanced Concepts (NIAC) technology gap assessment study.[23] This was followed by the NASA/JPL INSPIRE[24] technology demonstrator (3U), which is still awaiting launch. The prospect of obtaining space-qualified CubeSat transponder, propulsion, and attitude control then led to the selection in 2013 of three CubeSat missions to be launched with the Space Launch System's Exploration Mission 1 (EM-1) in 2018, which was focused on a range of science topics, including asteroid multiscale imaging, detection of lunar water, and the effect of deep space radiation on plants.

[21] T. Yoshimitsu, T. Kubota, and I. Nakatani, 2006, "MINERVA rover which became a small artificial solar satellite," *Proceedings of the 20th Annual AIAA/USU Conference on Small Satellites*, Session IV: The Past & Coming Years, SSC06-IV-4, http://digitalcommons.usu.edu/smallsat/2006/All2006/27/.

[22] I. Garrick-Bethell, R.P. Lin, H. Sanchez, B.A. Jaroux, M. Bester, P. Brown, D. Cosgrove, M.K. Dougherty, J.S. Halekas, D. Hemingway, P.C. Lozano, et al., 2013, Lunar magnetic field measurements with a CubeSat, *Proceedings of SPIE* 8739.

[23] R.L. Staehle, D. Blaney, H. Hemmati, D. Jones, A. Klesh, P. Liewer, J. Lazio, M. Wen-Yu Lo, P. Mouroulis, N. Murphy, P.J. Pingree, et al., 2013, Interplanetary CubeSats: Opening the solar system to a broad community at lower cost, *Journal of Small Satellites* 2(1):161-186.

[24] A. Klesh, J. Baker, J. Castillo-Rogez, L. Halatek, N. Murphy, C. Raymond, B. Sherwood, J. Bellardo, J. Cutler, and G. Lightsey, 2013, INSPIRE: Interplanetary Nano-Spacecraft Pathfinder in Relevant Environment, *Proceedings of the 27th AIAA/USU Conference on Small Satellites*, Technical Session XI: Around the Corner, SSC13-XI-8, http://digitalcommons.usu.edu/smallsat/2013/all2013/127/.

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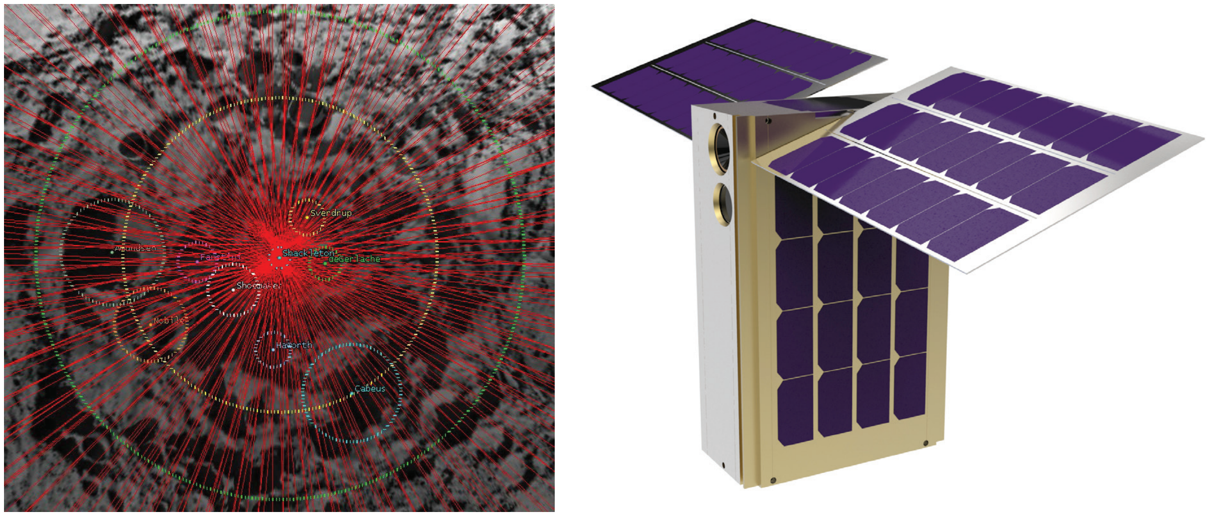

FIGURE 4.5 LunaH-Map is a 6U CubeSat that will enter a polar orbit around the Moon with a low altitude (5-12 km) perilune centered on the lunar South pole. *Left:* Orbit ground track shown for entire 60 (Earth) day science phase: 141 passes over target area initially (and periodically) centered on Shackleton Crater with close-approach of 5 km at each perilune crossing. Yellow circle denotes LunaH-Map altitude of 8 km; green circle denotes LunaH-Map altitude of 12 km. *Right:* LunaH-Map carries two neutron spectrometers that will produce maps of near-surface hydrogen (H). LunaH-Map will map H within permanently shadowed craters to determine its spatial distribution, map H distributions with depth (<1 meter), and map the distribution of H in other permanently shadowed regions (PSRs) throughout the South pole. SOURCE: NASA, "LunaH-Map: University-Built CubeSat to Map Water-Ice on the Moon," February 2, 2016. http://www.nasa.gov/feature/lunah-map-university-built-cubesat-to-map-water-ice-on-the-moon. Courtesy of Craig Hardgrove, LunaH-Map principal investigator, NASA.

In 2015, NASA's Planetary Science Division introduced the SIMPLEx (Small, Innovative Missions for Planetary Exploration) program whose selections in September 2015 included LunaH-Map (Figure 4.5) and Q-PACE (see Figure 4.7 in the "Astronomy and Astrophysics" section), a low-gravity laboratory in Earth orbit. Other missions in development include the Mars CubeSat One (MarCO) (Figure 1.9), a technology demonstration.

CubeSats have also been proposed as secondary payloads on bigger spacecraft to increase the science return of the whole mission by acquiring complementary observations. In October 2014, ESA selected five CubeSat concepts for further development to accompany the AIDA mission (Asteroid Impact and Deflection Assessment) currently in Phase A.[25]

Near-Term Future Science Opportunities for CubeSats in Planetary Science

CubeSats and platforms taking advantage of CubeSat technology have the potential to make unique contributions to planetary science by creating unique vantage points or multipoint measurements (e.g., in situ package(s) complementary to an orbiter); exploring high-risk or uncharted regions; and serving as low-gravity laboratories. As an example of exploring uncharted regions, NASA's Planetary Science Division selected for study 10 university-led concepts that would complement the Europa Clipper mission. CubeSats in LEO contribute to planetary exploration by providing natural low-gravity laboratories (see the section "Other U.S. Government Programs"), as well as observation platforms for astronomical observations of planetary bodies. Possible applications include the long-term monitoring of planetary atmospheres (Jupiter, Mars) and the tracking of meteors as they break up upon entering Earth's atmosphere.

[25] European Space Agency, "CubeSat Companions for ESA's Asteroid Mission," release date November 2, 2015, http://www.esa.int/Our_Activities/Space_Engineering_Technology/Asteroid_Impact_Mission/CubeSat_ companions_for_ESA_s_asteroid_mission.

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CubeSats can also be used as platforms for technology demonstration to enable future large missions. Two of the Discovery-13 proposals selected for Phase A study (September 2014) included CubeSats. One would obtain field measurements at an asteroid in coordination with its mothership while the other would obtain noble gas measurements in Venus's atmosphere, a high-priority objective of the 2011 decadal survey. Those technology demonstration options, if funded, would include the development of a deep space deployer capable of sustaining long cruise time and equipped with its own telecommunication and computer to limit the impact of the CubeSat on the mothership. CubeSat-based constellation networks have also been suggested as part of the telecom infrastructure to support the human exploration of the martian system,[26] which the MarCO mission plans to demonstrate.

Unique Challenges for Planetary Science CubeSats

Deep space CubeSat missions can have lower risk tolerance, and thus higher cost, than traditional CubeSats (although they may still be cheaper than the traditional alternative for planetary science) due to the constrained launch date and single launch opportunity typical of planetary missions. Therefore, the fly-learn-refly paradigm also does not apply. Additionally, planetary protection requirements may apply, depending on the destination. While these may be more easily implementable on CubeSats because of their small size, there is a perceived risk of contamination of a mothership. Other perceived risks, such as post-deployment impact with a mothership or pressurized containers, may pose a barrier to the use of CubeSats on future deep space missions.

The traditional CubeSat form factor is too restrictive for some planetary applications due to instrument or aperture size, thermal control issues, and radiation environment. For example, it can be difficult to maintain low temperatures for focal plane arrays and to maintain the thermal stability of optical systems in the presence of tightly stacked electronics and frequent and long radio-communication passes needed for long-distance communication. Free-flying planetary CubeSats can suffer from stringent limitations such as telecommunication back to Earth, implying the need for a larger antenna or supporting communication infrastructure. Existing and upcoming propulsion systems can provide the change in velocity required to reach a variety of targets, but the very low thrust implies flight times beyond the expected lifetime of CubeSat parts. Extra spacecraft volume may be required for larger propulsion systems.

Summary: CubeSats in Planetary Science

Even though there are no active planetary CubeSats or published science results from CubeSats in planetary science, there is demonstrated interest by the planetary science community, and multiple CubeSats are currently under development. However, the traditional CubeSat form factor is often not viable for planetary science due to telecommunications, propulsion, thermal, and other constraints.

Conclusion: CubeSats in planetary science have potential in three areas: creating unique vantage points or multipoint measurements, exploring high-risk or uncharted regions, and serving as low-gravity laboratories. However, they can have unique challenges: the traditional form factor may not be appropriate, and there may be lower risk tolerance due to the nature of single mission opportunities and potential risk to a mothership.

ASTRONOMY AND ASTROPHYSICS

Science Priorities in Astronomy and Astrophysics—Decadal Survey Highlights

The science goals for 2012-2021 put forward in the astronomy and astrophysics decadal survey report *New Worlds, New Horizons in Astronomy and Astrophysics*,[27] called "Astro2010," are the following:

[26] A. Babuscia, K-M. Cheung, and C. Lee, Jet Propulsion Laboratory, "Augmenting and Evolving the Mars Relay Network Using a Constellation of Identical CubeSats," presentation to the *Mars CubeSat/NanoSat Workshop*, November 20, 2014.

[27] NRC, 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, National Academy Press, Washington, D.C.

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- *Cosmic dawn:* searching for the first stars, galaxies, and black holes,
- *New worlds:* seeking nearby habitable planets, and
- *Physics of the universe:* advancing understanding of the fundamental physics of the universe.

The program envisioned to accomplish these goals primarily involved large observatories in space, such as the Wide-Field InfraRed Survey Telescope (WFIRST), the gravitational wave observatory LISA, and the X-ray observatory IXO. Large observatories such as these recommended missions and the James Webb Space Telescope (JWST)—the top priority from the 2001 decadal survey[28]—are required for many applications due to the natural faintness of observation targets that can only be detected with sufficient collecting power. Also included in Astro2010 was a major augmentation to the program of Explorer missions—small (i.e., hundreds of kilograms), cost-capped, PI-led spacecraft that are competitively selected. Smaller efforts in space include technology development for finding and characterizing nearby terrestrial exoplanets.

The History and Current Role of CubeSats in Astronomy and Astrophysics

Due to the large distances of the objects studied in astronomy and astrophysics, telescopic observations are needed. Space-based observations provide the ability to observe in wavelengths absorbed by the atmosphere or ionosphere (e.g., ultraviolet, X ray, <50 MHz radio, and parts of the infrared), observe without interruptions due to daylight and clouds, have very stable sensitivity and image quality, and observe without the distorting effect of atmospheric turbulence. Like any spacecraft, CubeSats can potentially provide the access to space required for these kinds of measurements, potentially at relatively low cost.

Astro2010 recognized that significant contributions have been made over the past decade by Explorer missions such as WMAP, Swift, WISE, GALEX, and NuSTAR, which utilized small (hundreds of kilograms) spacecraft. However, there is little mention of much smaller systems, such as CubeSats or nanosatellites, in the decadal survey. Furthermore, the astrophysics community's interest in the use of CubeSats has continued to lag behind that of other NASA science divisions because there are unique challenges in astrophysics. Many applications require large apertures for high angular resolution and sensitivity, precise attitude control, and large data rates. Nevertheless, the interest in the use of CubeSats is growing, and there are a number of mission concepts that address Astro2010 science goals.

The aperture of an instrument hosted by a CubeSat typically is constrained by the CubeSat's small size. However, CubeSats can provide dedicated observations of specific targets, thus somewhat compensating for the limited aperture size. Only a limited number of astronomy CubeSats have been selected to date, and none have resulted in published scientific results.

The Cosmic X-ray Background Nanosatellite-1 (CXBN-1) is a 2U CubeSat that was launched by the NASA CubeSat Launch Initiative's ELaNa program in 2012 to make precise measurements of cosmic (diffuse) X-ray (20-50 keV) background. The mission did not meet its science objectives due to a telemetry problem. However, a follow-on mission (CXBN-2) was selected for a 2016 launch.

Other missions make use the of the "stop and stare" ability of CubeSats, where each CubeSat in an array can be dedicated to observing a single object for long periods of time. The BRITE constellation (Figure 4.6) used this technique to study stellar variability. ExoPlanetSat[29] is a mission under development employing a suite of CubeSats to make ultra-stable brightness observations of Sun-like stars to search for transiting exoplanets.

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[28] NRC, 2001, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C.

[29] M.W. Smith, S. Seager, C.M. Pong, J.S. Villaseñor, G.R. Ricker, D.W. Miller, M.E. Knapp, G.T. Farmer, and R. Jensen-Clem, 2010, ExoplanetSat: Detecting transiting exoplanets using a low-cost CubeSat platform, *Proceedings of SPIE: the International Society for Optical Engineering* 7731:773127, http://hdl.handle.net/1721.1/61644.

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Achieving Science with CubeSats: Thinking Inside the Box

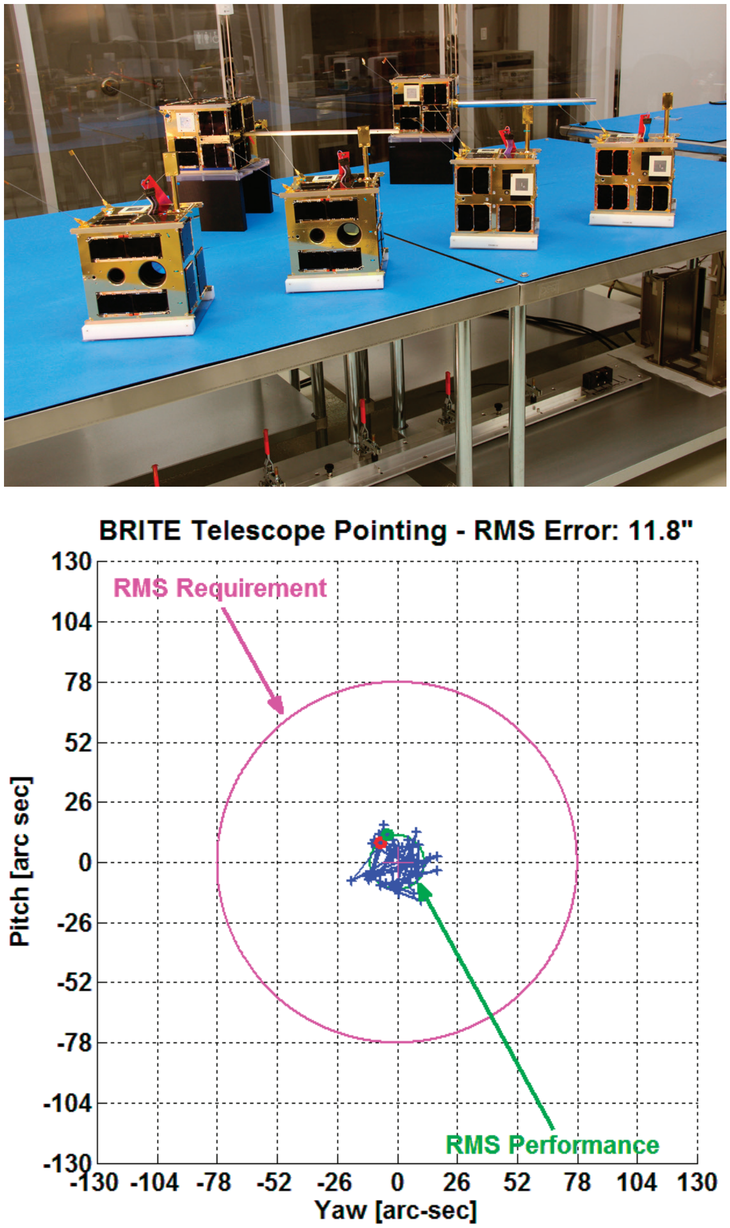

FIGURE 4.6 The BRITE (Bright Target Explorer) constellation consists of six 20-cm cube satellites, each employing one of two different optical filters to study variations in the intensity of massive stars. The periods of massive variable stars can range from minutes to months and can be due to a range of factors, including changes in surface temperature, stellar magnetic fields, etc. The goal of BRITE is to provide nearly continuous photometric data, with baselines up to 6 months, on all 286 stars that are brighter than magnitude +3.5. So far, BRITE has demonstrated 52 arcsecond pointing stability over several months. Preliminary results from the BRITE-Toronto CubeSat, which carries a startracker, show 15" pointing over a similar time frame. SOURCE: Courtesy of the Space Flight Laboratory of the University of Toronto.

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Near-Term Future Science Opportunities for CubeSats in Astronomy and Astrophysics

Addressing many of the science goals set out in the decadal survey requires arcsecond or better pointing to enable locking onto a astrophysical object or to allow integration of data from multiple exposures. The best CubeSat pointing capability currently claimed is 11 arcseconds,[30] although it has not yet been demonstrated in flight.[31] The 10 cm optics that fit in a 1U form factor give a 1 arcsecond FWHM diffraction limit at visible wavelengths, thus requiring arcsecond or better pointing for observations in the visible part of the spectrum. Several technology demonstration missions are under way to improve CubeSat pointing capabilities. The Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA) is a JPL Phaeton early-career project to achieve arcsecond-level line of sight pointing error and highly stable focal plane temperature control. If successful, missions such as this will enable the high-precision photometry required for transiting exoplanet detection, for example.

Deployables offer a potential workaround for the size constraints of a CubeSat. A structure such as a solar panel or antenna is folded up and housed in the CubeSat for launch and then unfolded into a larger structure after orbit insertion. A deployable petal telescope is currently under development to enable larger apertures.

Swarms or constellations will enable interferometric applications, another workaround for the size-constraint of a CubeSat. An interferometer at very low frequencies (<30 MHz) is currently being developed as a Chinese-European collaboration. The DSL mission, consisting of 10-50 CubeSats in lunar orbit, could provide images at frequencies not accessible from the ground and at significantly higher spatial resolution than ever achieved before at these frequencies. This mission would conduct a full sky survey to study transients, map diffuse galactic emission, possibly probe signals from the early universe, and address a number of other science goals. Precision guidance, navigation, and control—or at least knowledge of the relevant quantities—are critical for enabling interferometers at shorter wavelengths. In principle, interferometers could provide spacecraft separations larger than Earth, allowing for higher spatial resolution than is currently available from Earth-based Very Long Baseline Interferometry (VLBI).

Finally, CubeSats are being used to demonstrate enabling technologies that may feed into the development of the large missions of the future. The AAReST (Autonomous Assembly of a Reconfigurable Space Telescope) mission is a proof of concept mission to demonstrate the autonomous assembly of a large primary mirror using small independent spacecraft, each with a single mirror.[32]

Summary: CubeSats in Astronomy and Astrophysics

The small aperture size and pointing accuracy currently available with CubeSats has so far limited the use of the platform for astronomy and astrophysics. However, CubeSats can currently achieve niche mission objectives. They can be used as a dedicated spacecraft to stare at single bright targets for long periods of time, making them ideal for studying sources that vary on a variety of timescales. CubeSat constellations create opportunities for interferometry and other multi-aperture applications. Arcsecond pointing capability is needed to achieve many science objectives such as exoplanet detection.

Conclusion: Although many astronomy and astrophysics science goals require larger mission platforms than CubeSats, some science opportunities can be enhanced by the use of CubeSats. These include but are not limited to the following:

1. *Observations of variable sources including variable stars and transiting planets*—a CubeSat can stare for long time periods at targets of interest, for example;
2. *Interferometry*—CubeSats can form swarms and arrays that create new opportunities for multi-aperture observations; and

[30] The current Blue Canyon XACT appears to deliver 11 arcsecond 1-sigma 1-axis, which gives about 25 arcsecond FWHM.
[31] The first on-orbit test of the BCT XACT Attitude Determination and Control System Technology will be on the MinXSS mission that launched to the ISS in December, 2015.
[32] K. Fesenmaier, 2013, Using space wisely, *Engineering and Science* 76(4):14-19, http://www.its.caltech.edu/~sslab/2013_Winter_Using_Space_Wisely.pdf.

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Achieving Science with CubeSats: Thinking Inside the Box

3. *Technology de-risking*—CubeSats can be platforms for new technology development and testing of sensors and system methodologies that will enable larger missions.

BIOLOGICAL AND PHYSICAL SCIENCES IN SPACE

Relevant Science Priorities in Biological and Physical Sciences in Space from the Decadal Survey

This section addresses other areas where CubeSats have proved or have the potential to advance scientific knowledge, encompassing biology research in natural gravity and radiation environments and microgravity research for material physics. A comprehensive list of science objectives are presented in the 2011 biological and physical sciences in space decadal survey report *Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era*.[33] Some example objectives potentially relevant to CubeSats include the following:

- Plant and microbial growth and response to the space environment,
- Study of complex fluids and soft matter in the microgravity laboratory, and
- Advanced materials design and development for exploration.

Biology research is of particular interest to NASA because it helps characterize the impact of space environment on a human crew while characterizing the potential limits of terrestrial biology to move beyond Earth. Information of interest includes monitoring the metabolic activity and genome alteration of plants and possibly also microbes and small animals. This information has intrinsic value to terrestrial biology in extraterrestrial environments and can also be extrapolated to predict the impact of long-term exposure to deep space on the human body. It is also of interest to astrobiology in order to assess the potential for life to survive beyond Earth.

Spaceborne in situ laboratories also provide novel ways to approach fundamental and material physics questions. Indeed, it is very difficult to simulate microgravity on Earth over extended periods of time and expensive to develop and run that type of experiment on the ISS. Moreover, there are advantages in that CubeSats can more readily achieve longer periods of microgravity than on an operational platform such as the ISS. The need for microgravity research is also explicitly called out in the planetary science decadal survey.[34]

The History and Status of CubeSats in Biological and Physical Sciences in Space

Biology research in space motivated the early development of fully automated CubeSats, starting with GeneSat in 2006, the first science CubeSat. GeneSat provided a life support environment and nutrients to bacteria and tracked the production of proteins as a result of genetic activity. In 2007, NASA released a call for small payloads for astrobiology research that received a large number of concepts and resulted in the selection of the O/OREOS mission (Organism/Organic Exposure to Orbital Stresses) (Figure 1.8). More recently, NASA's Advanced Exploration Systems selected the BioSentinel 6U mission, led by NASA's Ames Research Center, to pursue radiation studies in an Earth trailing heliocentric orbit.

Two recent examples illustrate the value and potential offered by small and automated laboratories in space. O/OREOS monitored the effects of space exposure on organic molecules and biological organisms, advancing the state of the art by the first real-time analysis of the dynamic response of organics and biomarkers to direct solar irradiation for long exposures under simulated and controlled environments.[35] Another goal of the O/OREOS mis-

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[33] NRC, 2011, *Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era*, The National Academies Press, Washington, D.C.

[34] NRC, 2011, *Vision and Voyages*.

[35] A. Mattioda, A. Cook, P. Ehrenfreund, R. Quinn, A.J. Ricco, D. Squires, N. Bramall, K. Bryson, J. Chittenden, G. Minelli, E. Agasid, et al., 2012, The O/OREOS mission: First science data from the space environment viability of organics (SEVO) payload, *Astrobiology* 12(9):841-853; A.M. Cook, A.L. Mattioda, A.J. Ricco, R.C. Quinna, A. Elsasser, P. Ehrenfreund, A. Ricca, N.C. Jones, and S.V. Hoffmann, 2014, The Organism/Organic Exposure to Orbital Stresses (O/OREOS) satellite: Radiation exposure in low Earth orbit and supporting laboratory studies of iron tetraphenylporphyrin chloride, *Astrobiology* 14(2):87-101.

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Achieving Science with CubeSats: Thinking Inside the Box

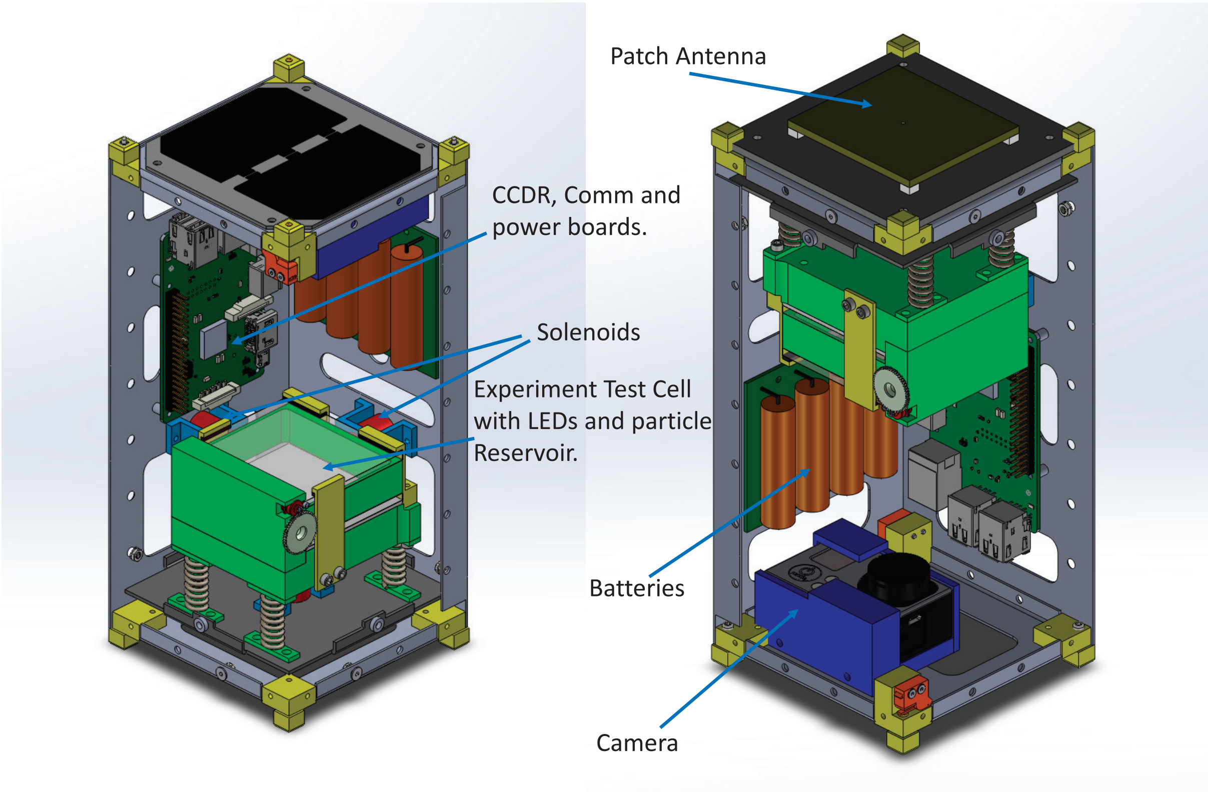

FIGURE 4.7 The goal of Q-PACE (CubeSat Particle Aggregation and Collision Experiment) is to explore the fundamental properties of low-velocity (<10 m/s) particle collisions in a microgravity environment, via imaging, in an effort to better understand the mechanics of early planetesimal development and accretion. This type of mission offers extended time in low gravity. NOTE: See J. Colwell, J. Brisset, and A. Dove, 2015, "A CubeSat Microgravity Experiment on Collisions in the Protoplanetary Disk," presented at 5th Interplanetary CubeSat Workshop, Oxford, United Kingdom. SOURCE: Courtesy of the University of Central Florida.

sion was to demonstrate the capability for CubeSats to autonomously perform in situ biological experiments in a relevant environment at low cost. Q-PACE (Figure 4.7), currently under development and selected for launch under the CSLI program in fall 2016, uses the microgravity environment to study the mechanics of early planetesimal development and accretion, important for understanding solar system formation. A similar mission, called AOSAT[36] (Asteroid Origins Satellite), is also under development, internally funded by the Arizona State University, selected in 2015 for launch as part of the ELaNa program.

For many applications, a micro-laboratory lends itself to the advantages provided by the CubeSat standard. Performance requirements (e.g., mass, power, pointing) are generally compatible with CubeSat resources. Data downlink is manageable with a UHF or S-band patch antenna, although the small data rates limit the return of high-quality science images (e.g., uncompressed). The observing sensors themselves have benefited from miniaturization advances over the past decade and the introduction of new technologies (e.g., 3-D printing, micro-eletromechanical systems), although the absence of off-the-shelf components in most cases require new technological and engineering solutions that may be resource intensive.

[36] J. Thangavelautham, A. Thoesen, F. Gadau, G. Hutchins, E. Asphaug, and I. Alizadeh, 2014, Low-cost science laboratory in microgravity using a CubeSat centrifuge framework, *Proceedings of 65th International Astronautical Congress*, http://space.asu.edu/IAC-2014-cubesat_centrifuge_laboratoryc.pdf.

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Achieving Science with CubeSats: Thinking Inside the Box

Near-Term Future Science Opportunities and Challenges for CubeSats in Biological and Physical Sciences in Space

The missions discussed in the previous subsection have been developed for LEO, which simplifies their design. Building on the success of the GeneSat, PharmaSat, and O/OREOS missions, NASA's Ames Research Center is now developing the Bio-Sentinel mission, which is scheduled to launch in 2018 with the first launch of the Space Launch System on EM-1. This 6U CubeSat includes a 4U science payload that will track the degradation and repair of yeast DNA as a result of radiation at the lunar orbit. This mission takes advantage of the space offered by a 6U CubeSat to increase the number, quality, and control of the samples and monitor radiation with multiple sensors.[37] Experience gained from the development of CubeSat-based laboratories was also leveraged to develop automated experiments that run on ISS NanoRacks without the need for crew monitoring.[38]

The implementation of CubeSat-based autonomous in situ laboratories comes with a number of challenges. The small resources available to the science experiment limit the extent of testing and monitoring. The small CubeSat form factor may introduce boundary effects in material physics experiments, which decreases the effective volume usable for science observations. Low downlink rates may prevent the use of high-resolution imaging that would be complementary to analytical measurement techniques, unless resources are traded between payload and telecommunications. Automated experimental protocols are complex to implement and in many cases, require the introduction of new technologies or engineering solutions that cannot be attained with commercial off-the-shelf components.[39]

Another major limitation that applies to both biological and, to lesser extent, material physics study is the long lead time required for flying on certain rockets (e.g., EM-1), which would require that the specimens be left under limited temperature control for periods of months and may also lead to contamination of the samples. This hinders biology investigations using complex organisms (e.g., small animals, most mammalian cultures, multicellular microorganisms). The long lead time may also impact the stability of reagents or drugs used as part of the experiment. This aspect may be addressed with new approaches to thermal engineering and packaging, which in turn adds to development complexity.

The scale of the CubeSat-based laboratory (~1U) is a constraint to the type of processes that can be simulated and may pose boundary issues. Still, they offer a novel avenue for studying processes that would remain poorly understood otherwise, due to the lack of access to low-gravity environments.

Summary: CubeSats in Biological and Physical Sciences in Space

CubeSats offer a platform for investigating processes in environments that cannot be reproduced on Earth or under constrained conditions. In particular, CubeSats can provide access to microgravity and relevant radiation environments for extended periods of time.

Conclusion: CubeSats have already performed science in microgravity and biological sciences and continue to offer opportunities for future investigations. However, the use of CubeSats as microgravity laboratories for live specimens is limited by size constraints and the difficulty of maintaining life support during satellite integration and launch delays.

SUMMARY OF CUBESATS IN SCIENCE

CubeSats play a different role in each science discipline, and therefore, there are a wide range of CubeSat mission concepts in terms of complexity and scale. The science potential of CubeSats has already been demonstrated

[37] W. Nicholson, University of Florida, and T. Ricco, NASA Ames Research Center, "Biological Science in Space: Role of CubeSats (aka Nanosatellites)," presentation to the committee, October 28, 2015.

[38] NASA, "NanoRacks-Ames Fruit-Fly Experiment (NanoRacks-AFEX)," release date September 24, 2015, http://www.nasa.gov/mission_pages/station/research/experiments/1360.html.

[39] W. Nicholson, University of Florida, and T. Ricco, NASA Ames Research Center, "Biological Science in Space: Role of CubeSats (aka Nanosatellites)," presentation to the committee, October 28, 2015.

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in the field of solar and space physics where CubeSats have delivered high-impact results and have augmented larger facilities. In Earth science, CubeSats and CubeSat-enabled technologies have so far been underutilized for science. However, the CYGNSS Venture-class mission heavily relies on CubeSat technology. A number of missions are under development in planetary science but have not yet flown. These missions can be higher cost and have lower risk tolerance than traditional CubeSats do (although they may still be cheaper than the traditional alternative for planetary science), and the fly-learn-refly paradigm generally does not apply. Most astronomy- and astrophysics-themed CubeSat concepts are still notional, with many requiring significant advances in pointing and other technologies to be scientifically useful. In biological and physical sciences in space, CubeSats complement research on the ISS and are the only viable alternative to the ISS as well, with the potential to provide access to deep space environments.

Technology development continues to play an important role in promoting the use of CubeSats. In particular, sensor development, optical, or other methods for high-rate communication, arcsecond pointing, and propulsion will enable future capabilities and science applications.

The set of science goals where the use of CubeSats would be enabling is evolving too quickly to comprehensively list, and, per the statement of task in Appendix A, this committee has not been tasked with prioritizing CubeSat missions. However, the following provides a sampling of high-priority science goals that could potentially be pursued using the CubeSats:

- *Solar and space physics, Earth science and applications from space—Exploration of Earth's atmospheric boundary region*. CubeSats are uniquely suited because of their expendability to explore the scientific processes that shape the upper atmospheric boundary using short-lifetime, low-altitude orbits.
- *Solar and space physics—Measurement of plasma processes in the magnetosphere-ionosphere system*. A 10-100 satellite constellation of CubeSats carrying magnetometers and plasma instrumentation can provide detailed information about the spatial and temporal evolution of magnetospheric plasmas.
- *Earth science and applications from space—Multipoint, high temporal resolution of Earth processes*. Satellite constellations in low Earth orbit could provide both global and diurnal observations of Earth processes that vary throughout the day, such as severe storms, and are currently under-sampled by Sun-synchronous observatories.
- *Earth science and applications from space—Mitigation of data gaps and continuous monitoring*. Anticipated and potential gaps (caused by launch or instrument failures and budget constraints) in weather satellite data, land surface imaging, and solar irradiance measurement may have the potential to be mitigated by observations from small spacecraft enabled by CubeSat technology.
- *Planetary science—Measuring the distribution of lunar water.* CubeSat concepts could map the distribution of water on the Moon with a variety of complementary techniques, such as neutron spectroscopy and infrared spectroscopy.
- *Planetary science—In situ investigation of the physical and chemical properties of planetary surfaces or atmospheres*. Deployable (daughter-ship) CubeSats could expand the scope of the motherships with complementary science or site exploration.
- *Planetary science—Measurements of planetary magnetospheres*. Constellation of CubeSats could provide simultaneous fields and particle measurements at multiple sites in planetary magnetospheres. Such measurements in the vicinity of large icy satellites could help determine the magnetic field induced in deep oceans.
- *Astronomy and astrophysics—Search for extrasolar planets*. A CubeSat could "stop and stare" for a long time at one bright Sun-like star to search for transiting exoplanets.
- *Astronomy and astrophysics, solar and space physics—Low-frequency radio science*. Interferometers made of CubeSats could explore the local space environment and also galactic and extragalactic sources with spatial resolution in ways not accessible from Earth.
- *Biological and physical sciences in space—Investigate the survival and adaptation of organisms to space*. CubeSats offer a platform to understand the effects of the environment encountered in deep space, such as microgravity and high levels of radiation.

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The committee made the following conclusions related to science:

Conclusion: CubeSats have already produced high-value science as demonstrated by peer-reviewed publications that address decadal survey science goals. CubeSats are useful as instruments of targeted investigations to augment the capabilities of large missions and ground-based facilities, they are enabling new kinds of measurements, and they have the potential to mitigate gaps in measurements where continuity is critical.

Conclusion: Although all science disciplines can benefit from innovative CubeSat missions, CubeSats cannot address all science objectives and are not a low-cost substitute for all platforms. Some activities, such as those needing large apertures, high-power instruments, or very-high-precision pointing, most likely will always require larger platforms because of fundamental and practical constraints of small spacecraft.

Conclusion: Constellations of 10 to 100 satellites can provide transformational science, particularly in solar and space physics and Earth science where high-cadence or multipoint measurements are essential for studying highly coupled systems. Constellations or swarms may also provide important science capabilities in astronomy. CubeSats provide a realistic and possible path toward such constellation missions.

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5

Technology Development: Current Status and Future Direction

CubeSats have significantly evolved during the past decade, which could be expected of a disruptive innovation, described in Chapter 2. The science capabilities of CubeSats ultimately depend on their technological status. Due to their geometrical and mass constraints, CubeSats provide a unique innovation platform from which to rethink many engineering subsystems, especially in the context of modern developments in integrated sensors, as well as advances in computational and communications technologies. Such development may have important consequences beyond CubeSats for spacecraft of various sizes.[1]

Table 5.1 presents some of the CubeSat enabling technologies and examples of potential applications derived from Chapter 4's discussion of each science discipline. For many disciplines, advancement in propulsion and high-bandwidth communications would be enabling. In particular, propulsion, which could enable significant new science applications, has rarely been used with CubeSats. Thermal control, as well as electrical power generation, storage, and management (although not listed for each discipline), are other challenging areas that are important for the continued evolution of CubeSats. See Table 5.2 for a brief overview of the status and capabilities of CubeSat technologies, from early CubeSats (past), to widely available and widely used systems (available), to capabilities on the cusp of development or that may not yet be widely available (emerging).

Many highly capable CubeSat technologies are under development, and as is common in rapidly evolving fields, notable gaps sometimes exist between flight-proven technologies and claimed performance levels. Moreover, the fast pace of the technology development, highly engaged academic and commercial communities, and rapid and frequent flight opportunities allow closing of technology gaps at a much quicker pace than elsewhere in the space sector.

COMMERCIAL PLAYERS AND THEIR RELEVANCE TO SCIENCE AND TECHNOLOGY DEVELOPMENT

Private industry is an important stakeholder in the CubeSat ecosystem—one that the government and scientific community can leverage to promote its own cost-effectiveness. Figure 1.3 shows that 76 percent of CubeSats launched in 2014 were commercial, and many technology developments in the sector are either made or driven by commercial actors. Many of the companies active in the CubeSat sector, especially operators and launch providers,

[1] As noted in previous chapters, more than three-quarters of publications related to CubeSats are in engineering and technology areas.

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TABLE 5.1 CubeSat Enabling Technologies and Potential Applications for Each Science Discipline

Science Discipline	Enabling Technology	Example Application
Solar and Space Physics	Propulsion	Constellation deployment and maintenance; formation flight
	Sub-arcsecond attitude control	High-resolution solar imaging
	Communications	Missions beyond low Earth orbit
	Miniaturized field and plasma sensors	In situ measurements of upper atmosphere plasmas
Earth Science and Applications from Space	Propulsion	Constellations for high-temporal-resolution observation and orbit maintenance
	Miniaturized sensors	Stable, repeatable, and calibrated data sets
	Communications	High data rate
Planetary Science	Propulsion	Orbit insertion
	Communications	Direct-to-Earth communications
	Radiation-tolerant electronics	Enhanced survival in planetary magnetospheres; long-duration flight
	Deployables	Enhanced power generation beyond Mars
Astronomy and Astrophysics	Propulsion	Constellations for interferometry; distributed apertures
	Sub-arcsecond attitude control	High-resolution imaging
	Communications	High data rate
	Deployables	Increase aperture and thermal control
	Miniaturized sensors	Ultraviolet and X-ray imaging
Biological and Physical Sciences in Space	Thermal control	Stable payload environment

TABLE 5.2 Brief Overview of the Status and Capability of CubeSat Technology

Subsystem	Past	Available	Emerging	Report Section
Attitude determination	±10°	±0.5 - 1° Electromagnets, Sun and Earth sensors	±0.002 – 0.01° Star trackers	Attitude and Orbit Determination and Control, p. 60
Attitude control[a]	±10° Passive, magnetic system and hysteresis	±0.5 - 5° Reaction wheels, with limited de-saturation	±0.1° (± ~0.01° by 2017) Reaction wheels, de-saturate via propulsion systems	Attitude and Orbit Determination and Control, p. 60
Orbit determination	Two Line Element tracking: low accuracy	2-way ranging. Accurate to <2 km, and GPS: ~10 m in position and 1 m/s in velocity	2-way Doppler ranging	Attitude and Orbit Determination and Control, p. 60
Orbit control	None	Differential drag, limited maneuvering	Non-propulsive systems and low-capability propulsive systems	Orbit Determination and Control, p. 60
Communications[b]	<9.6 kbps	~1 Mbps	Up to 50 Mbps (100-600 Mbps by 2017)	Communication, p. 61
Propulsion[c]	None	Cold gas and other simple systems	Chemical, Plasma, and Electrospray systems	Mobility and Propulsion, p. 62; Deorbit Control and Space Debris Mitigation, p. 101

continued

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TABLE 5.2 Continued

Subsystem	Past	Available	Emerging	Report Section
Electrical power generation[d]	Body mounted cells	Deployable solar arrays: ~50 W on a 3U	Deployable, sun-tracking solar arrays: >75 W on a 3U	Mobility and Propulsion, p. 62
Electrical power storage[e]	<30 Whr	30 - 160 Whr	>200 Whr	Mobility and Propulsion, p. 62
Thermal [f]	Passive	Passive and electrical heaters	Passive heat-pipes, thermal louvers, deployable Sun shield; new active systems, e.g., micro-cryocoolers	Electrical Power, Energy Storage, and Thermal Control, p. 63
Deployable systems	None	Solar arrays and UHF/VHF dipole antennas	Ka-band antennas, gossamer structures, and tethers	Deployable Systems, p. 64
Software[g]	Patchwork of scripts and lack of standards	Migration custom processors to Linux-based systems. Easing testing	Real-Time Operating Systems, multitasking, priority based scheduling and dynamic management	Flight and Ground Systems Software, p. 68
Data handling and storage	Consumer grade electronics	Multiple flight proven solutions with SRAM and Flash storage	Increases in reliability and performance, including radiation tolerance and mitigation	Data Handling, Processing, and Autonomy, p. 68
Systems and constellations	Single, one-off platforms with occasional re-flights	2-3 science platforms, plus commercial constellations	Off the shelf platforms (Science constellations of 10+ and formation flying by 2017)	System Integration, Platforms, and Constellations, p. 69
Ground segment	Based on systems derived or developed from within amateur community who can offer significant support. Inter-satellite links have flown. Operational costs can be a driver.			CubeSat Communication, p. 75; Tracking Technology Options, p. 101
Launch	Ease of integration a key enabler. Dispenser a well-established standard isolating from launch vehicle. Emerging small satellite launchers and even CubeSat-focused launch vehicles.			Launch as a Choke Point, p. 80; Integration with Launch Vehicle, p. 103

[a] Further improvement challenging without propulsion systems.
[b] Significant improvement enabled by improved attitude control. Moving from UHF/VHF through S and X-band, to Ka-band and low-power optical systems.
[c] Perhaps the least mature of the traditional sub-systems. Limited options due to volume and launch restrictions.
[d] More power can be generated on larger spacecraft (i.e., 6 or 12U, due to larger surface areas).
[e] Storage capabilities broadly tracking terrestrial capabilities using Lithium-ion and -polymer battery technology.
[f] Already an issue for certain science missions. As power density increases, thermal control will likely become an increasing challenge.
[g] Lags hardware development.
NOTE: A listing of capabilities, from early CubeSats (past) to widely available and widely used systems (available). Capabilities at the cusp of development or that may not yet be widely available (emerging) are also shown, along with technologies likely to be flown and demonstrated by 2017. The table notes in what sections detailed information can be found.

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are relatively new. A sign that these emerging players are an important element of the CubeSat ecosystem is the fact that all five of the winners of the first milestone of NASA's Cube Quest Challenge are entrepreneurial entities within universities or relatively unknown companies in the aerospace sector.[2]

Currently, most CubeSat companies are headquartered in the United States, although the sector has global participation. Spire, for example, has locations in the United States, the United Kingdom, and Singapore. Although it is not possible to separate CubeSat companies from small satellite companies, conference attendance statistics show that the dominant presence of both is from the United States. Nearly 600 companies were represented at the 2013 SmallSat Conference in Utah, of which approximately 75 percent were from the United States. However, as evidenced in the SmallSat conference, global participation is increasing. A review of participation statistics in the past 2 years shows that, excluding the United States, countries with the most industry presence are Japan and in Europe, in particular the United Kingdom, the Netherlands, and Sweden. In 2015, companies from 13 countries were represented that had not attended in 2014.

The commercial CubeSat sector is composed of a number of segments, such as the following:

- *Firms that focus on hardware and software manufacturing and development, including manufacture of components*. Current examples include both established and newer firms such as Blue Canyon Technologies, Black Swift Technologies, Maryland Aerospace Inc., Pumpkin Inc., SSBV Aerospace and Technology Group, Sinclair Interplanetary, Tyvak Nano-Satellite Systems Inc., and Tethers Unlimited, Inc., in the United States and Clyde Space, Gomspace, and Innovative Solutions in Space in Europe.
- *Firms that focus primarily on operations and data services*. Examples include Canopus Systems LLC, Planet Labs, Spire, and Terran Orbital, who operate CubeSats alongside larger but still small spacecraft. Planet Labs, for example, covers the entirety of the supply chain and manufactures its CubeSats, operates them, and sells imagery.
- *CubeSat-enabled companies that focus exclusively on downstream activities,* such as image analysis (examples include Mapbox, Orbital Analysis, and Windward), and use emerging techniques in big data (e.g., deep learning) to analyze the petabyte-sized data sets to which CubeSat data are added.
- *An emerging set of launch providers*, often not exclusively focused on CubeSats, includes both brokers—such as Spaceflight Industries, Tyvak, and Innovative Solutions in Space in Europe, that connect developers with launchers—as well as launch providers such as SpaceX, new launch systems like Virgin Galactic's LauncherOne, or emerging small launcher companies like Rocket Labs. Of the 24 or so companies that can launch CubeSats as primary and secondary payloads, fewer than 20 percent focus on CubeSats alone.

Most commercial CubeSats, and hence the companies operating them, are engaged in remote sensing and Earth observation and technology demonstrations. Of the total commercial CubeSats (177 out of the 425 total CubeSats launched since 2000), the vast majority are related to imaging (Figure 5.1). It is worth noting that most of the 177 were launched in the past 2 years, and 150 were imaging satellites launched by Planet Labs. Planet Labs plans to launch 250 CubeSats in 2016.

The sources of funds for CubeSat companies are varied and not generally publicly available or tracked. For example, Planet Labs has raised almost $200 million in venture capital, while Spire has raised $66.5 million.[3] Companies like Accion Systems and Phase Four, that are developing propulsion systems for CubeSats, have also been funded all or in part by angel or venture funds. Many companies find the United States to be an ideal location because of the better funding environment. For example, New Zealand's Rocket Labs has moved its headquarters to the United States for better access to investments and experienced partners. That said, companies in other

[2] NASA's Cube Quest is a competition to build flight-qualified, small satellites capable of advanced communication and propulsion near and beyond the Moon. Teams that achieve top performance at high-speed data communications, navigation, and survival after achieving lunar orbit or a minimum long-distance range from Earth compete for an unprecedented $5.5 million prize purse in NASA's first ever in-space challenge. Cube Quest is part of NASA's Centennial Challenges Program, which accelerates technology by engaging nontraditional sources in competition (see http://www.nasa.gov/directorates/spacetech/centennial_challenges/cubequest/nasa-awards-first-round-prizes-in-cube-quest-challenge.html).

[3] CrunchBase, "Spire," https://www.crunchbase.com/organization/nanosatisfi#/entity, accessed April 7, 2016.

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Achieving Science with CubeSats: Thinking Inside the Box

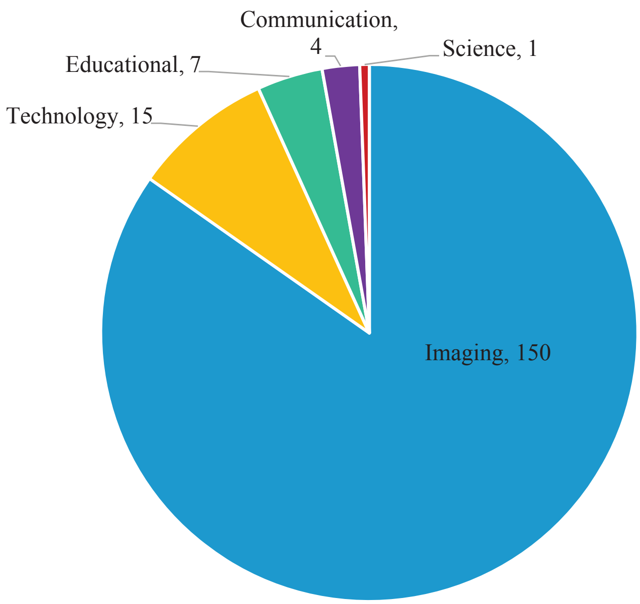

FIGURE 5.1 Distribution of commercial launches. More than three-quarters of the commercial CubeSats are focused on imaging. SOURCE: Data from M. Swartwout, St. Louis University, "CubeSat Database," PistachioTables 2.6.3, February 2016, https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database#refs, adjusted and updated by the committee.

countries are also able to raise venture funds, such as Lithuania's NanoAvionics, a seed stage company in Europe that has raised €200,000.[4]

Overall, with only very few exceptions, these companies have emerged outside of the mainstream aerospace community, which is consistent with the conclusion above that CubeSats are a disruptive innovation (see Chapter 2). Like other disruptive innovations, CubeSats use deeply entrepreneurial paradigms and funding mechanisms and new, often exploratory business models, making CubeSats a low-cost way to collect space-based data of commercial interest.

Impact of Industry on Science-Based Missions

The increasing number of commercial CubeSats and other small satellites in development have many benefits for science-based missions. First, commercial entities may be able to take greater levels of risk and test innovative ideas. As an example, while the principles of GPS radio occultation were developed and tested within government, firms like PlanetIQ and Spire were among the first to develop commercial applications based on them. Commercial approaches also tend to be low cost, providing researchers with lower-cost options for data collection, enabling the avenue of scientific data purchase. Lastly, commercial developments are able to create lower-cost components and technologies and have created a sizable market for spacecraft components and subsystems. There are now a number of vendors for off-the-shelf components, or those requiring minor modifications, useful for mission development. Star trackers, attitude control systems, momentum wheels, transponders, and power supplies are examples of such "stock" items, exploiting economies of scale not available to other space platforms to drive the price point down. However, some long-lead-time items, such as solar arrays, do remain.

[4] Practica Capital, "Practica Capital Invests 200,000 EUR in Space Start-Up Company NanoAvionics," http://practica.lt/en/news1/practica-capital-invests-200000-eur-in-space-startup-company-nanoavionics/, accessed April 7, 2016.

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Finding. Commercial firms are a driver of both innovative application and technology development in the CubeSat sector. Commercial activity has accelerated the development of technologies—for example, attitude control, making it more robust and reliable for use in science missions.

TECHNOLOGY AREAS

Attitude and Orbit Determination and Control

Attitude Determination and Control

Perhaps the most significant improvement in CubeSat technology performance has been in attitude determination and control because this has, in turn, enabled the development and application of other subsystems, such as enhanced communication.

Early CubeSats used simple, often passive attitude control systems such as permanent magnets or electromagnets, resulting in attitude control of order ±10 degrees in low Earth orbit (LEO). CubeSat attitude determination techniques have significantly advanced in the past decade, with many of the techniques found on larger spacecraft now also available on CubeSats. These include Sun and Earth sensors; angular rate sensors, including inertial measurement units; and star trackers. Likewise, attitude control systems have improved, with systems such as reaction wheels and control moment gyros now commercially available from a number of retailers. Consequently, attitude determination has seen significant advances (Figure 5.2), with some CubeSat systems now claiming accuracy capabilities of <10 arcseconds, enabling theoretical 3-axis control to tens of arcseconds (<30-40 arcseconds).

The Optical Communication and Sensor Demonstration series of CubeSats (OCSD-A through C) aims to demonstrate attitude control of ±0.1 degree (360 arcseconds),[5] comparable to many small spacecraft platforms currently used for Earth observation science missions. Furthermore, the MinXSS (Miniature X-ray Solar Spectrometer), due for deployment from the International Space Station in early 2016,[6] seeks to demonstrate attitude control in tens of arcseconds using a commercially available Attitude Determination and Control System (ADCS), a potential improvement of three orders of magnitude from early CubeSats.

Orbit Determination and Control

Many CubeSats depend on the observations made by the Joint Space Operations Center (JSpOC) (two-line elements), which are available free of charge.[7] However, some operators also use two-way ranging for increased accuracy. Orbits derived from two-way UHF ranging data can be accurate to within 2 km within 24 hours of the epoch.[8]

The onboard use of GPS is also becoming increasingly common for orbit determination, and it offers further improvements in accuracy to around 10 m in position and 1 m/s in velocity in post-processing. It should be noted that GPS is not used for attitude determination, as it can be on larger spacecraft, due to the challenge of gaining sufficient separation between antennas.

Attitude control is typically realized through the use of a reaction wheel system; however, their utility remains somewhat limited by the lack of a reactive propulsion system.[9] This challenge extends to that of orbit control; however, methods such as differential drag control have been used to gain orbit separation between spacecraft and do offer some limited orbit-maneuvering capability.

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[5] S.W. Janson, R.P. Welle, T.S. Rose, D.W. Rowen, D.A. Hinkley, B.S. Hardy, S.D. La Lumondiere, G.A. Maul, and N.I. Werner, 2015, "The NASA Optical Communication and Sensors Demonstration Program: Preflight Up-date," *Proceedings of the AIAA/USU Conference on Small Satellites*, Technical Session III: Next on the Pad, SSC15-III-1, http://digitalcommons.usu.edu/smallsat/2015/all2015/14/.

[6] MinXSS successfully deployed from the ISS along with the CADRE CubeSat on May 16, 2016.

[7] CelesTrak, updated March 3, 2015, http://www.celestrak.com/; Space-Track, https://www.space-track.org/auth/login/, accessed April 8, 2016.

[8] Commercial tracking services are emerging. These may offer further improvements but also with a recurring cost.

[9] Most systems rely on electromagnetic systems, such as torque rods.

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Achieving Science with CubeSats: Thinking Inside the Box

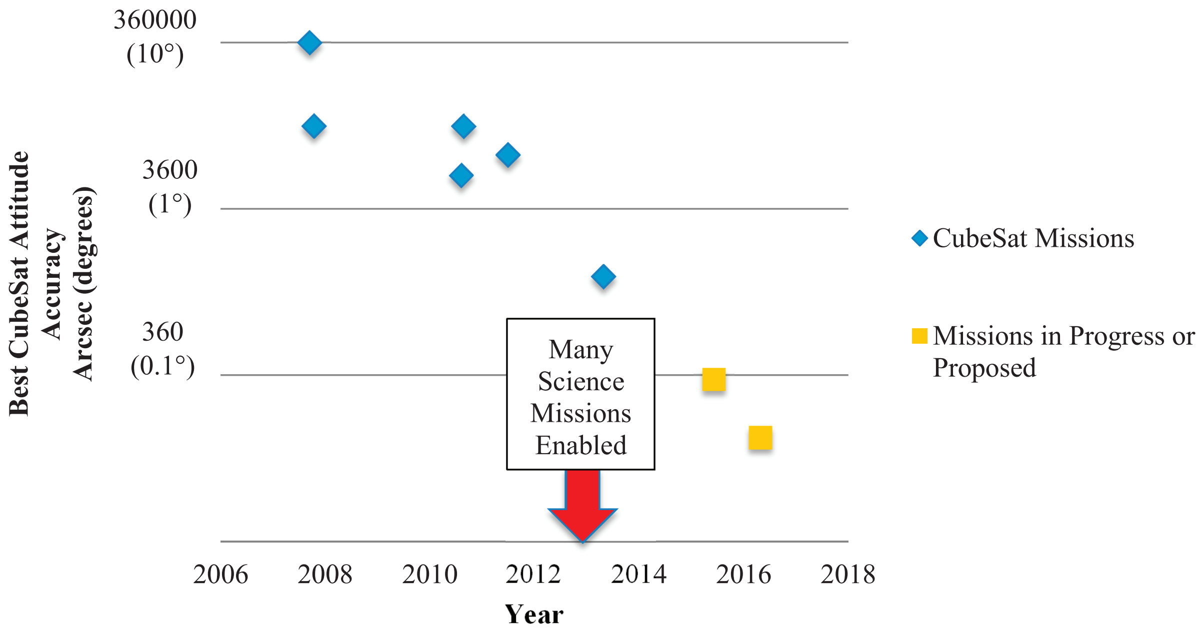

FIGURE 5.2 Improvement of attitude control capabilities with time. Many scientific missions, especially in astrophysics, would benefit from control below a few tens of arcseconds. SOURCE: Data from C. Frost, E. Agasid, D. Biggs, J. Conley, A. Dono Perez, N. Faber, A. Genova, A. Gonzales, A. Grasso, J. Harpur, S. Hu, et al., Mission Design Division, 2014, *Small Spacecraft Technology: State of the Art*, NASA Technical Report TP-2014-216648/REV1, NASA Ames Research Center, Moffett Field, California, http://cmapspublic3.ihmc.us/rid=1NG0S479X-29HLYMF-18L7/Small_Spacecraft_Technology_State_of_the_Art_2014.pdf.

Communication

Communication systems have been limited historically by the external surface area on CubeSats, the available power, and attitude control. Furthermore, the availability of suitable ground stations and adequate spectrum allocation means that communication is not only a technical issue but also a regulatory one. Many science missions in LEO can be accomplished with widely available antenna technology, as long as required data rates are moderate. Note that commonly available data rates have increased from around 9.6 kbps to over 1 Mbps in recent years. However, as missions become more sophisticated, it is expected that researchers and users will require faster access to ever-increasing amounts of data. This would put additional pressure on the technological requirements of CubeSat communication technology and in the development of ground stations. 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. If the mission had a radio with high enough bandwidth to retrieve all of the data, it would also have required significantly more power.[10]

The introduction of interplanetary CubeSats has driven the development of high-performance radios also capable of two-way communication (for command, navigation), such as the IRIS transponder developed for the INSPIRE and MarCO missions. Large antennae are also required in order to enable data retrieval for several of the deep space CubeSats under development or ready to launch, such as the Near Earth Asteroid (NEA) Scout and MarCO missions that will all communicate from about 1 AU from Earth. MarCO uses technology developed within ISARA (Integrated Solar Array and Reflectarray Antenna) technology demonstration mission.[11]

[10] Personal communication, Alex Crew.

[11] NASA, "Integrated Solar Array and Reflectarray Antenna (ISARA): Increasing CubeSat Downlink Data Rates to 100 Mbps," release date May 3, 2013, https://www.nasa.gov/directorates/spacetech/small_spacecraft/isara_project.html.

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Achieving Science with CubeSats: Thinking Inside the Box

A further potentially attractive solution for CubeSats would be the use of low-power optical communications. This could alleviate some spectrum regulation concerns while providing potential for multiple gigabits-per-second data rates. The NASA-sponsored, Aerospace Corporation-developed OCSD series plans to demonstrate data rates up to ~600 Mbps using optical communications in 2016, using an 80 cm diameter ground station (telescope).[12]

Mobility and Propulsion

Often, as secondary payloads, CubeSats are launched into an orbit selected by the primary launch payload, thus posing a limitation on the type of orbital designs available for nonmobile CubeSats. Mobility enabled by onboard propulsion (or other strategies discussed below) is, therefore, required to provide scientific CubeSats with the ability to change, or maintain, their orbits once they are in space. Mobility also enables formation flying, orbital deployment and maintenance of constellations, and an ability to compensate for atmospheric drag or trigger deorbit at the satellite's end of life. Mobility can be characterized by the effective change in satellite velocity, or delta-V (ΔV). For example, in LEOs, a ΔV of 100 m/s provides a change of about 200 km in orbital altitude. Mobility also complements the capability of CubeSats to control their attitude to the precision required by a particular mission and would be required to dump stored momentum from the reaction wheels for CubeSats beyond LEO, when the magnetic field of Earth can no longer be used. At present, limited mobility options exist without overly penalizing the volume available to the payload.

Chemical and electric propulsion devices have been proposed and developed for CubeSats, each having particular miniaturization and operational challenges. Chemical thrusters make use of reactions that increase the kinetic energy of propellants. In general, the performance of chemical thrusters improves at higher temperatures and pressures, both of which present a serious concern when launched as secondary payloads. To protect the primary payload, CubeSats have to comply with the Launch Services Program Level Poly Picosatellite Orbital Deployer (P-POD) and CubeSat Requirements Document (LSP-Req-317.01); a waiver is required to allow chemically reactive substances and pressurized vessels over 1.2 atm in a CubeSat.

Electric propulsion has much higher fuel efficiency than chemical propulsion has but, in general, produces lower forces. Given the small mass of CubeSats and assuming sufficient time to maneuver, electric propulsion could be effective and consume small quantities of propellant. In general, electric propulsion does not use reactive materials that could damage primary payloads, although most concepts with heritage from larger satellites still need to carry pressurized vessels. Fuel efficiency is directly linked to the specific impulse (I_{sp}) of a propulsion system; as I_{sp} increases, the amount of propellant needed will decrease exponentially (see Figure 5.3), as such chemical propulsion systems have a lower I_{sp} than do electric propulsion systems.

There are a few options at different stages of development that could circumvent the need for a launch waiver. For example, the chemical thruster HYDROS developed by Tethers Unlimited burns hydrogen and oxygen obtained from hydrolysis of water that is brought to space non-pressurized. Propulsion also has significant impact on system volumes because high-performance propulsion systems are generally difficult to miniaturize to <2U (two-unit) configurations. See Appendix C, Table C.1 for details on micro-propulsion options for CubeSats and their technical maturity to date.

Non-Propulsive Mobility Techniques

Non-propulsive mobility techniques include all other forms that do not require the use of propellants. For example:

- Differential drag can be used to control the relative separation between two or more spacecraft traveling along the same nominal orbit while on their relatively long orbital decay (e.g., used on Aerocube-6).

[12] Gunter's Space Page, "OCSD A, B, C (AeroCube 7A, 7B, 7C / IOCPS A, B, C)," http://space.skyrocket.de/doc_sdat/aerocube-7-ocsd.htm, accessed April 8, 2016; Aerospace, "Optical Communication and Sensor Demonstration (OCSD)," updated October 8, 2015, http://ocsd.aerospace.org/.

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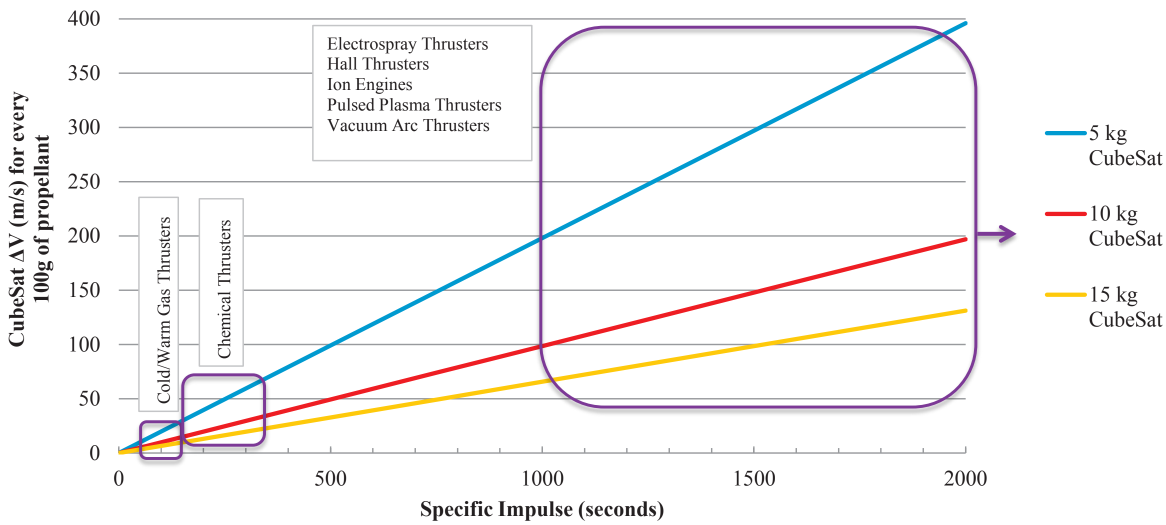

FIGURE 5.3 Propulsive capabilities in terms of effective CubeSat velocity change for every 100 g of propellant. In general, electric propulsion offers the best performance, but it is less developed (at lower technology readiness level). Cold/warm gas thrusters are most commonly used but provide low efficiency; specific examples are provided in Table 5.2. SOURCE: Data from C. Frost, E. Agasid, D. Biggs, J. Conley, A. Dono Perez, N. Faber, A. Genova, A. Gonzales, A. Grasso, J. Harpur, S. Hu, et al., Mission Design Division, 2014, *Small Spacecraft Technology: State of the Art*, NASA Technical Report TP-2014-216648/REV1, NASA Ames Research Center, Moffett Field, California, http://cmapspublic3.ihmc.us/rid=1NG0S479X-29HLYMF-18L7/Small_Spacecraft_Technology_ State_of_the_Art_2014.pdf.

- Deployable structures to significantly increase drag, accelerating orbital decay and forcing reentry at the satellite's end of life (e.g., used on CYGNSS).
- Systems based on electromagnetic forces, like the Electro-Magnetic-Formation Flight (EMFF) where each spacecraft includes orthogonal current coils that induce magnetic forces on its close neighbors to control relative attitude and spacing.
- Electrodynamic tethers, which are long conductive wires that are deployed from the spacecraft and could produce thrust or electrodynamic drag, depending on the direction of the electric current running along them while interacting with Earth's magnetic field.
- Solar sails making use of photon pressure to change the momentum of the spacecraft and enable propellant-less mobility with potential applications for deep space CubeSats.

Electrical Power, Energy Storage, and Thermal Control

Early CubeSats employed body-mounted solar arrays, generating an orbit average power of a few watts per CubeSat unit. With the growth of CubeSats from 1U to 3U and beyond, the available orbit-averaged power from body-mounted cells naturally increases. However, such mounting remains fundamentally limited; hence, the use of deployable solar array panels has become increasingly common—enabled by the improvement in attitude control systems discussed in the subsection "Attitude and Orbit Determination and Control." Consequently, orbit average powers of >50 W on a 3U CubeSat are now widely available.

Future solar cell power generation may theoretically reach efficiency values as high as 70 percent. However, to fully tap the potential of such increases in efficiency in CubeSats, cells need to be compact enough (low mass and volume), and efforts would likely be required to increase specific power. A potentially important future technology could be combining deployable systems with flexible solar cells. Terrestrial systems of >20 percent efficiency are available today, and so a 10 m^2 deployed surface could generate >2 kW of power in Earth orbit.

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Due to the low price point and efficiency, the use of Lithium-ion and Lithium-polymer batteries are relatively standard within CubeSats. A number of retailers offer off-the-shelf products that typically incorporate heaters, as well as protection against fire, thermal runaway, and other hazards. CubeSat Lithium-polymer batteries are readily available at power densities of >150 Wh/kg. As such, onboard power storage in excess of 30 Whr is widely available. Other units are available with storage levels up to 160 Wh, but they require greater volume, while some units can be connected in parallel to achieve higher capacities.

Low technology readiness level (TRL) concepts exist for CubeSat-compatible radioisotope thermoelectric generators. These concepts build on the principles developed for early artificial cardiac pacemakers, prior to Lithium-ion batteries becoming widespread, replacing the plutonium-238 with a more accessible fuel such as strontium oxide to produce around 5 mW at less than 7 percent efficiency. These devices could provide a useful source of heat in the outer solar system, but they also increase the complexity of the thermal design and may have possible issues with launch constraints.

Both onboard electrical power generation and storage have improved significantly since the first CubeSats. Although the improvement has not been of the magnitude seen in attitude control systems, storage capabilities continue to track terrestrial capabilities; however, peak power levels remain limited by battery discharge rates due to thermal concerns.

Thermal

Given the power-intensive characteristics and densely packed dimensions of payloads, thermal control can be a critical issue for many science missions; however, as the power density continues to increase, it is likely that thermal control of CubeSats will become even more challenging. Historically, CubeSats have largely employed passive thermal control techniques, including paint, thermal tape/straps, and Multi-Layer Insulation (MLI). Many missions addressing biological science objectives, such as Pharmasa and O/OREOS, used MLI and coatings to assist thermal regulation. Certain other passive techniques, such as heat-pipes or thermal louvers, have previously been considered ill-suited to CubeSats but are becoming more feasible (see Dellingr CubeSat).[13]

Recent development in the area of thermal control for CubeSats with applicability to low-temperature payloads, such as optical sensors and imaging spectrometers, include the concept of a deployable Sun shield, as planned for the 3U CryoCube-1,[14] which has an estimated launch date in 2016. This concept is anticipated to support multi-month experiments using the attitude control system coupled with the Sun shield to attain temperatures of approximately 100 K, while active cooling will reduce this further to around 30 K. Other developments, such as a pulse tube micro-cryocooler, are also being designed to fit within 0.5U and 0.345 kg.[15] A deployable radiator would offer the potential to dissipate significant amounts of heat; however, the concept is challenging on a CubeSat.

Deployable Systems

The widespread use of deployables on CubeSats for power generation with solar array panels, antennae, and Sun shields has already been discussed.

Another area of active research is the deployment of large gossamer structures and large area instrumentation surfaces (Figure 5.4). The NanoSail-D2 CubeSat deployed a 10 m^2 gossamer structure in 2011 to study the deployment of such structures both for application in solar sailing and as a drag augmentation device to reduce the orbit lifetime, hence, aiding adherence to space debris mitigation guidelines (discussed in Chapter 6). Similar so-called drag-sails of varying architectures are commercially available to purchase.

[13] NASA, "CubeSat Form Factor Thermal Control Louvers Project," data sheet, http://techport.nasa.gov/view/14545, accessed November 15, 2015.

[14] Sierra Lobo, "CryoCube," http://www.sierralobo.com/cryocube/, accessed April 8, 2016.

[15] J.R. Olson, P. Champagne, E. Roth, T. Nast, E. Saito, V. Loung, A.C. Kenton, and C.L. Dobbins, 2014, Microcryocooler for tactical and space applications, *AIP Conference Proceedings* 1573:357-364.

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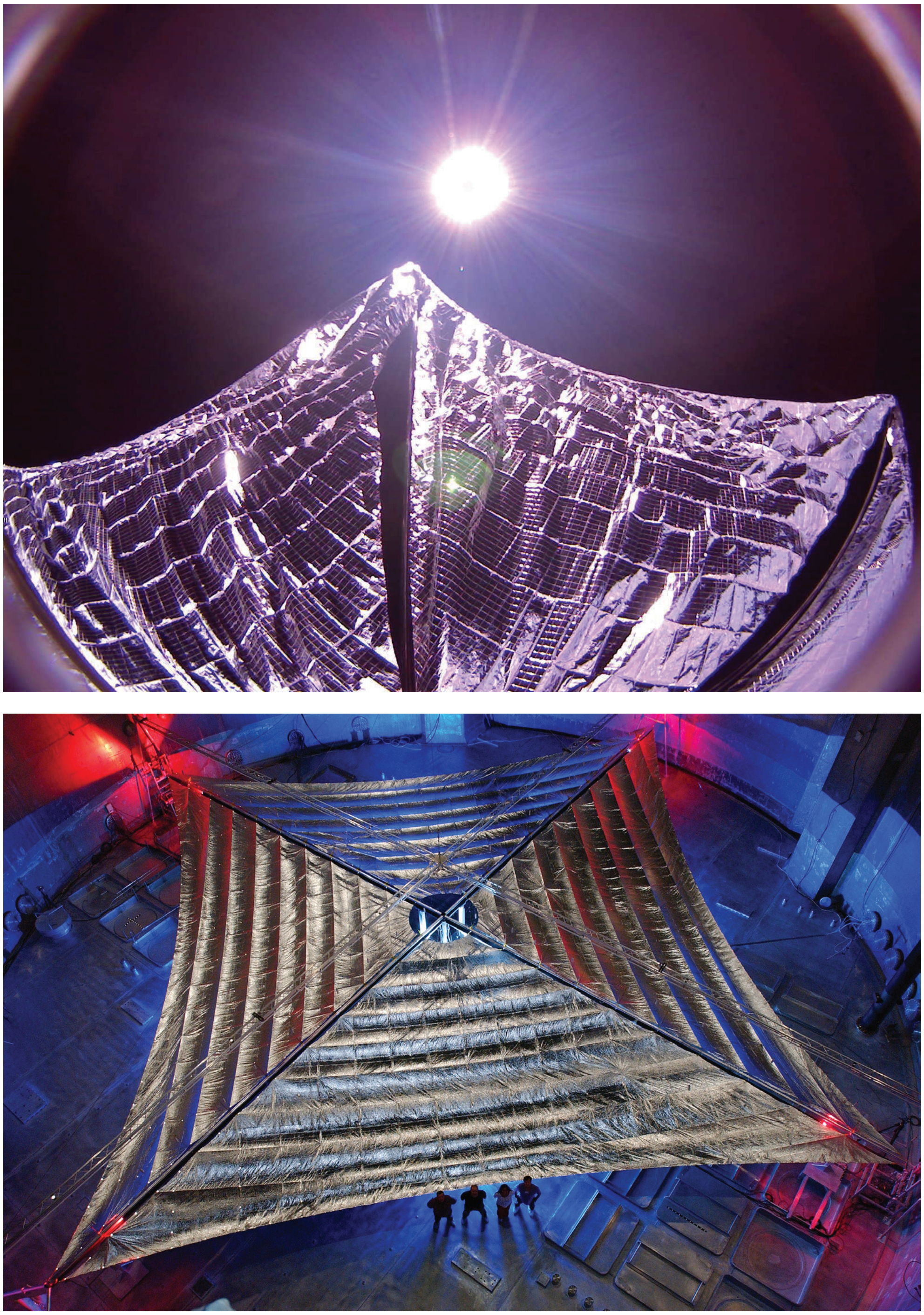

FIGURE 5.4 *Top:* The Planetary Society's LightSail A 3U CubeSat technology demonstrator deployed a 32 m^2 solar sail on June 8, 2015. *Bottom:* Ground deployment test of the 1,200 m^2 Sunjammer Solar Sail Demonstrator Mission in 2013. A space deployment test is not currently planned. SOURCE: *Top:* Courtesy of the Planetary Society, http://sail.planetary.org, Creative Commons Attribution-NonCommercial 3.0 Unported License. *Bottom:* NASA Marshall Space Flight Center, "NASA, Industry Partner Test 20-Meter Solar Sail System," July 26, 2005, http://www.nasa.gov/centers/marshall/ multimedia/photos/2005/photos05-121.html.

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Achieving Science with CubeSats: Thinking Inside the Box

The NEA Scout CubeSat mission, due to launch with the Orion EM1 mission on the maiden flight of the Space Launch System (SLS) planned for 2018, will deploy gossamer structures in a solar sailing mode. The structure as envisioned will be supported by four booms, giving a sail area of approximately 85 m^2.

Electrodynamic tethers have been proposed to assist in end-of-life deorbiting by generating drag force through an electromagnetic interaction with Earth's magnetic field. Such tethers need to be deployed to lengths of hundreds of meters to several kilometers and may require active electronics. Deploying a tether, especially from an inactive and potentially tumbling spacecraft, is a challenging concept. The AeroCube-5 CubeSats are currently flying end-of-life electrodynamic tethers, with expected activation in 2016.

There have also been recent developments in parabolic deployable mesh antennas to support interplanetary CubeSat communications and development of active sensors such as radars (see Figure 5.5). Examples include the 0.5 m Ka-band Parabolic Deployable Antenna (KaPDA)[16] developed for the NASA ESTO-sponsored RainCube 6U precipitation radar CubeSat (antenna stows within 1.5U), as well as the USC/ISI-designed 0.5 m deployable antenna that flew on the Aeneas CubeSat as a technology demonstration from which KaPDA was derived.[17]

Instruments and Sensors

The CubeSat form factor, power constraints, and thermal environments offer formidable challenges to the development of sensors that can perform valuable science measurements as part of CubeSat missions. The development of such instruments and novel sensors is thus a critical element for science CubeSats and, depending on the science requirements, will involve instruments that measure field, plasmas, and particles at a variety of masses and energies as well as electromagnetic radiation across the spectrum.

Often, heritage sensors have to scale down in size to fit within 1U of a CubeSat mission, leading to sensitivity changes of $1/R^2$ or even $1/R^3$ for a scaling factor R, especially for sensors that collect particles or photons. The sensitivity of these sensors and their dynamic range are markedly reduced, especially if $R > 2$. Depending on the measurement requirements, scaling heritage instruments therefore does not guarantee success, and often, new approaches need to be considered to perform the measurements.[18,19] CubeSat instrument builders are also reimagining their instruments based on commercial off-the-shelf (COTS) parts. For example, the CINEMA mission used a COTS-based magnetoresistive space magnetometer.[20] New detectors for imaging leverage progress in semiconductor technologies—for example, with the use of avalanche photodiodes. These enable the detection of very-low-intensity signals (i.e., down to a single photon), which compensate for decreased aperture and are of particular interest for astrophysics and for planetary imaging (e.g., during fast flyby or suboptimal illumination). An approach to the realization of very large apertures for cosmology is via the coordination of a large array of antennas and the synthesis of their observations. While the hardware is very simple (dipole antennas), science output relies on robust data handling and processing. Other imaging techniques also rely on strong support from science software and command and data handling (C&DH) systems, such as the cameras from Planet Labs and SkyBox, that use nonstandard techniques like time-delay integration and other super-resolution techniques that had been previously developed for microscopy.

[16] J. Sauder, N. Chahat, R. Hodges, E. Peral, M. Thomson, and Y. Rahmat-Samii, 2015, "Ultra-Compact Ka-Band Parabolic Deployable Antenna for RADAR and Interplanetary Communications," *Proceedings of the AIAA/USU Conference on Small Satellites*, Technical Session VI: Ground Systems and Communications, SSC15-VI-7, http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3207&context=smallsat.

[17] M. Aherne, J. Barrett, L. Hoag, E. Teegarden, and R. Ramadas, 2011 "Aeneas-Colony I Meets Three-Axis Pointing," *Proceedings of the AIAA/USU Conference on Small Satellites*, Technical Session XII: The Next Generation, SSC11-XII-7, http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1181&context=smallsat.

[18] A.B. Crew, B.A. Larsen, D.M. Klumpar, E. Mosleh, H.E. Spence, J. Legere, J.B. Blake, L. Springer, M. Widholm, S. Driscoll, S. Longworth, et al., 2012, Focusing on size and energy dependence of electron microbursts from the Van Allen radiation belts, *Space Weather* 10(11):1-3.

[19] G.B. Andrews, T.H. Zurbuchen, B.H. Mauk, H. Malcom, L.A. Fisk, G. Gloeckler, G.C. Ho, J.S. Kelley, P.L. Koehn, T.W. LeFevere, S.S. Livi, R.A. Lundgren, et al., 2007, The energetic particle and plasma spectrometer instrument on the MESSENGER spacecraft, pp. 523-556 in *The Messenger Mission to Mercury* (D.L. Domingue and C.T. Russell, eds.), Springer, New York.

[20] M.O. Archer, T.S. Horbury, P. Brown, J.P. Eastwood, T.M. Oddy, B.J. Whiteside, and J.G. Sample, 2015, The MAGIC of CINEMA: First in-flight science results from a miniaturised anisotropic magnetoresistive magnetometer, *Annales Geophysicae* 33(6):725-735.

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Achieving Science with CubeSats: Thinking Inside the Box

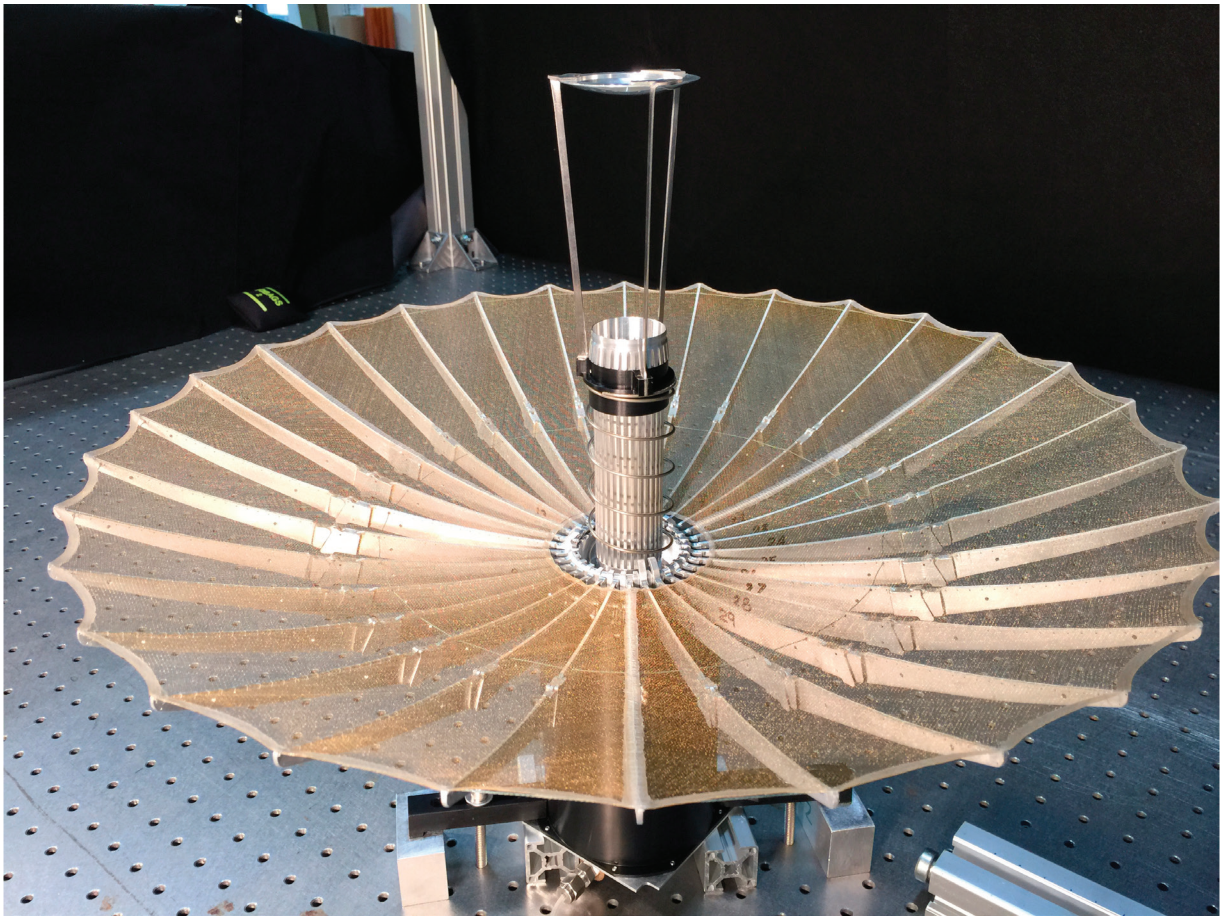

FIGURE 5.5 Deployed KaPDA mesh antenna based on an Aeneas design. SOURCE: Courtesy NASA/JPL-Caltech.

Of special importance to various science-based CubeSat missions are technologies that require a stable and highly calibrated performance (i.e., for Earth observations), good thermal stability, especially at low temperatures (i.e., for infrared observations and some microgravity science), and measurements that require distributed apertures (i.e., for interferometry applications). The high-operating-temperature barrier infrared detector (HOT-BIRD[21]) holds particular promise in that area with the novel combination of multiple alloys. HOT-BIRD has a thermal sensitivity of 0.02°C and can be utilized for a variety of Earth, planetary, and astrophysical applications without the need for active cooling.

In summary, most CubeSat instruments are not just smaller copies of heritage instruments built for flight. Some instrument developments are evolutionary—focused on miniaturized sensors and science requirements consistent with smaller sensitivity or dynamic range than their heritage systems. However, many CubeSat instruments are revolutionary and use novel technology, they are COTS-based, or they use novel ways of detection or analysis of data.

[21] NASA and Tech Briefs Media Group, "High-Operating-Temperature Barrier Infrared Detector With Tailorable Cutoff Wavelength," release date February 1, 2011, http://www.techbriefs.com/component/content/article/ntb/tech-briefs/manufacturing-and-prototyping/9144.

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Flight and Ground Systems Software

Numerous studies have contributed to a good general understanding of how to manage complexity in spacecraft flight software development, but the emphasis has been on large missions with hundreds of contributors developed over many years.[22] The development and evolution of flight software for CubeSats has been fundamentally different: teams are smaller, are more willing to adopt new technology, rely more on testing than on formal verification methods, and often produce complete flight software solutions consisting of a few thousand lines of code as opposed to the millions of lines of code seen on large flight projects. The need for highly reliable, safe, and effective flight software for CubeSats remains, but the rapid pace of change in this area has not yet produced a set of widely adopted community standards. Identifying and developing flight software technology to address these challenges for CubeSats remains unresolved. Many of the spacecraft flown thus far have utilized a patchwork of scripts unsupported by an underlying CubeSat flight software architecture.

Software has progressed from custom hardware specific codes to integrated development environments, including open-source software. In practice, however, operations are sequential, with minimal capabilities for multitasking, scheduling, and priority-based actions. They remain highly impacted as changes are introduced to address new required capabilities as the operational needs of flight systems mature. Real-time operating systems are starting to address these challenges, increasing system responsiveness to support dynamic management of flight system resources such as power consumption.[23] Nevertheless, challenges still remain for the science community developing new instruments that are not immediately compatible with such systems.

Many commercial hardware companies, such as Clyde Space, are including flight software systems that are modular and compatible with their hardware bus and associated subsystems. However, custom software interfaces may still be needed to integrate scientific payloads.

Specific areas where advances are needed include autonomy, robustness, extensibility, fault protection (tolerance and recovery), and auto-code generation. The ability to support high-performance multiprocessor architecture for spacecraft operations and payload processing would also be enabling. Flight and ground software system verification and validation with dynamic resource optimization also is necessary as a means of managing spacecraft resources effectively. In particular, for constellation and other advanced science opportunities, more capability will be demanded of CubeSat flight software.[24,25]

There are new efforts to develop provably correct general-purpose CubeSat flight software, such as CubedOS,[26] which is intended for use on the Lunar IceCube mission. While experimental, such efforts are trying to advance the leading edge of how CubeSat flight software would be developed.[27]

Data Handling, Processing, and Autonomy

CubeSat development has benefited from the increasing availability of low-cost consumer electronics for data processing and storage. Examples of this include CubeSats such as STRaND-1 and PhoneSat, which used unmodified consumer-grade off-the-shelf smartphones.[28] Science missions may, however, require systems with

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[22] NASA, 2009, *NASA Study on Flight Software Complexity* (D.L. Dvorak, ed.), http://www.nasa.gov/pdf/418878main_FSWC_Final_Report.pdf.

[23] A. Kalman, 2015, "How a Lightweight RTOS can Drive CubeSat Flight Software," presented at CubeSat Developers' Workshop, Utah State University, http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3290&context=smallsat.

[24] C. Brandon, and P. Chapin, 2015, High integrity software for CubeSats and other space missions, *Proceedings of 66th International Astronautical Congress*, http://web.vtc.edu/users/pcc09070/papers/brandon-chapin-IAC-2015.pdf.

[25] G. Manyak, 2011, Fault tolerant and flexible CubeSat software architecture [Master's thesis], California Polytechnic State University, San Luis Obispo, California.

[26] Vermont Technical College, "CubeSat Laboratory," updated August 3, 2015, http://www.cubesatlab.org/CubedOS.jsp.

[27] Communication and navigation control of multiple craft in swarms has been studied and implemented for autonomous underwater vehicles. Such techniques may be applicable to CubeSats as well. W. Gao, Y. Liu, B. Xu, and Y. Che, 2014, An improved cooperative localization method for multiple autonomous underwater vehicles based on acoustic round-trip ranging, paper presented at IEEE/ION Position, Location and Navigation Symposium, Monterey, California, http://ieeexplore.ieee.org/xpl/articleDetails.jsp?tp=&arnumber=6851518&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D6851518.

[28] The software was modified; however, the electronics were not. Both flew a Google NEXUS phone.

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Achieving Science with CubeSats: Thinking Inside the Box

increased robustness and reliability, at the cost of reduced capability, with a wide range of such systems already available for purchase.

The most common source of onboard memory is SRAM.[29] However, other technologies are available, and Flash is popular for mass storage. Consideration is also being given to levels of radiation tolerance as well as mitigation techniques as CubeSat developers begin to develop missions beyond LEO.

Within the ground segment, once again the use of commercial hardware and software is more common than in traditional space systems. Indeed, many are based on systems derived or developed from within the amateur community and are dependent on a single antenna. However, drawing on the amateur community, a large ad hoc network can be established—typically, clustered in North America and Europe. As more complex onboard communication systems are developed, the CubeSat ground segment will need to keep pace.

A driver in all space missions is the operations cost; hence, automation significantly reduces CubeSat mission costs and risks. A further innovation in the ground segment is the GENSO (Global Educational Network for Satellite Operations) concept, developed and maintained under the auspices of the European Space Agency (ESA), which sought to provide educational CubeSat operators with access to a global network of ground stations to maximise CubeSat utilization.

Inter-satellite communication hardware necessary for many constellation and formation flying missions has been used by a number of organizations. This includes systems in both LEO (i.e., Globalstar terminals) and in geostationary orbit. Data relays are therefore viable and flight-proven options to both reduce ground-segment setup costs and, potentially, reduce data latency. Onboard data processing, autonomous systems, and navigation could further reduce the burden and cost of the ground segment and mission operations in CubeSats.

For science missions using constellations or swarms of CubeSats, the issue of "fleet management" must be considered. In particular, the ground segment to operate such a fleet must be carefully developed for both nominal operations and for overcoming anomalies.

System Integration, Platforms, and Constellations

Given the number of science missions that can benefit from constellation architectures, several technologies for constellation networking are in development. The technologies required to enable constellations include streamlined manufacturing, constellation launch and deployment, constellation operations, and data management and analysis.

An early example of large swarms is the European QB50 project,[30] where every CubeSat is independent but will fly a common payload selected from a set of three options to study the lower thermosphere. Several European developers offered QB50 compatible platforms (Figure 5.6). Extending this concept further, Clyde Space, based in Scotland, is working with Outernet Inc., USA, as the anchor customer to further develop high-performance off-the-shelf spacecraft buses.[31] Other European and North American operators are also developing similar off-the-shelf spacecraft buses. These off-the-shelf platforms are designed to be mission independent, giving them a large operating envelope that is not optimised for any particular use. The development of high-performance, off-the-shelf CubeSats is expected to drive down the unit cost, which in turn will reduce the cost of constellation and swarming science mission concepts that seek to make rapidly repeating measurements.

Most CubeSats have been launched as secondary payloads; however, constellations launches are most likely to occur in dedicated vehicles. Constellation setup and orbit maintenance have been discussed in the subsection "Mobility and Propulsion."

[29] SRAM = Static random-access memory.
[30] See the QB50 project website at https://www.qb50.eu/, accessed April 8, 2016.
[31] Gov.UK, "CubeSats to provide telecomms through international partnership," release date March 13, 2015, https://www.gov.uk/government/news/cubesats-to-provide-telecomms-through-international-partnership.

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Achieving Science with CubeSats: Thinking Inside the Box

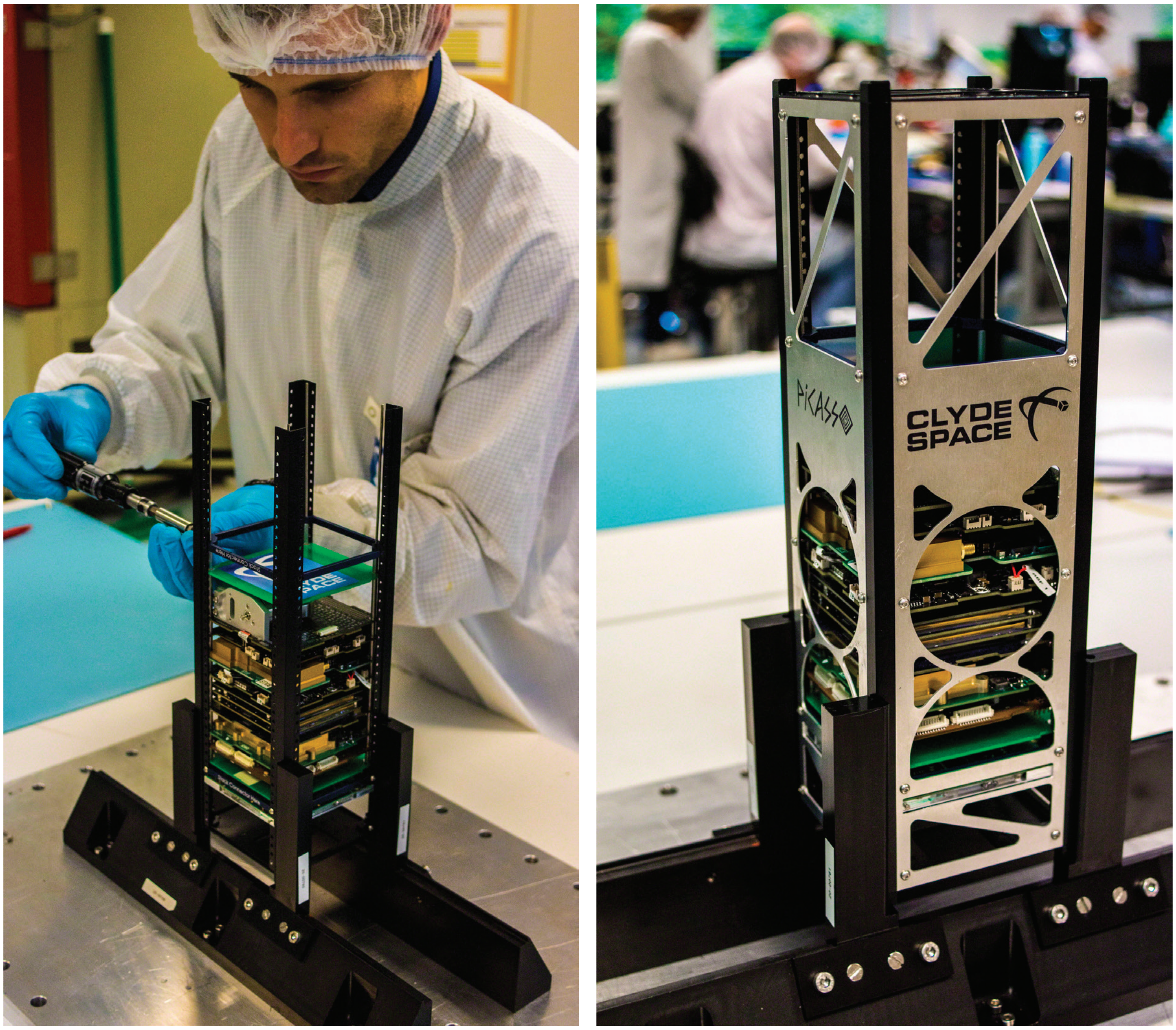

FIGURE 5.6 The Picasso 3U CubeSat technology demonstration mission will use a miniaturized multispectral imager for atmospheric "limb sounding" with the Sun as the light source, and a multineedle Langmuir probe sampling the electron density of the space around it. Picasso is one of a number of CubeSat missions being backed by the In-Orbit Demonstration element of the European Space Agency's General Support Technology Programme. It will be launched in 2016 as part of QB50, a network of 50 CubeSats to probe largely unexplored layers of Earth's atmosphere. SOURCE: Courtesy of Clyde Space.

Constellations will rely on multielement autonomy, coordinated fleet navigation, and the development of a variety of quality of service and routing techniques. Furthermore, enhanced intra-satellite communication approaches may be required—for example, involving switchable-beam directional antennas for direct control of data routing. Current science data management techniques (tracking instrument health, calibration changes, and anomaly response) do not generally include more than 10 spacecraft.

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6

Policy Challenges and Solutions

There are several challenges that could adversely affect the development of science-focused CubeSats. The principal ones include the reality and the perception of CubeSats generating orbital debris, spectrum challenges, and difficulties related to obtaining affordable access to space. This chapter discusses each of these multifaceted challenges, especially as they affect the future of CubeSats as science platforms.

CUBESAT ORBITAL DEBRIS

Background on Orbital Debris

Any object in orbit around Earth that no longer serves any useful purpose is referred to as orbital debris. This includes spent rocket stages, old satellites, and fragments as small as paint particles.[1] While there are only about 1,300 active spacecraft in orbit, there are estimated to be about 500,000 objects between 1 and 10 cm in diameter and more than 100 million particles smaller than 1 cm that are not systematically tracked.[2] Although the probability of accidental collisions is low, at relative impact velocities greater than 35,400 km per hour, debris as small as half a centimeter across can substantially damage a spacecraft.[3]

The U.S. Air Force's Joint Space Operations Center (JSpOC) tracks about 23,000 objects in space larger than around 10 cm in diameter and provides close approach warnings to all satellite operators. In 2014, JSpOC provided an average of 23 "emergency" notifications per day (almost 700,000 possible collision warning notifications were provided throughout the year to satellite owners and operators[4]), and operators performed hundreds of avoidance maneuvers to reduce risk of potential collisions. In addition, during 2014, NASA executed or assisted

[1] J.-C. Liou, 2012, "The Near-Earth Orbital Debris Problem and the Challenges for Environment Remediation," presented at the 3rd International Space World Conference, Frankfurt, Germany, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120012893.pdf.

[2] NASA Orbital Debris Program Office, "Orbital Debris Frequently Asked Questions," updated March 2012, http://orbitaldebris.jsc.nasa.gov/faqs.html.

[3] SpaceRef Business, "NewSpace 2014 Conference—Day 3 Video," posted July 28, 2014, http://spaceref.biz/organizations/space-frontier-foundation/newspace-2014-conference---day-3-video.html.

[4] U.S. Government Accountability Office, "Space Situational Awareness: Status of Efforts and Planned Budgets," October 8, 2015, http://www.gao.gov/assets/680/672987.pdf.

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Achieving Science with CubeSats: Thinking Inside the Box

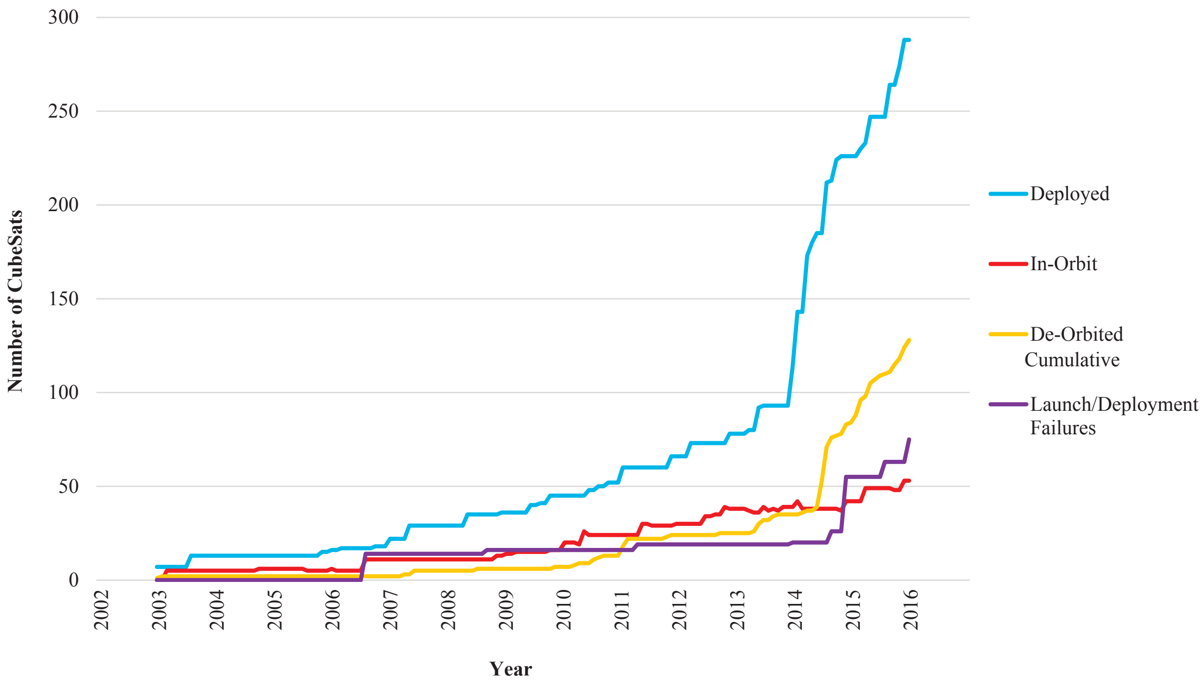

FIGURE 6.1 CubeSats deployed, in orbit, and deorbited each month going back to 2003, plus a cumulative total of CubeSats deorbited. SOURCE: Figure courtesy of Emma Kerr and Malcolm Macdonald, University of Strathclyde; data courtesy of T.S. Kelso, CelesTrak, http://celestrak.com/, accessed February 2016.

in the execution of more than two dozen collision-avoidance maneuvers by robotic spacecraft.[5] Because of the risk of collision, the International Space Station (ISS) has had to conduct 25 collision-avoidance maneuvers since 1999.[6] NASA, analyzing data from six space agencies, estimates that there will be a catastrophic collision every 5 to 9 years. Managing orbital debris is therefore an important challenge for the entire space community.

CubeSats as an Orbital Debris Challenge

To date, CubeSats have not been a significant part of the orbital debris challenge. As Figure 6.1 shows, there are about 155 CubeSats in low Earth orbit (LEO). As such, they comprise a very small fraction of objects 10 cm and larger—approximately 1 percent of the current resident space objects catalog. Even with optimistic projections with respect to CubeSat launches (see later this chapter), CubeSats will remain a very small fraction of objects in space.[7] Scientific CubeSats are an even smaller fraction (Figure 1.3), with much of the future growth expected to be in the commercial sector.

[5] J.-C. Liou, NASA, "USA Space Debris Environment, Operations, and Measurement Updates," presentation to the 52nd Session of the Scientific and Technical Subcommittee, Committee on the Peaceful Uses of Outer Space, United Nations, February 2-13, 2015, http://www.unoosa.org/pdf/pres/stsc2015/tech-28E.pdf.

[6] Ibid.

[7] The number of debris objects larger than one centimeter will reach around 1 million in year 2020 (European Commission 2013). About 2,000-2,750 micro/picosatellites are projected to be launched through 2020. It is not known how many of these will be CubeSats.

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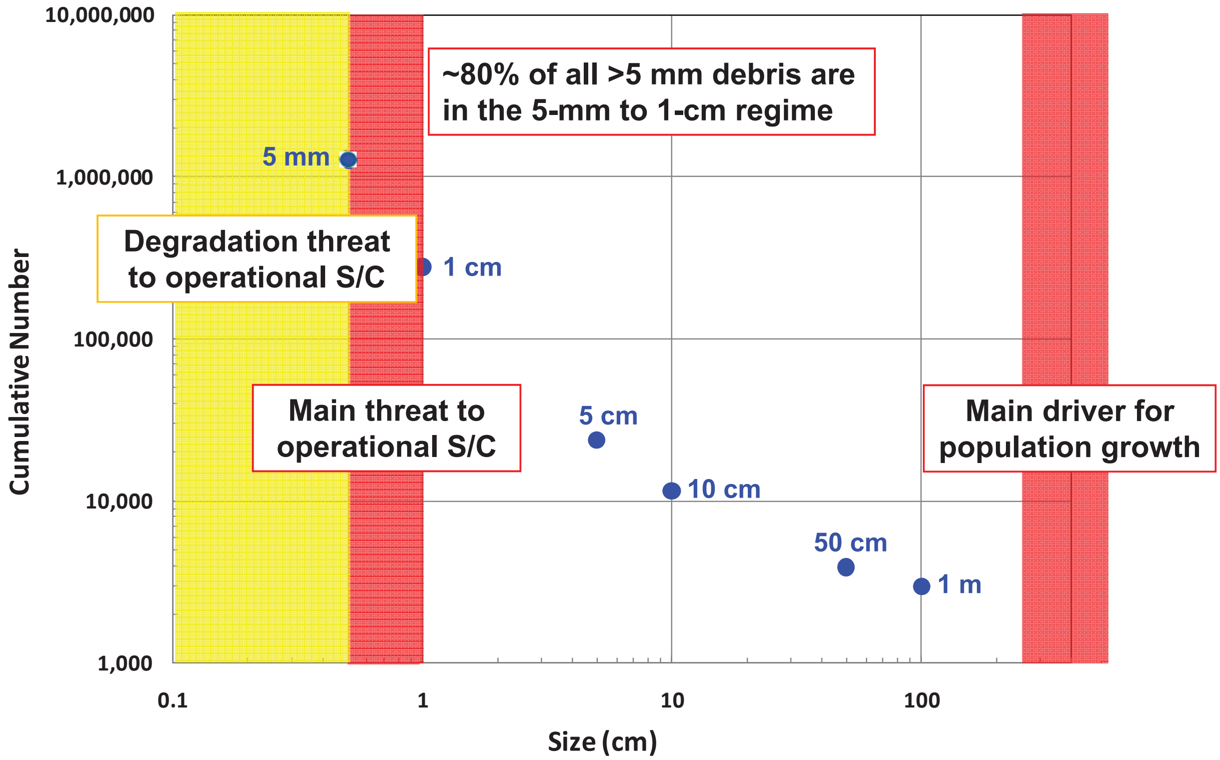

FIGURE 6.2 CubeSats, at scales of 10-30 cm, are not a primary target for remediation in low Earth orbit, indicated by red and yellow bars. SOURCE: J.-C. Liou, NASA Johnson Space Center, "The Near-Earth Orbital Debris Problem and the Challenges for Environment Remediation," presentation to the 3rd International Space World Conference, Frankfurt, Germany, November 6-8, 2012, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120012893.pdf.

With one exception, a picosatellite release from a Peruvian 1U CubeSat, all CubeSat-related objects in orbit are successfully tracked by JSpOC.[8] To the best of the committee's knowledge, while there have been some conjunction warnings related to CubeSats, only one spacecraft has had to maneuver out of the way of a CubeSat. And while the ISS has had several conjunctions or close approaches with CubeSats, only one has led to a maneuver, indirectly.[9] All NASA- and NSF-funded CubeSats have complied with the guideline that satellites deorbit within 25 years after mission completion.[10] Also, the average lifetime of the 126 CubeSats that have decayed is approximately 290 days, with a max of 1,340 days and minimum of only 2 days. On the debris remediation front as well, as Figure 6.2 shows, given the size distribution of objects, experts propose[11] that the focus be on either large

[8] Correspondence with JSpoC; NASA, *Orbital Debris: Quarterly News* Volume 19, Issue 3, July 2015, http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv19i3.pdf.

[9] Personal correspondence with NASA; NASA, *Orbital Debris: Quarterly News* Volume 19, Issue 3, July 2015, http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv19i3.pdf.

[10] In February 2007 and after a multiyear effort, the IADC (Inter-Agency Space Debris Coordination Committee), created under the aegis of the United Nations' Committee on the Peaceful Uses of Outer Space (COPUOS), adopted a set of space debris mitigation guidelines which includes a 25-year deorbit requirement from low Earth orbit. The guidelines were accepted by the COPUOS in June 2007 and endorsed by the United Nations in January 2008, http://www.unoosa.org/documents/pdf/spacelaw/sd/IADC-2002-01-IADC-Space_Debris-Guidelines-Revision1.pdf.

[11] J.-C. Liou, NASA, "Orbital Debris Mitigation Policy and Unique Challenges for CubeSats," presentation to the committee on October 30, 2015.

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objects (>100 cm, which can be tracked and may become a source of small objects) or very small ones (<1 cm, where shielding can mostly mitigate effects), with secondary focus on CubeSat-sized objects (1-10 cm, which are difficult to track and not easy to shield against) (Figure 6.2).

Despite the record to date of minimal CubeSat related conjunctions and debris avoidance maneuvers and no collisions to date, and the recommendation by experts to focus on the far ends of the size spectrum rather than the CubeSat range, as the number of CubeSats grow,[12] there is growing concern that CubeSats may become a space debris hazard.[13] This could be an issue because, in theory, CubeSats do not necessarily have a lower collision risk (collision probability is a function of the combined radius of the CubeSat and the larger body with which it might collide, not just the smaller object).[14] If there were to be a collision related to a CubeSat, even if it is not a science CubeSat, it may be detrimental to all users of CubeSats as a science, technology, or commercial platform.

Given this risk, even a nonscience CubeSat involved in a collision may result in the creation of an onerous regulatory framework and affect the future disposition of science CubeSats. Therefore, it befits the science community to take the risk of *any* conjunctions seriously—not just those of science CubeSats. In this section, the committee briefly discusses the challenges CubeSats face with respect to orbital debris and what measures may be considered to address these challenges. It is important to note here that these challenges apply to an even greater extent to larger satellites, and thus, CubeSats can serve as an innovation platform for broader benefit.

There are three major orbital debris challenges related to CubeSats (for more technology-related details, refer to Appendix C and Chapter 5). The first relates to mobility or maneuverability. Most CubeSats do not have onboard propulsion. As a result, CubeSats cannot maneuver out of the way if they come across other space objects such as the ISS. While is it not unusual for spacecraft to be non-maneuverable, this puts the onus of maneuvering out of the way on the other object, which can become expensive for the operator. They have to expend more propellant, which will shorten the spacecraft lifetime and reduce either science returns or commercial revenue, and their insurance cost might increase,[15] for example.

The second challenge relates to "trackability." There is no specific requirement that any spacecraft carry active (e.g., transponder) or even passive (e.g., RFID, retro-reflectors) tracking devices. Lack of such devices makes it difficult to track them and presents an increased risk of collision. Tracking is even more important when CubeSats are launched in clusters (e.g., from the ISS), because their separation times are long, which adds to the workload of entities assigned to track space objects, such as JSpOC.

The third challenge relates to a CubeSat's end of life. Most CubeSats today, by design or otherwise, stop working after a few months or years of operation. However, they stay in orbit for a long time and not all are in compliance with the 25-year guideline mentioned above.

It is worth noting that there are no domestic or international norms on maneuverability or the ability to track or deorbit CubeSats or other satellites. Neither are there any agreed-upon norms as to how CubeSat constellations will be designed, manufactured, deployed, or operated (beyond what is the case for all satellites), domestically or globally.

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[12] Planet Labs is expected to launch 250 CubeSats in 2016.

[13] P. Marks, "CubeSat craze could create space debris catastrophe," *New Scientist*, release date September 24, 2014, https://www.newscientist.com/article/mg22329882-500-cubesat-craze-could-create-space-debris-catastrophe/; I. O'Neill, "CubeSats: A Space Junk Hazard?", *Discovery News*, release date September 30, 2014, http://news.discovery.com/space/cubesats-a-space-junk-hazard-140930.htm; S. Clark, "NASA: Tracking CubeSats is easy, but many stay in orbit too long," *Spaceflight Now*, release date July 30, 2015, http://spaceflightnow.com/2015/07/30/nasa-tracking-cubesats-is-easy-but-many-stay-in-orbit-too-long/; J. Rotteveel, "Another View on CubeSats and Debris," *SpaceNews Commentary*, release date October 27, 2014, http://spacenews.com/42329another-view-on-cubesats-and-debris/; A. Anzaldua and D. Dunlop, "Overcoming non-technical challenges to cleaning up orbital debris," *The Space Review*, release date November 9, 2015, http://www.thespacereview.com/article/2863/1; G. Harris, "Space debris expert warns of increasing CubeSat collision risk," *Phys Org*, release date September 30, 2014, http://phys.org/news/2014-09-space-debris-expert-cubesat-collision.html.

[14] Indeed, analyses show that the collision risk between a large satellite and a CubeSat is not significantly lower than the risk between a large satellite and a 1 m^2 object. A.J. Abraham, and R.C. Thompson, The Aerospace Corporation, 2015, "CubeSat Collision Probability Analysis," presentation at the Small Payload Ride Share Association Conference, https://www.sprsa.org/sites/default/files/conference-presentation/Cubesat_Probability_Charts_v2.3.pptx.

[15] According to the European Commission, satellite operators in Europe lose approximately $152 million per year due to collisions, and that total is predicted to rise to about $228 million within the next decade. S. Cruddas, "Cleaning Up Space," *RAeS Quarterly*, Summer 2015, Royal Aeronautical Society Quarterly Newsletter, Washington D.C. Branch, http://raeswashingtondcbranch.cloverpad.org/Resources/Documents/RAeS_15_Summer_Quarterly_Newsletter.pdf, p. 12.

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Possible Actions

Operators, and others tasked with tracking space objects, propose several actions that can be taken, together or individually, to address the potential challenge of orbital debris from CubeSats. The first action is to give CubeSats some level of onboard propulsion to allow them to maneuver out of the way if needed, with all of the technical challenges already discussed in Chapter 5 and Appendix C.

A second action is to ensure that CubeSats are trackable. This could be done with greater coordination between operators and trackers (e.g., JSpOC) so the latter can track CubeSats more precisely (e.g., provide detailed information on launch plans and payload deployment to ensure that individual CubeSats are quickly identified upon separation or release from the payload deployer).[16] Planet Labs publicly disseminates its ephemerides, which could be one potential good practice to consider. Further orbital zoning has also been recommended to promote ease of tracking. As discussed in the technology chapter above, the challenge can also be addressed by technology—for example, the use of active and passive tracking devices (see Appendix C for more details).[17]

A third action is to ensure that, given the probability, however low, that they may collide with other objects, CubeSats deorbit soon after they stop working instead of staying in orbit for the full, allowed lifetime of 25 years.[18] In the domain of orbital debris removal, there are also proposals for active debris removal (ADR) or the active rehabilitation (ADRe) of defunct spacecraft, but they apply less to CubeSats than they do to larger satellites.

Given that there is no CubeSat-specific domestic or international regime that can require CubeSats to be maneuverable, trackable, or deorbited appropriately,[19] it may be feasible to put voluntary agreements or standards in place and have designers, manufacturers, or launchers impose requirements. It is important to note that the CubeSat community is international, and U.S.-only rules will not suffice.[20] For example, there are more U.S. CubeSats launched on foreign vehicles (38 out of 108) than foreign CubeSats launched on U.S. vehicles (1 out of 116). As a result, having U.S. launch providers impose rules will not shift the system. However, there may be an opportunity for the United States, perhaps in coordination with Europe and Japan, to take a leadership role in setting best practices.

Finding: Because CubeSats typically are not maneuverable, they are seen as orbital debris threats, especially in near Earth orbits, with low Earth orbit being a special challenge because of the presence of the International Space Station. CubeSats comprise less than a percent of all resident objects in space and are expected to remain a small fraction, even as their number in space grows. The number of science-focused CubeSats is an order of magnitude lower than that.

Conclusion: Although CubeSats are a very small fraction of all resident objects in space, the risk of a CubeSat conjunction or collision is not insignificant. Thus, the CubeSat community has an opportunity to avoid potential future problems by continuing to proactively engage in policy discussions and seek technological solutions, such as low-cost means for CubeSats to be maneuverable, trackable, and deorbited appropriately.

CUBESAT COMMUNICATION

In the United States, transmitting radio signals to or from a space object (including a CubeSat) requires regulatory approval. The requirement to obtain a license applies to all CubeSats that transmit, regardless of orbit or

[16] Recommendations from a government representative.

[17] Chapter 5 discusses some of these technologies.

[18] Chapter 5 discusses some of these technologies.

[19] Although there are domestic and international policies, guidelines and requirements related to orbital debris mitigation apply to all satellites, including CubeSats. These include NASA Procedural Requirements for Limiting Orbital Debris, the U.S. Government Orbital Debris Mitigation Standard Practices, the IADC Space Debris Mitigation Guidelines, and the UN Space Debris Mitigation Guidelines.

[20] "International coordination would be required for any sustained effort to capture and remove debris because many nations have contributed to the problem and the United Nations 1967 Outer Space Treaty states that space-based objects, including spent rocket boosters and satellite fragments, belong to the nation or nations that launched them." D. Werner, "NASA's Interest in Removal of Orbital Debris Limited to Tech Demos," release date June 22, 2015, http://spacenews.com/nasas-interest-in-removal-of-orbital-debris-limited-to-tech-demos/.

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final destination. Simply put, it is illegal for a space object to emit any type of radio signal, or for an Earth station to transmit to a satellite from the ground, without authorization.[21] Unfortunately, the methods and procedures for obtaining appropriate authorization are spread among voluminous rules and regulations issued by domestic regulatory authorities and are also subject to additional regulations established through international treaties (see Appendix C). Understandably, few CubeSat developers are familiar with the details of these rules, but discovery too late in the development process creates substantial risk that a CubeSat project will be denied a ride to space.

CubeSat developers and operators face a number of challenges in obtaining the needed regulatory approvals. Among them are the following:

- The timescale for obtaining satellite and Earth station licenses can be substantially longer than the development cycle for a CubeSat. The filings to obtain satellite and Earth station licenses are not particularly streamlined, and most CubeSat developers will have no prior experience navigating the process.
- Every desirable frequency in the radio spectrum is already being used. Satellite visibility covers a very large footprint on the surface of Earth, so their transmissions must be coordinated over large areas with potentially many other users.
- CubeSat developers tend to favor lower frequencies, where equipment is less expensive and more readily available, but lower frequencies are the most congested parts of the radio spectrum. Even if a developer can obtain coordination for the use of such frequencies, they will typically be faced with substantial interference from other users when trying to receive weak signals from their satellite.
- Traditionally, the regulatory authorities prefer to know details of satellite orbits, such as elevations and inclinations, when filings are made, but these parameters may be uncertain for some CubeSats until late in the process.

Although the U.S. and international regulatory authorities are becoming more aware of the challenges facing small satellite spectrum use, they have so far declined to change their rules to better accommodate these systems. Instead, it is incumbent upon the CubeSat community to understand the challenges and opportunities of the existing regulatory structure and to become more aware of how this structure will impact their development and operational plans.

CubeSat Spectrum Use

To date, CubeSat developers and operators have used a variety of options to obtain spectrum authorizations (Appendix C provides some background information on spectrum related issues). In an examination of CubeSat spectrum use from 2009 through March 2015,[22,23] the following breakdown of licensing schemes was revealed:

- 53 percent were licensed as amateur radio satellites, through the Federal Communications Commission (FCC);
- 26 percent were authorized under FCC experimental licenses;
- 9 percent were authorized as federal government satellites through the National Telecommunications and Information Administration (NTIA);
- 6 percent were licensed through the FCC under a particular radio service other than amateur-satellite, including Earth exploration-satellite, meteorological satellite, and space research services; and
- 6 percent were either not licensed or their license status could not be determined.

[21] Station Authorization Required, 47 C.F.R.§ 25.102(a) (2010).

[22] B. Klofas, and K. Leveque, 2013, "A Survey of CubeSat Communication Systems: 2009-2012," http://www.klofas.com/papers/Klofas_Communications_Survey_2009-2012.pdf; B. Klofas, "CubeSat Communications System Table," updated March 10, 2015, http://www.klofas.com/comm-table/.

[23] The statistics include the Planet Labs Flock-1 release of 28 satellites counted as 1 instance of licensing as Earth Exploration. Such large-scale commercial operations typically employ a team of legal experts that acquire licensing through the FCC under an appropriate service, an option normally not available to the science-focused CubeSat developer because of expense and because timescale to deployment is usually much shorter than for commercial operations.

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Each of these licensing schemes is discussed below.

Amateur Radio Licensing

The amateur-satellite service is allocated many bands throughout the radio spectrum. Three particularly popular bands for CubeSat use are 144-146 MHz, 435-438 MHz, and 1260-1270 MHz. The use of amateur radio frequencies is, on the face of it, very appealing for the following reasons:

- Any individual may obtain an amateur radio license upon passing an examination. While the examination is not particularly easy, it is well within the reach of students, educators, faculty, and technicians typically involved in CubeSat projects.
- Licensed amateur radio operators are granted blanket authorization to use any appropriately allocated amateur radio frequency. Therefore, CubeSat teams that include a licensed amateur radio operator can use that operator to communicate with the satellite, with no additional licensing requirements, subject to a significant caveat discussed below.
- Thousands of amateur radio operators in the United States, and many more abroad, possess suitable equipment for listening to CubeSat transmissions. Therefore, an extensive and readily available worldwide network of volunteer Earth stations is available.
- Amateur radio equipment (both for the satellite and for the Earth stations) is relatively inexpensive and readily available.

However, there are several significant drawbacks to using the amateur-satellite service:

- Amateur radio communications are generally limited to transmissions necessary to exchange messages with other stations in the amateur service.[24]
- Amateur radio licensees may not use amateur radio for any communications in which they have a pecuniary interest.[25] Therefore, amateur radio operators that are paid members of a CubeSat team or receive a stipend or tuition are not abiding by the amateur radio rules.
- Amateur radio satellites must coordinate on an international basis through the International Amateur Radio Union (IARU), a volunteer group, to avoid interference to existing amateur and planned operations.
- Limited bandwidth is available. Within the two most popular bands (144-146 and 435-438 MHz), only a total of 5 MHz of bandwidth is available.
- With the limited bandwidth and the need to coordinate frequencies, the use of amateur-satellite spectrum for CubeSats is not sustainable, given the anticipated growth in the number of CubeSat launches. The amateur-satellite service has been accustomed to a handful of operational amateur satellites at one time. Dozens or hundreds more CubeSats (both domestic and international) would overwhelm the available bandwidth at the lower frequencies.

Experimental Licensing

The FCC provides for the issuance of experimental licenses for terms of 6 months to 5 years. Such authorizations may be provided for a variety of purposes, including the following that are relevant to CubeSats:[26]

- Experimentations in scientific or technical radio research;
- Experimentations under contractual agreement with the U.S. government, or for export purposes;
- Communications essential to a research project; and
- Technical demonstrations of equipment or techniques.

[24] Station Authorization Required, 47 C.F.R.§ 97.111 (2010).
[25] Station Authorization Required, 47 C.F.R.§ 97.113 (2010).
[26] Station Authorization Required, 47 C.F.R.§ 5.3 (2010).

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The use of experimental licenses is advantageous for two main reasons:

- Authorizations are typically granted more expeditiously than for traditional licensing; and
- Experimental licenses may utilize any frequency in the spectrum, including government or nongovernment frequencies, upon proper justification.

The use of experimental licenses has the significant drawback, however, that such operations are on a non-interference basis. If such operations cause interference to other services, transmissions must be stopped until the situation is rectified.[27] Stations operating under experimental licenses must also accept interference caused to them by stations operating under regular authority.

While approximately 26 percent of CubeSats (2009 through March 2015) have operated under experimental licenses, many of these satellites utilized amateur radio spectrum. This licensing method leveraged the benefits of using amateur radio spectrum while avoiding the limitations on the use of amateur communications for pay.

Federal Government Authorization

NTIA, instead of the FCC, authorizes transmissions from federal government stations. If a CubeSat qualifies as a government satellite, it may utilize the NTIA process. What exactly constitutes a government satellite is not precisely defined, however. Generally, considerations may include the following:

- What entity positively controls the transmissions emanating from the satellite and its associated Earth stations?
- Who funded the CubeSat?
- Who owns and operates the Earth station facilities?

The first consideration is important. Although a CubeSat may be fully funded by the National Science Foundation (NSF) or NASA, if the satellite and Earth station transmissions are operated by an academic institution, and thus NSF or NASA does not have full control, the satellite will not generally be considered a federal government satellite. There are some methods to satisfy the requirement, however. For example, if the satellite is funded by NSF and operated under a cooperative agreement where NSF retains full control of the satellite and Earth station facilities, the CubeSat may be considered a federal government satellite and authorized through the NTIA process.

The main advantage to obtaining an authorization through NTIA is that the CubeSat developer may leave most of the application process in the hands of government spectrum managers who perform such duties on a regular basis. For example, a NASA-funded CubeSat, if determined to be a federal government satellite, could utilize the standard NASA authorization process to obtain NTIA authorization, and this process is routine among NASA spectrum managers. An additional advantage is that the satellite may utilize federal government frequencies, which may be less congested than nongovernment frequencies are.

On the other hand, the NTIA authorization process can take a long time. Satellites must be certified first (a process through which NTIA determines that the satellite and Earth stations meet all technical rules and that sufficient spectrum resources are expected to be available). Only after the satellite and its Earth station(s) achieve certification may a particular frequency be applied for. The process of certification followed by frequency assignment can easily take more than 1 year, with the process involving collecting and submitting all relevant technical information, followed by submission to NTIA by a government agency, followed by analysis and action by NTIA, which, like most government agencies, has limited resources to deal with increasing workloads. The CubeSat application goes into a general queue that can include applications for major systems, such as air traffic control radars, federal law enforcement radio systems, weather satellites, general agency dispatch radio, and military satellite constellations, among hundreds of other systems processed by NTIA on an ongoing basis.

Very early in the development process, CubeSat developers have to talk with their agency sponsors to determine whether federal government spectrum authorizations are an option.

[27] Station Authorization Required, 47 C.F.R.§ 5.111(a)(2) (2010).

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Licensing Under Satellite Services

Only a small fraction of CubeSat developers have opted for licensing under a recognized non-amateur satellite service, such as the Earth exploration-satellite, space research, or meteorological-satellite services. Typically, licensing under the FCC's "regular" satellite licensing process is utilized by major satellite systems whose development cycle takes years and whose satellite operations are expected to continue for many years. Although such licensing has the advantage of providing firm interference protections and regulatory certainty, it is also the most time-consuming, and potentially expensive, route to pursue, and operations generally are limited to bands specifically allocated to these services, whether the licensee goes through the FCC or the NTIA processes. The advantages of experimental licensing, as discussed above, typically outweigh the advantages of licensing under a recognized satellite service.

Unlicensed

In the early days of CubeSats, a small number were apparently flown without any frequency authorization at all. The developers designed their satellites to utilize "unlicensed" or Industrial Scientific and Medical (ISM) spectrum bands, such as those used for cordless phones, Wi-Fi, baby monitors, microwave ovens, and other terrestrial devices that operate without a license requirement. Unfortunately, this use is forbidden under FCC and NTIA rules, as the concept of unlicensed or ISM spectrum use does not extend to space. All domestic CubeSats and their affiliated Earth stations must be licensed.

Future Spectrum Requirements

As CubeSats and their associated science goals become increasingly sophisticated, bandwidth requirements are likely to continue to grow. To date, most CubeSats have utilized downlink data rates similar to 1980s and 1990s vintage computer modems, at 1 to 57 kbps, with most around 9.6 kbps.[28] (One CubeSat program, by virtue of access to a wider bandwidth satellite allocation, achieved ~2.6 or even 3.0 Mbps downlink speed, but that program was unique[29] and beset by regulatory and interference challenges.[30])

For LEO CubeSats, these data rates effectively translate to low total data downloaded over the life of the satellite, given the limited visibility of satellites from the surface of the Earth and, therefore, limited opportunities for data download. The total lifetime throughput for typical operational CubeSats to date range from a few hundred kilobytes to a few hundred megabytes.

In fact, total data throughput depends on signal bandwidth, and wider bandwidths are more challenging to fit within existing spectrum constraints, especially at frequencies below 1 GHz that are favored by CubeSat developers. It is reasonable to assume that as the science objectives of CubeSats become more ambitious, their bandwidth requirements—and associated regulatory challenges—will also grow. The most obvious solution to increased bandwidth requirements is to move to higher frequencies where more bandwidth is available, although this is accompanied by its own challenges, among them the following:

- Increased radio hardware cost,
- The need for directional antennas and associated pointing requirements,
- Lower power efficiency, and
- Coordination with a larger number of other spectrum users within the larger bandwidth.

[28] B. Klofas, and K. Leveque, 2013, "A Survey of CubeSat Communication Systems: 2009-2012," http://www.klofas.com/papers/Klofas_Communications_Survey_2009-2012.pdf.

[29] NSF and NASA, 2013, *National Science Foundation (NSF) CubeSat-Based Missions for Geospace and Atmospheric Research Annual Report*, p. 7, NP-2013-12-097-GSFC, Arlington, Va., http://www.nsf.gov/geo/ags/uars/cubesat/nsf-nasa-annual-report-cubesat-2013.pdf.

[30] J. Gunther, C. Swenson, and C. Fish, 2013, "'High Data Rate' Communications for DICE," presented at CubeSat Developers' Workshop, Cal Poly, http://mstl.atl.calpoly.edu/~bklofas/Presentations/ DevelopersWorkshop2013/GroundStation_Workshop_Gunther_DICE.pdf.

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Conclusion: Spectrum licensing for CubeSats is required and can be complicated and time-consuming. The increasing use of CubeSats for science will likely also increase the need for higher bandwidth, further complicating the licensing difficulty. This will remain a problem for the growing CubeSat community. CubeSat developers will likely rely extensively on experimental licenses, because a permanent long-term solution for the CubeSat "bandwidth crunch" is not in sight. Because experimental licenses are always issued on a noninterference basis, their use will create an additional element of risk for CubeSat developers.

LAUNCH AS A CHOKE POINT

As discussed above, since 2000, more than 400 CubeSats have been launched through one of the following four alternatives: obtaining a rideshare or "piggyback" on board a vehicle with an established primary satellite; buying a dedicated small launch vehicle; ridesharing with a group of CubeSats on a "cluster launch"; and being a hosted payload permanently attached to another satellite. Roughly half of the launches to date have been just the first option—secondary payloads—on just three vehicles: U.S.-based Antares and Minotaur rockets and Russia-based Dneper. Going forward, however, the United States and Russia no longer have the nanosat launch market duopoly. Since 2014, nearly 300 nano- and microsatellites have been launched by 12 launch vehicle families in six countries (Figure 6.3).

Rideshares are often challenging for CubeSat operators because they have design constraints due to the "do no harm" requirement for secondary payloads. There are other downsides to ridesharing. CubeSat operators have no control over the orbit, and they have to go where the primary payload is going. Their schedule is also driven by the schedule of the primary payload.[31]

Only a small fraction of rockets carry small satellites (in the past 5 years, less than 15 percent of attempted launches had nano- or microsatellites [1-50 kg] payloads on board).[32] Rideshares are not necessarily inexpensive either. Launch costs vary from free to $10 million.[33] For those CubeSats where the development cost in the range of $10,000-$1,000,000, paying millions of dollars in launch costs is unrealistic.

Some low-cost opportunities for rideshare are emerging, especially for scientific payloads. The NASA Launch Services Program runs the Educational Launch of Nanosatellites (ELaNa) program under the CubeSat Launch Initiative (CSLI), run by the NASA Launch Services Program. CSLI provides competitive opportunities for CubeSats to launch to the ISS, or as secondary payloads with other missions through the ELaNa program at no cost to the CubeSat project. Pending the completion of the Space Launch System (SLS), there will also be opportunities for beyond LEO CubeSat launches.[34] On February 2, 2016, NASA announced that 13 science and technology CubeSats would be carried on the first flight of the SLS launch, along with the SLS Orion crew vehicle on a mission called EM-1.

Outside the government, the U.S. launch provider United Launch Alliance (ULA) recently announced a program to provide competitive free rides on future launches for university-based CubeSats.[35] Companies like Spaceflight Industries, Tyvak Nanosatellite Systems, and Nanoracks in the United States, while they do not provide

[31] E. Nightingale, L. Pratt, and A. Balakrishnan, 2015, The CubeSat ecosystem: Examining the launch niche, *Proceedings of 66th International Astronautical Congress*, IAC-15,B4,5,3,x31157, October 12-16 2015, Jerusalem, Israel, available at https://www.ida.org/idamedia/Corporate/Files/Publications/STPIPubs/2016/D-5678.ashx.

[32] E. Buchen, 2015, "Small Satellite Market Observations," *Proceedings of the AIAA/USU Conference on Small Satellites*, SSC15-VII-7, http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3215&context=smallsat.

[33] C. Niederstrasser and W. Frick, 2015, "Small Launch Vehicles—A 2015 State of the Industry Survey," *Proceedings of the AIAA/USU Conference on Small Satellites*, Technical Session II: Launch, SSC15-II-7, http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3176&context=smallsat.

[34] For the moment, this opportunity is for NASA only. However, it is important to note because it shows interest by NASA in furthering the use of CubeSats beyond Earth orbit. E. Nightingale, L. Pratt, and A. Balakrishnan, 2015, The CubeSat ecosystem: Examining the launch niche, *Proceedings of 66th International Astronautical Congress*, IAC-15,B4,5,3,x31157, October 12-16 2015, Jerusalem, Israel, available at https://www.ida.org/idamedia/Corporate/Files/Publications/STPIPubs/2016/D-5678.ashx.

[35] United Launch Alliance, "United Launch Alliance Reveals Transformational CubeSat Launch Program," release date November 19, 2015, http://www.ulalaunch.com/ula-reveals-transformational-cubesat-launch.aspx.

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Achieving Science with CubeSats: Thinking Inside the Box

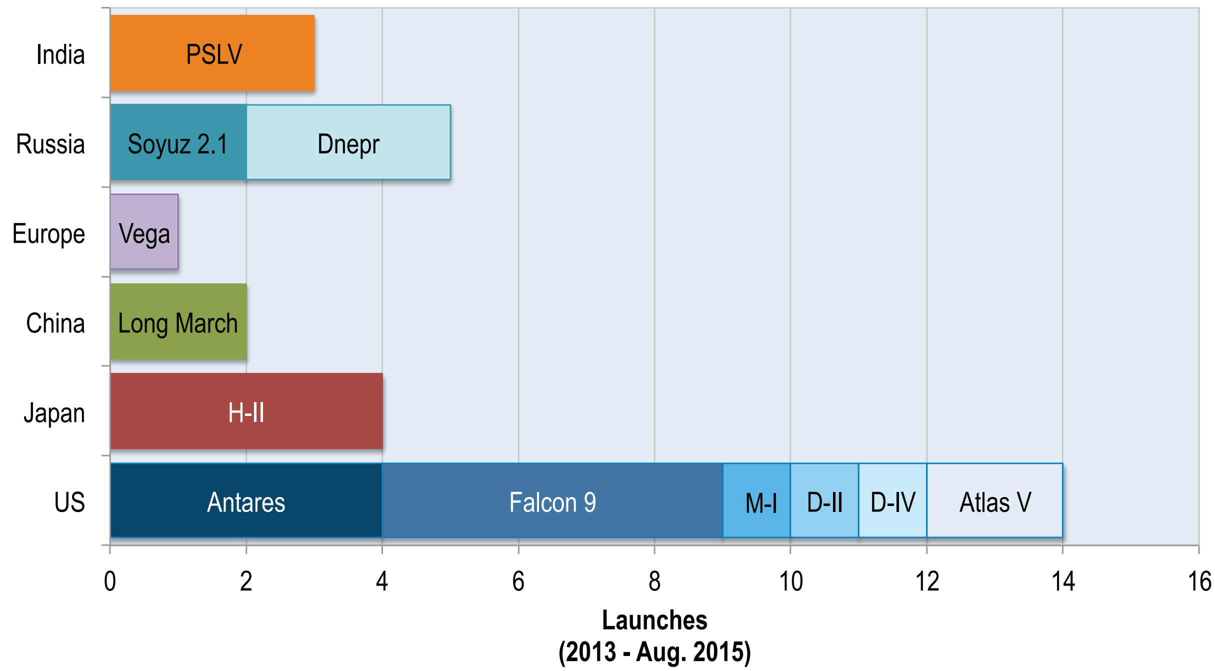

FIGURE 6.3 Countries of Launch of nano- and micro-satellites. By the end of 2015, the United States has provided 14 launches, compared to 15 by other countries. SOURCE: Courtesy of SpaceWorks Enterprises, Inc.

launch, act as a "one stop shop" or broker for launch coordination and integration.[36] Several launch vehicles for small satellites (including 4 that focus on CubeSats)—more than 20 according to recent compilations—are under development.[37] However, as was shown in the recent failure of the Super Strypi vehicle,[38] there is no guarantee that these firms will survive technological and financial challenges and be able to provide the services, especially to the scientific community.

Despite the opportunities, there is a pent-up demand for affordable launch. The NASA CSLI has a waiting list of 62 CubeSats awaiting launch while 43 of 105 selections have launched as of 2015.[39] The new 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. If CubeSats grow in number and utility as expected, low-cost launch availability will need to increase.

Conclusion: As of the end of 2015, most CubeSats have been deployed as secondary payloads on large rockets. This can be cost-effective, but it is also limiting the variety of orbits available for science CubeSats. There are many entities offering vehicles for launch of smaller payloads, including CubeSats. However, their success is uncertain, and low-priced launch remains an elusive target for CubeSats. NASA supports the launch of scientific

[36] There are international brokers as well. Two known ones are "The Group of Astrodynamics for the Use of Space Systems" and "Adaptive Launch Solution."

[37] E. Nightingale, L. Pratt, and A. Balakrishnan, 2015, The CubeSat ecosystem: Examining the launch niche, *Proceedings of 66th International Astronautical Congress*, IAC-15,B4,5,3,x31157, October 12-16 2015, Jerusalem, Israel, available at https://www.ida.org/idamedia/Corporate/Files/Publications/STPIPubs/2016/D-5678.ashx.

[38] NASA Spaceflight.com, "Super Strypi conducts inaugural launch—Fails during first stage," release date November 3, 2015, http://www.nasaspaceflight.com/2015/11/super-strypi-spark-inaugural-launch/.

[39] NASA, "CubeSat Launch Initiative Selectees," release date February 28, 2013, https://www.nasa.gov/directorates/heo/home/CSLI_selections.html#.VwfZF_krJhF.

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Achieving Science with CubeSats: Thinking Inside the Box

and educational CubeSats, but there is a backlog of requests for launches. Thus, low-cost launch remains a barrier for the deployment of scientific and educational CubeSats.

OTHER CUBESAT-RELATED POLICY CHALLENGES

The CubeSats community is directly affected by rules of the International Traffic in Arms Regulations (ITAR) that control the export and import of defense-related articles and services on the U.S. Munitions List (USML). Whereas ITAR is often mentioned as a major hurdle for international science collaborations and also competitiveness, the issues are very difficult to assess at this time. It is too early to see the impact of recent (2014) changes in the ITAR regime on the academic and educational CubeSat community. However, university representatives still find them complicated, are concerned that students are missing opportunities to be exposed to the latest technologies, and believe that the compliance burden could hinder science, invention, business, and innovation, especially between international partners or when including graduate students who are not U.S. born.

Planetary protection is another policy concern related to CubeSats for deep space or planetary science missions. Planetary protection, a part of NASA exploration since the Apollo Era, deals with the practice of protecting solar system bodies from Earth contaminants (forward contamination) as well as protecting Earth from extraterrestrial contaminants that might be returned within the solar system (backward contamination). It is essential that spacecraft are not responsible for depositing or returning contaminants that would obscure the ability to conclusively determine the existence of life elsewhere in addition to the need to protect Earth's biome. NASA directives define policy and procedures associated with inbound and outbound spacecraft, and at this current time, CubeSats need to adhere to the requirements as specified for existing spacecraft systems. For the time being, for CubeSats, this includes trajectory analysis to ensure that systems will not impact other solar system bodies and requirements for spacecraft cleanliness that are dependent on type of mission, such as a flyby, orbiter, or lander, as well as the target body such as a planet, moon, comet, or asteroid. JPL's MarCO flyby mission to Mars has procedural requirements that must be met for planetary protection.

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7

Conclusions and Future Program Recommendations

EVOLUTION FROM A NOVEL EDUCATIONAL TOOL TO A STANDARDIZED COMMERCIAL PLATFORM

Previous chapters have described the evolution of CubeSats as an educational, technology development, and science platform. The case has been made that CubeSats share many characteristics of disruptive innovations, and consistent with that, the CubeSat platform is undergoing rapid development toward growing performance and potential for enhanced science impact. Although CubeSats were introduced as a teaching tool, their evolution as a technology and science platform has been rapid and caused, in part, by a fast "fly-learn-refly" process enabled by comparatively low development cost and timely availability of affordable launch opportunities. Fueled by the excitement of access to space, a newfound pioneering spirit, and sometimes even overenthusiastic optimism of first adopters in academia, industry, and the government, the progress of CubeSats toward becoming a science platform has been rapid. Since 2010, the use of CubeSats for science has grown exponentially. More than 80 percent of all science-focused CubeSats have been launched in the past 4 years. Similarly, more than 80 percent of the peer-reviewed papers describing new science results based on CubeSat data have been published in the past 5 years. Some of the disciplines where CubeSats appear to have much promise (i.e., Earth sciences) have only recently begun exploring CubeSats as a scientific platform.

Since 2012, there has also been a rapid growth in commercial applications using CubeSats, with venture-funded companies such as Planet Labs and Spire focusing on providing data products and services. The industry supporting CubeSat components and technologies is also growing and taking advantage of the increased market size by designing and selling CubeSat and small spacecraft buses, subsystems, and ground station services. These commercial firms are now major drivers of development in technologies such as attitude control and propulsion, as well as subsystems such as power boards and communication systems standardized to the CubeSat form factor. Some of this technology can now be purchased off the shelf and is available for science teams that seek to employ CubeSats to address science questions. Development kits are now available that provide an entry point for newcomers, or such groups may partner with companies that sell spacecraft buses along with payload integration, test, and mission operations. These advances in purchased spacecraft subsystems and common software now permit a science-driven CubeSat mission to focus primarily on development of the science instrumentation.

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SCIENCE PROMISE OF CUBESATS

Based on the review of the scientific literature and inputs from a broad range of scientific communities, the committee concluded that CubeSats have already proven themselves to be an important scientific tool. CubeSats can produce high-value science, as demonstrated by peer-reviewed publications that address decadal survey science goals. They are useful as targeted investigations to augment the capabilities of large missions and ground-based facilities, are enabling new kinds of measurements, and may have the potential to mitigate gaps in measurements where continuity is critical. Although all science disciplines can benefit from innovative CubeSat missions, CubeSats cannot address all science objectives and are not a low-cost substitute for all platforms.

Some activities, such as those needing large apertures, high-power instruments, or very-high-precision pointing, most likely will always require larger platforms because of fundamental and practical constraints of small spacecraft. Also, large spacecraft excel at large-scale investigations, when, for example, several instruments need to be collocated. CubeSats excel at simple, focused, or short-duration missions, missions that need to be low cost, or those that require multipoint measurements.

Sample Science Goals

Because of their size, cost, and length of development cycle, CubeSats can transform the conduct of space science in two ways. First, they can enable some fraction of science traditionally done by larger and more expensive platforms to be conducted in more cost-effective ways. Second, CubeSats can enable and support science not feasible with traditional missions. It is via constellations of dozens or even hundreds of CubeSats where the most transformational science might be enabled. In space physics and Earth science especially, high-cadence, simultaneous multipoint measurements are essential for studying complicated, highly coupled systems, and these kinds of investigations so far have not been feasible. CubeSat-based constellations have the potential to provide important and truly enabling science capabilities in astronomy and planetary sciences—for example, by using instruments with distributed apertures such as radio interferometers.

The set of scientific goals where the use of CubeSats would be enabling is evolving too quickly for the committee to create a comprehensive list, and this committee was not tasked with prioritizing CubeSat missions. However, the following list, restated from Chapter 4, provides a sampling of high-priority science goals that could potentially be pursued using CubeSats:

- *Solar and space physics, Earth science and applications from space—Exploration of Earth's atmospheric boundary region*. CubeSats are uniquely suited because of their expendability to explore the scientific processes that shape the upper atmospheric boundary using short-lifetime, low-altitude orbits.
- *Solar and space physics—Measurement of plasma processes in the magnetosphere-ionosphere system*. A 10-100 satellite constellation of CubeSats carrying magnetometers and plasma instrumentation can provide detailed information about the spatial and temporal evolution of magnetospheric plasmas.
- *Earth science and applications from space—Multipoint, high temporal resolution of Earth processes*. Satellite constellations in low Earth orbit could provide both global and diurnal observations of Earth processes that vary throughout the day, such as severe storms, and are currently under-sampled by Sun-synchronous observatories.
- *Earth science and applications from space—Mitigation of data gaps and continuous monitoring*. Anticipated and potential gaps (caused by launch or instrument failures and budget constraints) in weather satellite data, land surface imaging, and solar irradiance measurement may have the potential to be mitigated by observations from small spacecraft enabled by CubeSat technology.
- *Planetary science—Measuring the distribution of lunar water.* CubeSat concepts could map the distribution of water on the Moon with a variety of complementary techniques, such as neutron spectroscopy and infrared spectroscopy.
- *Planetary science—In situ investigation of the physical and chemical properties of planetary surfaces or atmospheres*. Deployable (daughter-ship) CubeSats could expand the scope of the motherships with complementary science or site exploration.

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Achieving Science with CubeSats: Thinking Inside the Box

- *Planetary science—Measurements of planetary magnetospheres*. Constellations of CubeSats could provide simultaneous fields and particle measurements at multiple sites in planetary magnetospheres. Such measurements in the vicinity of large icy satellites could help determine the magnetic field induced in deep oceans.
- *Astronomy and astrophysics—Search for extrasolar planets*. A CubeSat could "stop and stare" for a long time at one bright Sun-like star to search for transiting exoplanets.
- *Astronomy and astrophysics, solar and space physics—Low-frequency radio science*. Interferometers made of CubeSats could explore the local space environment and also galactic and extragalactic sources with spatial resolution in ways not accessible from Earth.
- *Biological and physical sciences in space—Investigate the survival and adaptation of organisms to space*. CubeSats offer a platform to understand the effects of the environment encountered in deep space, such as microgravity and high levels of radiation.

PROGRAMMATIC RECOMMENDATIONS

As CubeSat-enabled missions evolve, the programs and management processes that currently fund and support them will have to evolve as well. The scientific potential offered by CubeSats continues to depend on investments in a number of programs, including the National Science Foundation (NSF), where the first CubeSat-based science program originated; NASA, where most CubeSats programs reside currently; and the Department of Defense Air Force Research Laboratory, which supports a large fraction of technology development and education efforts. During the ongoing, rapid expansion of scope and capability of this disruptive platform, the programmatic investments would benefit from continued broad access and also rapid dissemination of lessons learned among the different agency programs and the commercial sector, both of which will be addressed in subsequent recommendations to NSF and NASA.

The first such recommendation focuses on the CubeSat program that is part of NSF. This program has the dual goals of supporting small satellite missions to advance space weather-related research and of providing opportunities to train the next generation of experimental space scientists and aerospace engineers. The committee believes that the program has been successful with regard to both goals, and NSF's current program continues to be valuable. The program is particularly well aligned with the goals and recommendations of the 2013 decadal survey in solar and space physics; however, other disciplines at NSF, such as Earth science and astronomy and astrophysics, could also benefit from the scientific and educational opportunities that CubeSats provide.

Recommendation: The National Science Foundation (NSF) should continue to support the existing CubeSat program, provide secure funding on a multiyear basis, and continue to focus on high-priority science and the training of the next generation of scientists and engineers. In particular, NSF should consider ways to increase CubeSat opportunities for a broad range of science disciplines going beyond solar and space physics, with financial support from those participating disciplines.

Although most science results published to date have come from NSF-sponsored CubeSat investigations, that is expected to change within the next few years as a result of NASA's increased interest in CubeSats. NASA is developing at least 13 science-focused CubeSats, sponsored from five or more different NASA programs. Several science communities are still in the very early phases of learning to design and operate CubeSats, while others are actively developing promising science missions. The current diversification and rapid expansion of CubeSats within NASA are characteristic of the early phase of disruptive innovation, as discussed in Chapter 2.

CubeSats have proven their usefulness in the pursuit of science, most notably demonstrated by the increase in the publication of scientific results as described in Chapter 4 and Appendix B. The explosion of interest in the deployment of CubeSats and proliferation of NASA programs that sponsor CubeSat missions has led to some inefficiencies. For example, a university group interested in becoming involved with CubeSats might find it difficult to identify the best opportunities and NASA partners for the desired endeavor. Similarly, a company with interesting new technologies does not have a clear pathway to make those products available to all of the different teams. In addition, the committee encountered multiple instances where more than one mission team within NASA

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was independently developing the same technology: examples include laser communications, cold-gas propulsion systems, and the ability to modify the orbits of multiple spacecraft by atmospheric drag.

Conclusion: The rapidly increasing potential of CubeSats as a platform for scientific discovery translates into a need for better coordination and management at NASA. Spacecraft development, launch and radio license approvals, technology development, and mission operations efforts to support scientific CubeSat missions are being duplicated at multiple centers and at investigator facilities.

Other existing programs within NASA (e.g., the sounding rocket and balloon programs) provide examples of possible management approaches. The committee believes that the following three aspects of those programs are relevant to CubeSats: (1) the program office provides a single point of contact within NASA and support for technical and policy related issues common to a given platform; (2) the program office creates an appropriate level of oversight matched with the development cycle and risk profile of balloons and rockets, respectively; and (3) the program office becomes a champion within NASA and the science community. However, one should not push these analogies too far as CubeSat missions face different technical and programmatic challenges from those of sounding rockets and balloons.

Recommendation: NASA should develop centralized management of the agency's CubeSat programs for science and science-enabling technology that is in coordination with all directorates involved in CubeSat missions and programs, to allow for more efficient and tailored development processes to create easier interfaces for CubeSat science investigators; provide more consistency to the integration, test, and launch efforts; and provide a clearinghouse for CubeSat technology, vendor information, and lessons learned. The management structure should use a lower-cost and streamlined oversight approach that is also agile for diverse science observation requirements and evolutionary technology advances.

Centralized management should make it possible to increase the overall scientific return and advance sophisticated uses of CubeSats such as large constellations. At the same time, it is important to encourage innovation by maintaining a variety of programs.

Recommendation: NASA should develop and maintain a variety of CubeSat programs with cost and risk postures appropriate for each science goal and relevant science division and justified by the anticipated science return. A variety of programs are important to allow CubeSats to be used for rapid responses to newly recognized needs and to realize the potential from recently developed technology.

For example, a solar and space physics-focused CubeSat with a short development cycle and lower cost might be able to take rapid advantage of a technological breakthrough. On the other hand, a CubeSat flying as part of a planetary science mission might be developed on the same timescale as the larger spacecraft of the mission and require higher reliability, which is typically associated with higher cost.

Education and Training

One critical benefit of NASA's engagement in CubeSats is the role of CubeSats in training students, early career project scientists, engineering teams, and project managers. Care must be taken to not inadvertently stifle such training opportunities as CubeSats evolve toward more-capable science missions and as the proposed new management structure is implemented.

Recommendation: NASA should use CubeSat-enabled science missions as hands-on training opportunities to develop principal investigator leadership, scientific, engineering, and project management skills among both students and early career professionals. NASA should accept the risk that is associated with this approach.

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Constellations

There is one type of mission class that is of high priority for multiple disciplines and which deserves focused investment and development—the creation of swarms and constellations for high-priority measurements. As discussed in detail in Chapter 4, constellations are of high priority in the decadal survey for solar and space physics, a community that has evolved from single space missions to research that requires data from multiple missions, toward an approach of two to five identical spacecraft that are analyzed as a constellation. Many high-priority science investigations of the future require data from constellations or swarms of 10 to 100 spacecraft that, for the first time, would have the spatial and temporal coverage to map out and characterize the physical processes that shape the near Earth space. Constellations are also critical to Earth science, in which the number of spacecraft relates directly to coverage and temporal evolution of a given phenomenon. Similarly, some constellation-based missions have also been discussed for astrophysics or planetary applications. Because of these and several other opportunities across the science disciplines for high-priority science by constellations and swarms, the time is ripe to develop this new capacity. The Cyclone Global Navigation Satellite System (CYGNSS) Earth Venture mission with eight LEO spacecraft—small, but not CubeSats—is an important step for science constellation development. NASA, with its distributed ground systems and established new mission opportunities, can further advance the capabilities for constellation and swarm science missions. Historically, the cost associated with large constellations for spacecraft numbers between 10 to 100 spacecraft has been prohibitive.

Recommendation: Constellations of 10 to 100 science spacecraft have the potential to enable critical measurements for space science and related space weather, weather and climate, as well as some astrophysics and planetary science topics. Therefore, NASA should develop the capability to implement large-scale constellation missions taking advantage of CubeSats or CubeSat-derived technology and a philosophy of evolutionary development.

TECHNOLOGY INVESTMENTS

Since the beginning of the CubeSat missions in 2000, the capacity to do science with CubeSats strongly depends on the technological capabilities available to the investigators. CubeSat technology advances are markedly noticeable since 2008 when government funding of CubeSat technology and missions began, and many science CubeSat missions are now in development by NSF and NASA. Nonetheless, the spacecraft technology capabilities are currently limiting the use of CubeSats in some science applications.

Conclusion. The key gaps in technology related to CubeSats for science applications are high bandwidth communications, precision attitude control, propulsion, and the development of miniaturized instrument technology.

If these capabilities can reach maturity, they will be able to support flight formation, orbital deployment and maintenance, precise pointing for persistent and high-resolution observations, and high-bandwidth communications. One important benefit of such developments is that they enable missions that consist of constellations or swarms of CubeSats or CubeSat-technology enabled satellites. See Chapter 4 and Table 5.1 for details of specific scientific applications of these enabling technologies.

Recommendation: NASA and other relevant agencies should invest in technology development programs in four areas that the committee believes will have the largest impact on science missions: high-bandwidth communications, precision attitude control, propulsion, and the development of miniaturized instrument technology. To maximize their impact, such investments should be competitively awarded across the community and take into account coordination across different agencies and directorates, including NASA's Science Mission Directorate and Space Technology Mission Directorate, and between different NASA and Department of Defense centers.

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Achieving Science with CubeSats: Thinking Inside the Box

An additional area of technology development that is important to several disciplines is thermal control, a much broader, system engineering-related topic than are those recommended above. Aspects of thermal control vary from maintaining low temperatures for imaging spectrometers to creating a stable payload environment for biology experiments with live specimens.

One benefit of CubeSat technology developments is the maturing of specific instrumentation and space technologies available to spacecraft that are not necessarily consistent with the CubeSat norm. There are already numerous applications for Explorers or Venture-class missions that benefit from the availability of technologies developed for CubeSats either commercially or by federal research and development programs.

Conclusion: CubeSats have been and will likely remain an important and cost-effective in-space platform for research, development, testing, and demonstration of technologies relevant to scientific discovery.

The private sector has been growing both in terms of capabilities in and investments for CubeSat applications and is likely to remain an important partner in technology development programs for small satellites. However, in some areas, private-sector investments are less likely to occur, such as infrastructure and facilities (e.g., a test and prototyping center); development of deorbiting; tracking and other technologies related to orbital debris reduction goals; and approaches to enable affordable launch for CubeSats.

Recommendation: As part of a CubeSat management structure, NASA should analyze private capabilities on an ongoing basis and ensure that its own activities are well coordinated with private developments and determine if there are areas to leverage or that would benefit from strategic partnerships with the private sector.

POLICY

Although CubeSats are only a small fraction of the cost, mass, and complexity of other spacecraft launched by commercial and government entities, they are subject to a comparable policy framework. If applied improperly and without consideration of the short development cycle, low costs, and rapid increase in the number of commercial, technology, and science CubeSats, such policy constraints could have a chilling effect on the scientific and technology return of CubeSats.

The committee focused principally on three policy issues that have the potential to limit the applicability of CubeSats for science—orbital debris, communications and frequency allocations, and launch availability—including, in particular, regulatory framework.

Orbital Debris

Finding: Because CubeSats typically are not maneuverable, they are seen as orbital debris threats, especially in near Earth orbits, with low Earth orbit being a special challenge because of the presence of the International Space Station. CubeSats comprise less than a percent of all resident objects in space and are expected to remain a small fraction, even as their number in space grows. The number of science-focused CubeSats is an order of magnitude lower than that.

Conclusion: Although CubeSats are a very small fraction of all resident objects in space, the risk of a CubeSat conjunction or collision is not insignificant. Thus, the CubeSat community has an opportunity to avoid potential future problems by continuing to proactively engage in policy discussions and seek technological solutions, such as low-cost means for CubeSats to be maneuverable, trackable, and deorbited appropriately.

Communications and Frequency Allocation

Conclusion: Spectrum licensing for CubeSats is required and can be complicated and time-consuming. The increasing use of CubeSats for science will likely also increase the need for higher bandwidth, further complicat-

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ing the licensing difficulty. This will remain a problem for the growing CubeSat community. CubeSat developers will likely rely extensively on experimental licenses, because a permanent long-term solution for the CubeSat "bandwidth crunch" is not in sight. Because experimental licenses are always issued on a noninterference basis, their use will create an additional element of risk for CubeSat developers.

Launch Availability

Conclusion: As of the end of 2015, most CubeSats have been deployed as secondary payloads on large rockets. This can be cost-effective, but it is also limiting the variety of orbits available for science CubeSats. There are many entities offering vehicles for launch of smaller payloads, including CubeSats. However, their success is uncertain, and low-priced launch remains an elusive target for CubeSats. NASA supports the launch of scientific and educational CubeSats, but there is a backlog of requests for launches. Thus, low-cost launch remains a barrier for the deployment of scientific and educational CubeSats.

Recommendation: NASA, with the National Science Foundation, and in coordination with other relevant federal agencies, should consider conducting a review and developing a plan to address CubeSat-related policies to maximize the potential of CubeSats as a science tool. Topics may include, but are not limited to, the following: guidelines and regulations regarding CubeSat maneuverability, tracking, and end-of-mission deorbit; the education of the growing CubeSat community about orbital debris and spectrum-licensing regulatory requirements; and the continued availability of low-cost CubeSat launch capabilities. It is important to consider that current and new guidelines promote innovation, rather than inadvertently stifling it, and ensure that new guidelines are science-based, equitable, and affordable for emerging players within the United States and internationally.

BEST PRACTICES TO GUIDE ONGOING CUBESAT DEVELOPMENT

History has shown that the likelihood of success and economic impact of potentially disruptive innovations, such as CubeSats, is difficult to predict in the early days of the disruption. At this point, it seems that CubeSats will become an effective tool for a specific and eventually well-defined performance envelope, like balloons or sounding rockets. However, it is possible that CubeSats will have a much bigger impact and lead to new types of missions and scientific data, and perhaps even lead to a more macroscopic realignment of the space industry. The principles of disruptive innovations informed the above recommendations and also led the committee to suggest some best practices that can guide the ongoing development of CubeSats.

- *Avoid premature focus*. Although the committee recommends a NASA-wide management structure to create opportunities for new investigators and provide a clearinghouse for information and lessons learned, premature top-down direction that eliminates the experimental, risk-taking programs would slow progress and limit potential breakthroughs.
- *Maintain low-cost approaches as the cornerstone of CubeSat development*. It is critical to resist the creep toward larger and more expensive CubeSat missions. Low-cost options for CubeSats are important because more constrained platforms and standardization, coupled with higher risk tolerance, tend to create more technology innovation in the long run.
- *Manage appropriately*. As missions grow more capable and expensive, management and mission assurance processes will have to evolve. Yet, it is critical to manage appropriately, without burdening low-cost missions with such enhanced processes, by actively involving CubeSat experts in policy changes and discussions as well as in proposal reviews.

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Appendixes

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A

Statement of Task

An ad hoc committee under the auspices of the National Research Council will review the current state of the scientific potential and technological promise of CubeSats. 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). In particular, the committee will review the potential of CubeSats as platforms for obtaining high priority science data including, but not limited to, the priority science challenges identified in (a) recent NRC decadal surveys in astronomy and astrophysics, Earth science, planetary science, and solar and space physics (heliophysics) and (b) the science priorities identified in the 2014 NASA Science Plan. The committee's review will provide a set of recommendations on how to assure the scientific return on future federal agency support of CubeSat programs.

The committee will:

- Develop a brief summary overview of the status, capability, availability, and accomplishments of a selection of existing CubeSat programs in the government, academic, and industrial sectors.
- Recommend any potential near-term investments that could be made (a) to improve the capabilities that have a high impact on the increased science and technology return—thereby increasing the value of CubeSats to the science community—and (b) to enable the science communities' use of CubeSats.
- Identify a set of sample priority science goals that describe near-term science opportunities—such as providing continuity of key measurements to mitigate potential gaps in measurements of key parameters—and that can be accomplished given the current state of CubeSat capabilities.

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B

CubeSat Publications—Descriptive Statistics

INTRODUCTION

The purpose of this section is to review and assess publications related to CubeSats, in support of Chapter 4. Two types of publications are of interest. The first set includes publications (both reviewed and conference contributions) that introduce enabling technologies and novel mission designs. Such publications appear in a wide variety of engineering and scientific journals. The second set of publications contains those that document the scientific findings emerging from CubeSats. The latter papers are published only after CubeSats have operated for an adequate amount of time and the data are analyzed and interpreted. Given the recent emergence of CubeSats, one would therefore expect a high number of the first type of publications, followed with a delayed and possibly smaller number of the second kind.

NUMBER OF PUBLICATIONS

Due to the fast growth and diversity of the communities involved in CubeSats (see Chapter 1), there is currently no authoritative count of publications that have come from this platform. A search of the scientific citation indexing service Web of Science (WoS) with the keyword "CubeSat*" in all topics[1] results in 959 publications, the first of which was published in 2000.[2] Figure B.1 shows the distribution of these publications: 724 of the publications cite engineering as a research area, and 29 have education or educational research as a keyword.

Excluding all records that are not cataloged as articles leaves 290 publications. Figure B.2 shows how these articles are distributed in time and highlights the rapid and nearly exponential increase in the number of articles since 2007. These articles fall in over 40 topical areas, but the majority (219, or over 75 percent) list engineering as the research area (potentially among others). The scientific topic area with the largest number of articles was astronomy/astrophysics, with 71 records, which includes a significant number of publications in solar and space physics. There were 7 articles that listed education research as a topic area.

[1] The search included the following Web of Science databases: Web of Science Core Collection, Inspec, Current Contents Connect, KCI-Korean Journal Database, and MEDLINE.

[2] It is important to note that not every paper based on research conducted via CubeSats lists the term in the publication. It may, for example, use the term "nanosatellite," or even "small satellite." So a search on the term "CubeSat*" alone is a likely undercount of the publications based on CubeSats.

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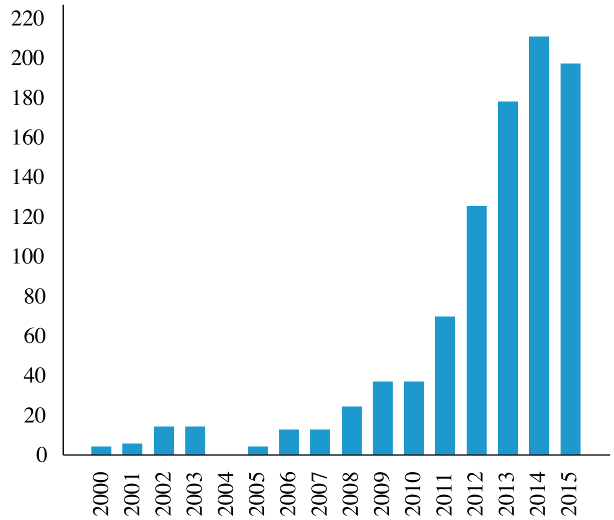

FIGURE B.1 All publications (959) with the keyword CubeSat* through 2015. NOTE: Count for 2015 may be incomplete although the search was performed early in 2016. SOURCE: Web of Science search conducted on January 10, 2016, http://www.webofscience.com.

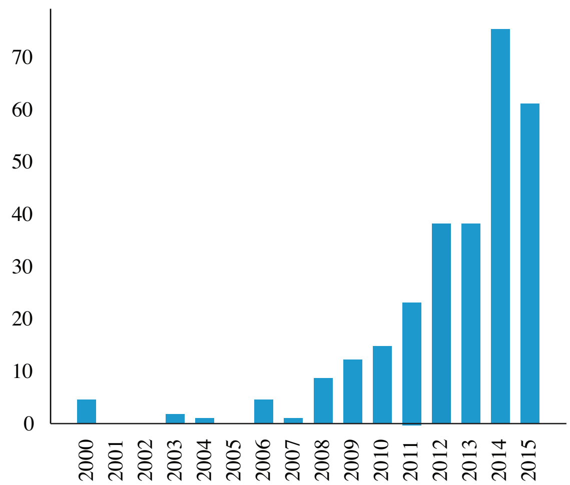

FIGURE B.2 Articles (290) with the keyword CubeSat* through 2015. NOTE: Count for 2015 may be incomplete although the search was performed early in 2016. SOURCE: Web of Science search conducted on January 10, 2016, http://www.webofscience.com.

A search on a different scientific citation indexing service, Scopus, leads to a different number of publications. A search on the term "CubeSat*" in Scopus results in 2,283 records. This number is likely higher because Scopus covers more engineering journals and conference proceedings than does WoS. Limiting the search to Abstract, Title and Keywords leaves in 1,264 records.

Selecting only articles results in 202 records. As with WoS, the bulk of the papers (170) are characterized as engineering, followed by Earth and planetary science (49). And as with WoS, there is steep increase in the number of publications in recent years (Figure B.3). Scopus follows a different classification scheme than does WoS, and the papers cover 19 scientific disciplines. However, the top research area of publications remains engineering (Figure B.4).

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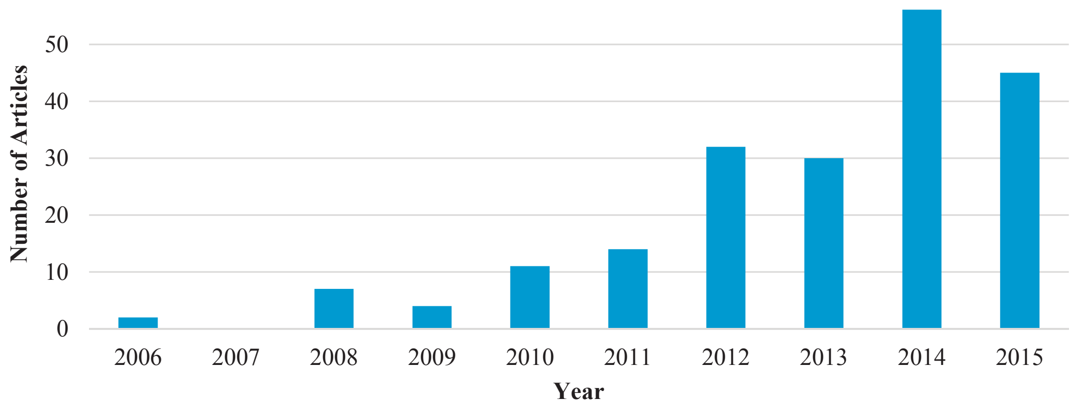

FIGURE B.3 Articles with the keyword CubeSat* in title, abstract, and keywords. NOTE: Count for 2015 may be incomplete although the search was performed early in 2016. SOURCE: Scopus search conducted on January 10, 2016, http://www.scopus.com/.

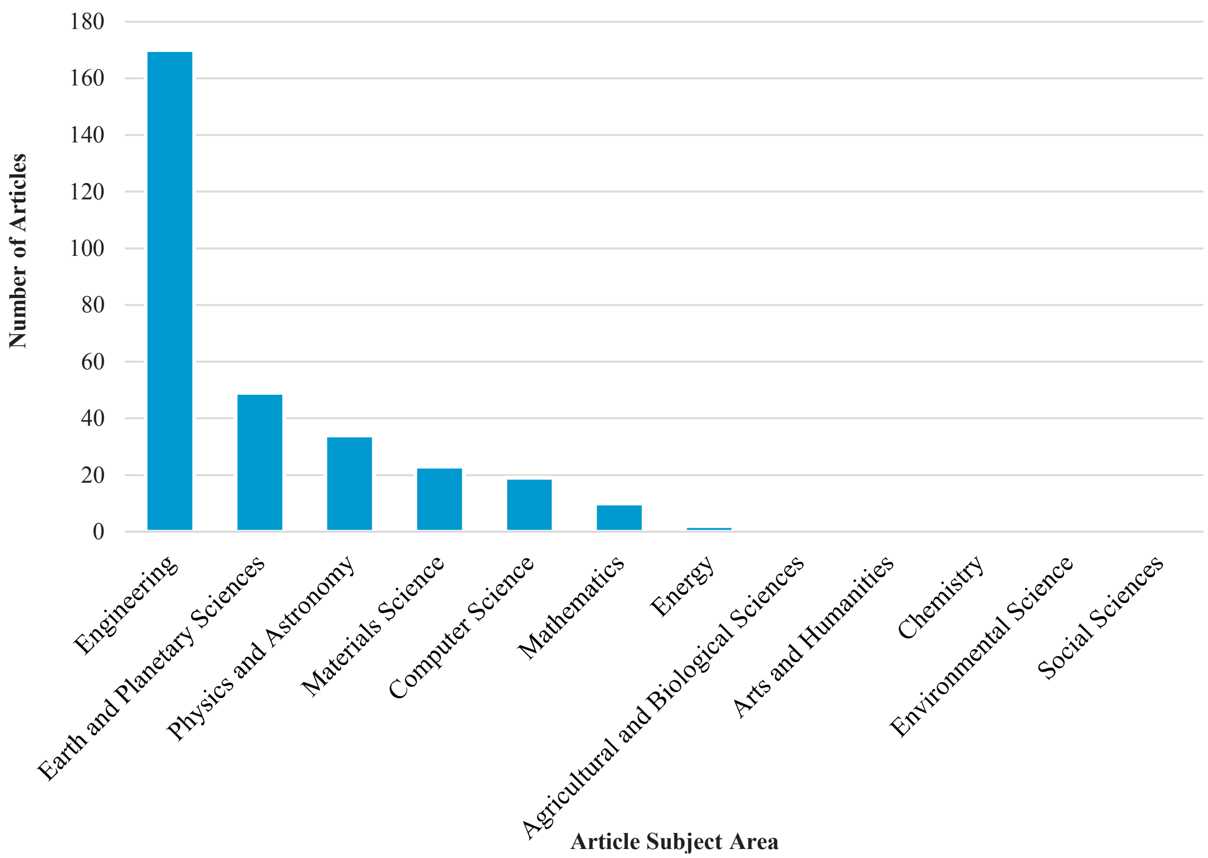

FIGURE B.4 Distribution of articles with the keyword CubeSat* in title, abstract, and keywords by subject area. NOTE: Count for 2015 may be incomplete although the search was performed early in 2016. SOURCE: Scopus search conducted on January 10, 2016, http://www.scopus.com/.

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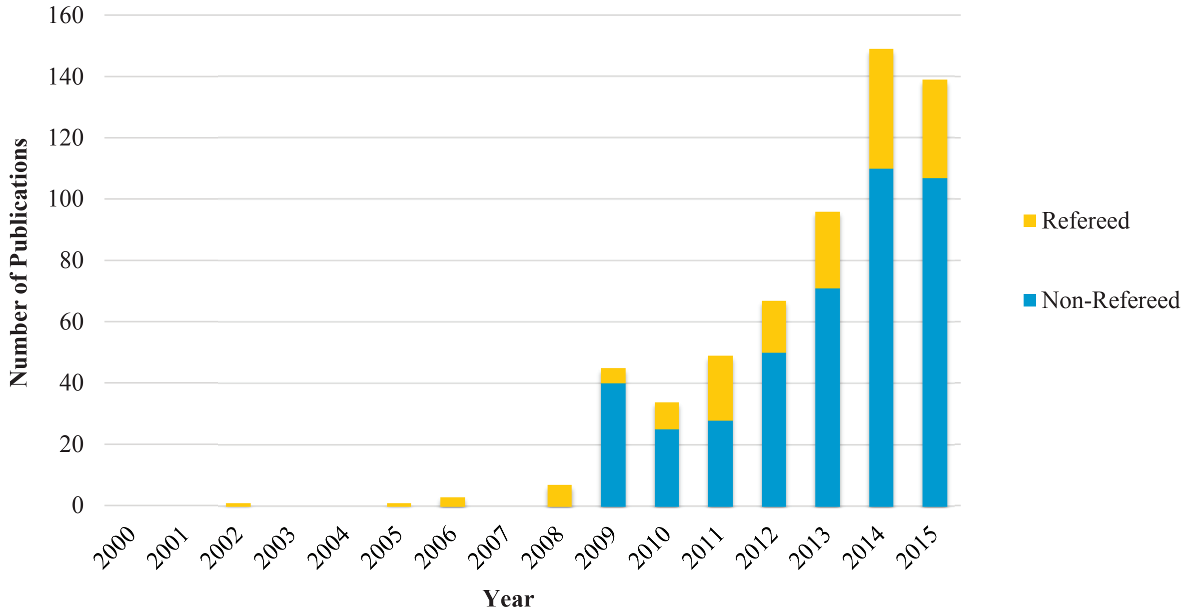

FIGURE B.5 All publications with the keyword "CubeSat" or "CubeSats" in both title and abstract. NOTE: Count for 2015 may be incomplete although the search was performed early in 2016. SOURCE: SAO/NASA ADS (Smithsonian Astrophysical Observatory/NASA Astrophysics Data System) search conducted on January 25, 2016, http://www.adsabs.harvard.edu/, accessed January 2016.

A third source used to catalog CubeSat publications was the Smithsonian Astrophysical Observatory/NASA Astrophysics Data System, which includes a much broader set of journals than might be implied by the title. Searches were conducted using the terms "CubeSat" or "CubeSats" in either the title or abstracts of each entry. This search leads to a total of 536 publications, 160 of which are refereed journal papers (Figure B.5).

The 160 refereed papers were manually classified into seven categories: engineering; astronomy and astrophysics; solar and space physics/heliophysics; planetary science; Earth sciences, biological sciences, and other. As Figure B.6 shows, almost three-quarters of these papers are engineering oriented; 41 publications are devoted to the five scientific fields of interest.[3]

Figure B.7 presents a time series of these 41 refereed papers in the five scientific fields of interest, and it shows that over the years, heliophysics has been the dominant field of publication, with planetary science, astronomy, and biology entering the domain in recent years.

[3] The category "other" includes publications on policy or educational topics or survey-type articles.

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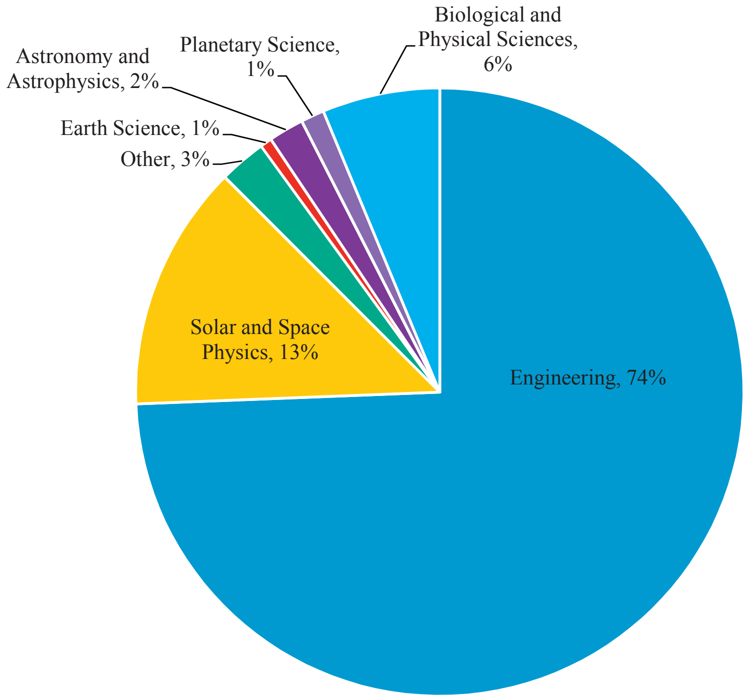

FIGURE B.6 Distribution of refereed publications by fields of interest. SOURCE: Committee assessment using data set from SAO/NASA ADS (Smithsonian Astrophysical Observatory/NASA Astrophysics Data System) search conducted on January 25, 2016, http://www.adsabs.harvard.edu/, accessed January 2016.

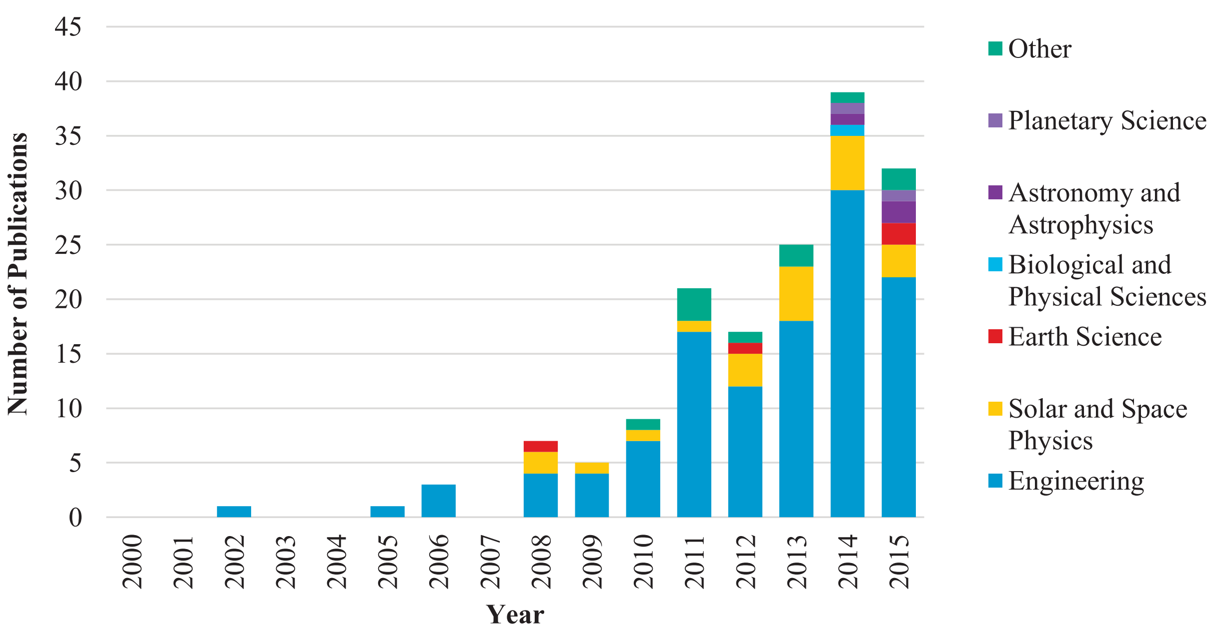

FIGURE B.7 Distribution of refereed publications distributed over scientific research areas by year. SOURCE: Committee assessment using data set from SAO/NASA ADS (Smithsonian Astrophysical Observatory/NASA Astrophysics Data System) search conducted on January 25, 2016, http://www.adsabs.harvard.edu/, accessed January 2016.

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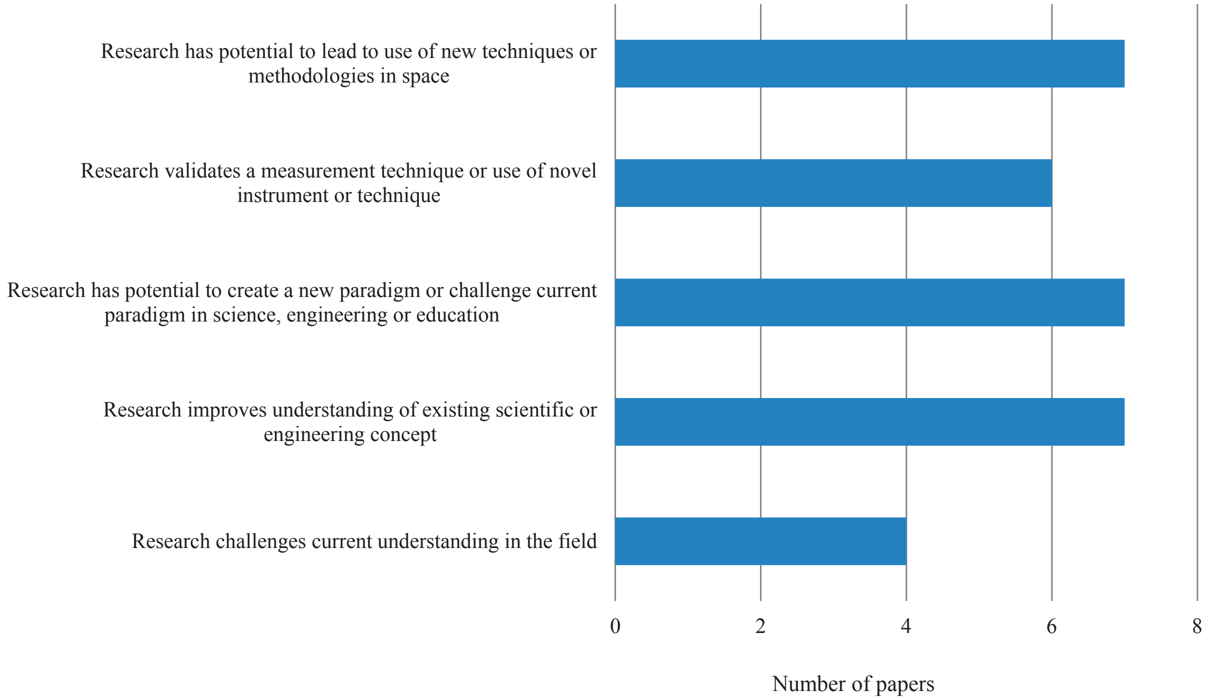

FIGURE B.8 Qualitative assessment of science impact by reviewers. Research was rated in five categories: (1) research challenges current understanding in the field; (2) research improves understanding of existing scientific or engineering concept; (3) research has potential to create a new paradigm or challenge current paradigm in science, engineering or education; (4) research validates a measurement technique or use of novel instrument or technique; and (5) research has potential to lead to use of new techniques or methodologies in space. More than one contribution could be selected for each paper.

QUALITATIVE ASSESSMENT

Although the committee identified only 41 scientific publications based on CubeSats,[4] it is important to note that refereed papers are being published, and some of them have important consequences for the understanding of science in solar and space physics (see Chapter 4 for examples).

A subset of 15 of these papers were reviewed qualitatively by the committee to assess impact. Naturally, the depth of scientific impact of these papers is aligned with the availability of science-focused CubeSats that are in flight, which is dominated by solar and space physics and heliophysics (out of the set, 9 publications were in the domain of solar and space physics). Refereed publications in astronomy and astrophysics or planetary sciences are mostly focused on the description of new measurement techniques or data strategies enabled by CubeSats.

The result of this qualitative analysis is provided in Figure B.8. Committee members rated the contributions of the research in five categories: research that challenges current understanding; research that improves understanding; research with the potential to create a new paradigm in science, engineering, or education; research that validated a measurement technique; or research that could lead to new methodologies in space. Overall, the scien-

[4] These papers were gathered from the previously mentioned literature searches, from publication lists sent by the NSF CubeSat program teams, and from the committee's request to attendees of the community input symposium in Irvine, California.

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tific benefit of CubeSats was spread across a small number of topics. CubeSats had the potential to be paradigm altering or to improve understanding of the underlying physical processes that were studied. Yet, the engineering and educational impact was considered to be important for many of the investigations, especially because a number of them proved new technologies or instrument techniques.

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C

Additional Technology and Policy Details

This appendix is written in support of the technology chapter (Chapter 5) and the chapter focused on policy-related issues (Chapter 6) to provide enhanced technical depth for the interested reader.

TRACKING TECHNOLOGY OPTIONS

Operationally, a space surveillance system perceives objects whose isotropic UHF radar cross sections are 10 cm diameter in low orbit. Tracking of CubeSats in this way can be *active and cooperative* (e.g., the owner/operator participates in tracking by emitting signals via a transponder, or sharing telemetry with JSpOC or other entities responsible for tracking spacecraft). Among active technology, there is development effort under way at the Air Force Research Laboratory and National Laboratories. Los Alamos National Laboratory, for example, is developing an optical beacon called ELROI (Extremely Low Resource Optical Identifier) to attach to everything that goes into space and broadcasts satellite identity at all times.

Tracking can also be *passive and uncooperative* (e.g., ground-based radar that radiates energy pulses that reflect off of the object back to a receiver without the object's participation). Passive technology benefits from anything that increases the radar cross section (e.g., by the deployment of dipole structures) or increases the optical visibility (e.g., by the use of highly reflective surface materials). Corner cube retro-reflectors as a passive device are currently under development.

Tracking of deep space CubeSats for navigation is similar in nature to the tracking of large missions. It involves communication with the Deep Space Network (DSN), but in the case of the lunar CubeSats, tracking and commanding may be achieved via antennae outside the DSN. Deep space tracking and navigation are planned for demonstration with the INSPIRE and MarCO missions.

DEORBIT CONTROL AND SPACE DEBRIS MITIGATION

The control of orbital debris involves both regulatory and technological issues. Most technologies that mitigate the negative effects of CubeSats' contribution to space debris are focused on their removal from orbit and subsequent disintegration when reentering the Earth's atmosphere. As such, these technologies are directly linked to the ability of CubeSats to modify their orbits, passively or actively. These have been discussed already in the

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subsection "Mobility and Propulsion" of this report. However, in a more general sense, the problem of debris control includes situations when nonresponsive spacecraft need to be actively tracked down and deorbited.

Currently, there is no deorbiting system that could remove space debris from orbit. Nevertheless, there is a large amount of work under way related to this effect, primarily dedicated to spacecraft larger than CubeSats. In particular, there is interest in the removal of space debris from geostationary orbits (no deorbit in this case) and large rocket stages and components. The largest threat to operational satellites comes from smaller debris in low Earth orbit (LEO), objects with dimensions of 10 cm or smaller, which can include inactive CubeSats. In most cases, a spacecraft is used to rendezvous and force the debris into an orbit that facilitates deorbit. Relevant technologies include those for identifying target properties, performing flight formation with non-cooperative targets, and docking and propulsive tugging. Switzerland's CleanSpace One is an example using a 3U CubeSat to demonstrate this capability by deorbiting a 1U CubeSat by 2017.

Other approaches, known as "sweepers," would capture small objects onto a large but light aerogel-based structure and then reenter Earth's atmosphere using onboard propulsion. Other approaches include the use of ground- and space-based lasers that would target debris and ablate a fraction of their surfaces, thus imparting momentum to decrease their orbital energies.

Table C.1 shows the mission capabilities for some of these micro-propulsion options for CubeSats together with their quoted technology readiness level (TRL), a scale from 1-9 to define the development state, with 1 being pure conceptual and 9 reserved for mission-proven, readily available, and reliable technologies.

RADIO SPECTRUM BACKGROUND

The radio spectrum is exceedingly valuable. Auctions of radio spectrum for various uses such as cellular phones, paging, and broadcast have raised well over $50 billion in the United States since auctions were first used as a licensing tool in 1994. But the value of the radio spectrum as an economic driver is estimated to be much larger still, with a tremendous variety of commerce enabled or assisted by wireless services. The direct value of spectrum is driven by demand for wireless services and broadband access, while its indirect value is related to its use for the public good, such as air traffic control, public safety, national defense, weather monitoring and prediction, and science.

In the United States, spectrum is regulated by two separate agencies. Federal government users of the radio spectrum (NASA, the National Oceanic and Atmospheric Administration, the Department of Defense, the Federal Aviation Administration, and others,) are regulated by the National Telecommunications and Information Administration (NTIA), a component of the Department of Commerce. All other users of the spectrum (private citizens, state and local governments, and businesses, etc.) are regulated by the Federal Communications Commission (FCC), an independent agency. Whether a CubeSat is considered a federal government satellite or not may sometimes not be entirely clear, as discussed below, but the developer must determine this before embarking upon the licensing process. The FCC and the NTIA have entirely different processes for obtaining spectrum authorizations. The complexity of the licensing process is shown in Figure C.1.

The United States is also a signatory to the Radio Regulations[1] issued by the International Telecommunication Union (ITU), a specialized agency of the United Nations. Particularly with regard to satellite use, the United States has agreed to abide by the Radio Regulations to the extent required to avoid interference to radio services of other nations. The practical impact to CubeSat developers is that a filing to the ITU will typically be required, in addition to the domestic regulatory filings.

The radio spectrum (which is defined as all frequencies below 3 THz) is divided into roughly 600 different bands. Each band is allocated to one or more services, such as mobile, broadcast, and Earth exploration satellite, to name a few of the ~30 different services. While some bands are reserved for federal government (NTIA) use only, and other bands are held for nongovernment (FCC) use only, most of the spectrum is shared between federal government and nongovernment users. Figure C.2 is a graphical representation of how the radio spectrum is allocated across bands and services.

[1] International Telecommunication Union, edition of 2012,"Radio Regulations," https://www.itu.int/pub/R-REG-RR.

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TABLE C.1 Propulsion Technologies for CubeSats

Thruster	Propellant	Pressurization	Isp (s)	Size (U)	Power Efficiency	Thrust (mN)	TRL
Hydros[a]	Water	No	60 (cold gas)-300	1	N/A	<800	4
Hydrazine Aerojet MPS-120[b]	Hydrazine	Yes	220 (est)	>1	N/A	260-2800	6
Electrospray Busek, MIT[c]	Ionic Liquid	No	1100-2300	0.2-1	30-70%	0.1-1	5
Vacuum arc uCAT (GWU), VAT (Alameda)[d]	Metal	No	1500-3000	0.2	9-15%	0.001-0.050	4
Pulsed Plasma Thrusters Busek BmP-220[e]	Teflon	No	536	0.7	<10%	<0.1 per pulse	5-7
Ion Thrusters MiXI JPL[f] Busek BIT-1,3	Xenon, Iodine	Yes (Xenon), No (Iodine)	2000-3200	1-2	20%	0.5-3	3
CAT	Xenon	Yes	400-800	2	<40%	0.5-4	3
Monoprop green[g] Busek GMT	AF-M315E	Yes	220	>1	N/A	500	5
Solar Sail	Sun	No	N/A	>2	N/A	1 for 800^2 m^2 at 1 AU	5
Cold gas VACCO/CU Aerospace[h]	Sulfur dioxide	Yes	70	1	N/A	450	6
Solid[i] DSSP	HIPEP-501A	No	900	0.5	N/A	300 (250 pulses, 2 ms each)	9

[a] Tethers Unlimited, "HYDROS Thruster: Powerful 'Green' Propulsion for Small Satellites," brochure, http://www.tethers.com/SpecSheets/Brochure_HYDROS.pdf.
[b] Aeroject Rocketdyne, "MPS-120™ CubeSat High-Impulse Adaptable Modular Propulsion System (CHAMPS)," http://www.rocket.com/CubeSat/mps-120, accessed April 8, 2016.
[c] Busek Space Propulsion and Systems, http://www.busek.com/, accessed April 8, 2016; D. Krejci, F. Mier-Hicks, C. Fucetola, A. Hsu-Schouten, F. Martel, and P. Lozano, 2015, "Design and Characterization of a Scalable ion Electrospray Propulsion System," paper presented at Joint Conference of 30th International Symposium on Space Technology and Science, 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium, Hyogo-Kobe, Japan, http://erps.spacegrant.org/uploads/images/2015Presentations/IEPC-2015-149_ISTS-2015-b-149.pdf.
[d] M. Keidar, S. Haque, T. Zhuang, A. Shashurin, D. Chiu, and G. Teel, 2013, "Micro-Cathode Arc Thruster for PhoneSat Propulsion," *Proceedings of the AIAA/USU Conference on Small Satellites*, Technical Session VII: Propulsion, SSC13-VII-9, http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=2964&context=smallsat.
[e] Busek Space Propulsion and Systems, http://www.busek.com/, accessed April 8, 2016.
[f] R.W. Conversano and R.E. Wirz, 2013, Mission capability assessment of CubeSats using a miniature ion thruster, *Journal of Spacecraft and Rockets* 50(5):1035-1046.
[g] Busek Space Propulsion and Systems, http://www.busek.com/, accessed April 8, 2016.
[h] VACCO Industries, "MEPSI Micro Propulsion System," http://www.vacco.com/images/uploads/pdfs/MicroPropulsionSystems_0714.pdf, accessed April 18, 2016.
[i] Digital Solid State Propulsion, "CAPS-3," brochure, http://dsspropulsion.com/wp-content/uploads/2015/07/Brochure-Inlet-CAPS-3-Website.pdf.

INTEGRATION WITH LAUNCH VEHICLE

NASA's Launch Services Program has awarded multiple Venture Class Launch Services contracts to support this emerging sector of the launch business, and it will support the agency's CubeSat Launch Initiative. The three selected companies are Firefly Space Systems Inc. (400 kg into low Earth orbit for $8 million), funded at $5.5 million; Rocket Lab USA Inc. (up to 45 kg into low Earth orbit for $2.5 million), funded at $6.9 million; and Virgin Galactic LLC (200 kg into a Sun-synchronous orbit, and up to 400 kg into other low Earth orbits (LEOs), for less than $10 million), funded at $4.7 million.

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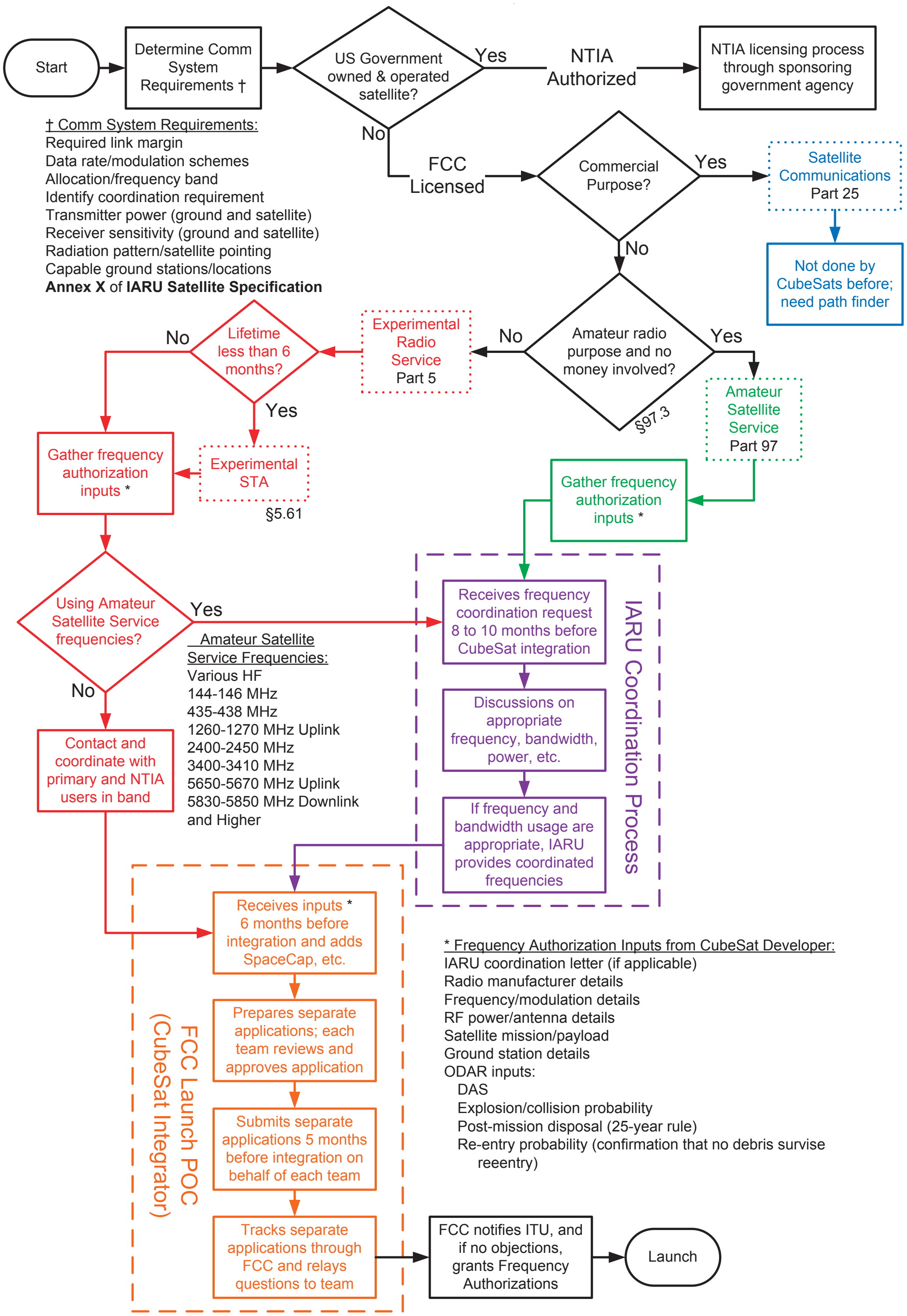

FIGURE C.1 Schematic of domestic frequency licensing process for CubeSats. SOURCE: B. Klofas, and K. Leveque, 2013, "A Survey of CubeSat Communication Systems: 2009–2012," http://www.klofas.com/papers/Klofas_Communications_Survey_2009-2012.pdf. Courtesy of Byran Klofas and Kyle Leveque.

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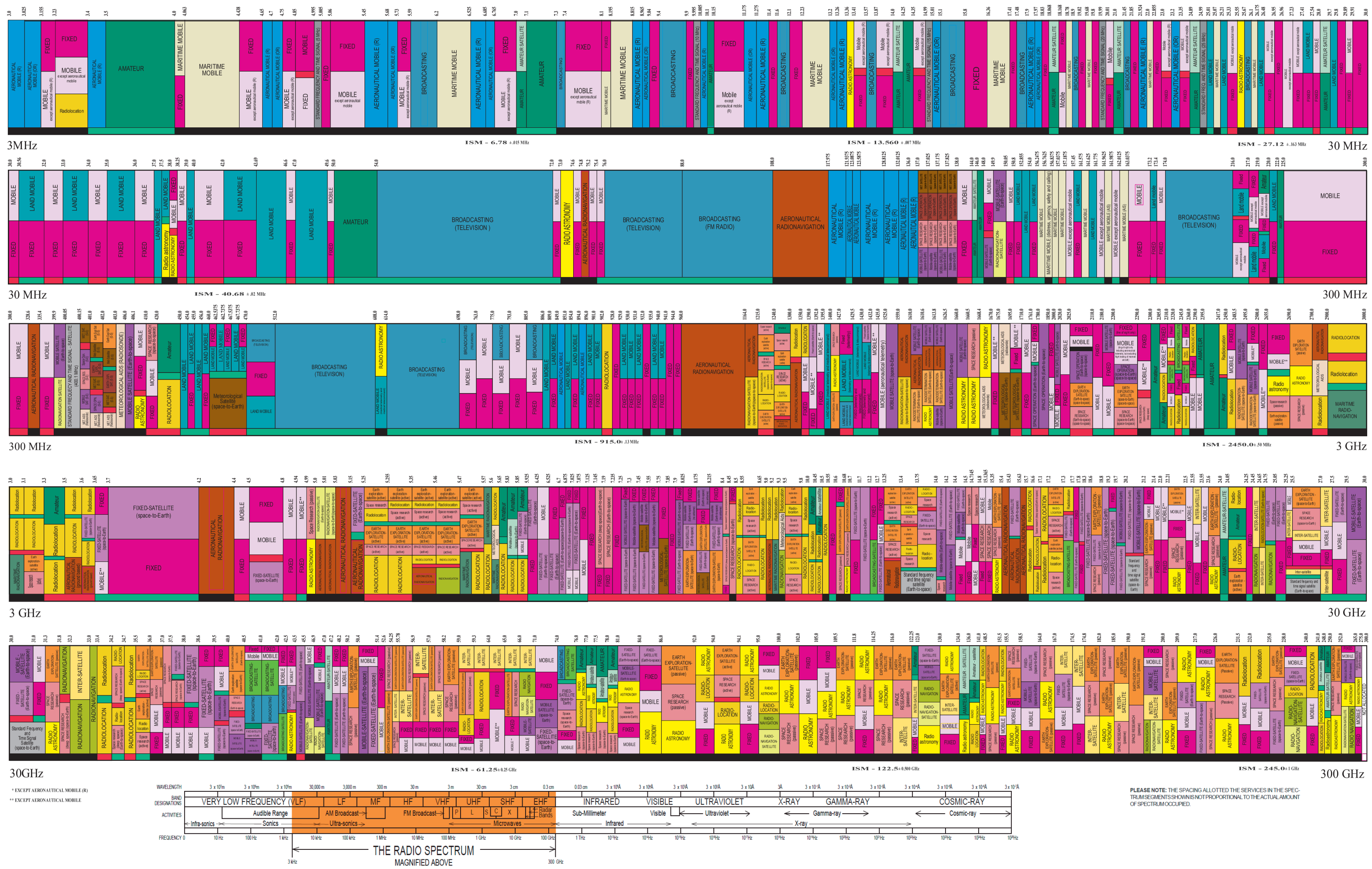

FIGURE C.2 U.S. radio spectrum allocations, from 3 MHz (*top left*) to 300 GHz (*bottom right*). Each colored block represents an allocation to one of 30 different services. Allocations to services most amenable to CubeSats are in orange (Earth exploration-satellite), dark brown (space operation), pale pink (space research), and light blue (amateur-satellite), but are generally too small to see at this scale. The largest blocks in this chart (blue) are for radio and television broadcasting. Note that this figure is presented as a visual example of the complicated nature of spectrum allocation. Full-resolution, specific details may be viewed on the NTIA's webpage. SOURCE: U.S. Department of Commerce, National Telecommunications and Information Administration, "United States Frequency Allocation Chart," https://www.ntia.doc.gov/page/2011/united-states-frequency-allocation-chart, accessed April 8, 2016.

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Other examples include the recently canceled Defense Advanced Research Projects Agency (DARPA) Airborne Launch Assist Space Access (ALASA) program, which was at TRL5,[2] targeting a payload of 45 kg into low Earth orbit for $1 million, with a lead time of 24 hours launching from an F-15E jet. CubeCab are developing another airborne system that will be launched from an F-104 jet; this is a CubeSat-specific system, however. With a TRL of 4, the projected launch costs are around $100,000/U, putting it on par with current commercial CubeSat launch costs. Another airborne system is the Bloostar launch vehicle, which uses a helium balloon to reach 20 km, after which a three-stage rocket system will insert up to 75 kg into a 600 km polar orbit for between €2 million and €4 million.

[2] C. Frost, E. Agasid, D. Biggs, J. Conley, A. Dono Perez, N. Faber, A. Genova, A. Gonzales, A. Grasso, J. Harpur, S. Hu, et al., Mission Design Division, 2014, *Small Spacecraft Technology: State of the Art*, NASA Technical Report TP-2014-216648/REV1, NASA Ames Research Center, Moffett Field, California, http://cmapspublic3.ihmc.us/rid=1NG0S479X-29HLYMF-18L7/Small_Spacecraft_Technology_State_of_the_Art_2014.pdf.

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D

Biographies of Committee Members and Staff

COMMITTEE

THOMAS H. ZURBUCHEN, *Chair*, is a professor of space science and aerospace engineering at the University of Michigan. He was associate dean of entrepreneurial programs in the college of engineering 2009-2015, founder of the college's center for entrepreneurship, and also senior counselor to the provost 2012-2015. In these roles, he is responsible for educational and research programs focused on innovation, entrepreneurial thought and action, and enhancing research impact. He has been at the University of Michigan for over 20 years. He is a part-time visiting scientist to the International Space Science Institute in Bern. Dr. Zurbuchen has received numerous awards, including the prestigious U.S. Presidential Early Career Award, which represents the highest honor bestowed by the U.S. government on scientists and engineers beginning their independent careers. He has also received Outstanding Accomplishment Awards at the University of Michigan from his department, college, and university focused on service, mentorship, and research, as well as multiple NASA Group Achievement Awards, due to his involvement in missions such as Ulysses, MESSENGER, Wind, ACE, and Solar Orbiter. Dr. Zurbuchen, a specialist in the robotic exploration of space and expert in space plasmas, is a founder of the Solar and Heliospheric Research group currently responsible for more than 10 instruments in flight and two more under development. He served as team leader for the development of NASA's Fast Imaging Plasma Spectrometer, an instrument that was part of the MESSENGER spacecraft in orbit about Mercury 2011-2015. He serves on the boards of four companies and nonprofits (none of which are CubeSat or space related), including as a governor-appointed trustee of Northern Michigan University. Dr. Zurbuchen holds a Ph.D. in physics and an M.S. in physics, mathematics, and astronomy from the University of Bern, Switzerland. He is currently a member of the Space Studies Board (SSB) and its executive committee at the National Academies of Sciences, Engineering, and Medicine and has had extensive previous experience as vice chair for the Committee on a Decadal Strategy for Solar and Space Physics, vice chair and a former member of the Committee on Solar and Space Physics, member of the Plasma Science Committee, member of the Workshop Organizing Committee on Solar Systems Radiation Environment and NASA's Vision for Space Exploration, and member of the Panel on the Sun and Heliospheric Physics.

BHAVYA LAL, *Vice Chair*, is a research staff member at the IDA Science and Technology Policy Institute (STPI) where she supports the White House Office of Science and Technology Policy, NASA, Federal Aviation Administration, Office of the Director for National Intelligence, and other federal agencies advancing space technology and policy. Recent and ongoing projects include detecting and mitigating the effects of near Earth objects, evalu-

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ating civilian space situational awareness role and capability, exploring commercial and global trends in space and their implications for the United States, and in general applying innovation theory to the aerospace sector (most recently in the space nuclear power and small satellite areas). Before joining STPI, Dr. Lal was president of C-STPS, a science and technology policy research and consulting firm in Waltham, Massachusetts. Prior to that, she was the director of the Center for Science and Technology Policy Studies at Abt Associates, Inc., a global policy research firm in Cambridge, Massachusetts. Dr. Lal holds B.S. and M.S. degrees in nuclear engineering from the Massachusetts Institute of Technology (MIT), an M.S. from MIT's Technology and Policy Program, and a Ph.D. from George Washington University. She has previously served on the Academies' Committee on Space-Based Additive Manufacturing.

JULIE CASTILLO-ROGEZ is a planetary scientist at the Jet Propulsion Laboratory (JPL), California Institute of Technology. Her research focuses on water-rich objects from modeling and experimental perspectives applied to the formulation, design, and planning of planetary missions. Her current activities focus on Ceres, target of the Dawn mission, Mars's moons in the frame of the human exploration program, as well as other small bodies whose study can help improve understanding of the early Solar system. Dr. Castillo-Rogez serves as the science principal investigator for NASA's Near Earth Asteroid Scout mission, is a participating scientist in NASA's Mars Atmosphere and Volatile Evolution mission (MAVEN), and is the investigation scientist for NASA's Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission to Mars. Dr. Castillo-Rogez also served as the infusion scientist for the INSPIRE CubeSat mission. She cofounded the Ice Physics Laboratory at JPL in 2007, and she previously was a member of the Cassini Mission Radio Science Team. She earned a B.S. in geology from the University of Nantes, France, a M.S. in geophysics from the University of Rennes, France, and a Ph.D. in planetary geophysics from the University of Rennes, France.

ANDREW CLEGG is the spectrum engineering lead at Google, Inc. Prior to Google, he served 11 years as a program manager at the National Science Foundation (NSF), where he created the Enhancing Access to the Radio Spectrum (EARS) program, which was focused on funding research in radio spectrum efficiency and access. He also served as NSF's Electromagnetic Spectrum Manager, where, among other tasks, he helped the nascent CubeSat movement gain access to spectrum resources and represented the U.S. at two World Radiocommunication Conferences. Prior to NSF, he was principal member of technical staff at Cingular Wireless (now AT&T Mobility), and a senior engineer for Comsearch. He was also a member of the Remote Sensing Division at the Naval Research Laboratory immediately after graduation. Dr. Clegg earned his M.S. and Ph.D. in radio astronomy and electrical engineering from Cornell University.

PAULO C. LOZANO is an associate professor and chair of the graduate program in the Department of Aeronautics and Astronautics at MIT. He is also the director of MIT's Space Propulsion Laboratory. His main interests are plasma physics, space propulsion, ion beam physics, small satellites, and nanotechnology. Part of Prof. Lozano's research topics includes the development of highly efficient and compact ion propulsion systems for pico- or nanosatellites. He has published over 80 conference and journal publications on his research. He received the Young Investigator Program Award from the Air Force and the "Future Mind" Award from Quo/The Discovery Channel. Prof. Lozano is an associate fellow of the American Institute of Aeronautics and Astronautics (AIAA) and member of the American Physical Society. He earned his Ph.D. in space propulsion from MIT. Previous service for the Academies includes the panel on Mitigation Strategies for Potentially Hazardous Near Earth Objects and the Panel on Prioritization of NASA Technology Roadmaps.

MALCOLM MACDONALD is a reader of space technology at the University of Strathclyde and director of the Scottish Centre of Excellence in Satellite Applications, based at the University of Strathclyde. Until 2008, he worked at SciSys (UK) Ltd. on several projects, including ADM-Aeolus and LISA-Pathfinder. His work has an end-to-end focus on development and application of space mission systems to challenge conventional ideas and advance new concepts in the exploration and exploitation of space for the betterment of life on Earth. This end-to-end philosophy enables new space-derived data product concepts through advances in space technology,

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including new platforms concepts such as CubeSats. Specific interests are in the use of multiple spacecraft to enable new space science and services through the application of concepts from swarm engineering, combined with astrodynamics and space system design. Dr. Macdonald has received a number of awards, including the Royal Society of Edinburgh Sir Thomas Mackdougall Brisbane Medal (2016) and the Ackroyd Stuart Propulsion Price (2003) awarded by the Royal Aeronautical Society. He is currently deputy chair of the U.K. Space Agency's Space Programme Review Panel, an associate editor of the *Journal of Guidance, Control, and Dynamics*, a fellow of the Royal Aeronautical Society, and an associate fellow of the AIAA. He also has an honours degree and a Ph.D. from the University of Glasgow.

ROBYN MILLAN is an associate professor of physics and astronomy at Dartmouth College. Her research includes the use of high-altitude scientific balloon experiments to study Earth's radiation belts. Dr. Millan is principal investigator for the BARREL (Balloon Array for Radiation-belt Relativistic Electron Losses), which makes observations in conjunction with NASA's Van Allen Probes to study atmospheric loss of radiation-belt electrons. Her prior positions include research appointments at Dartmouth and at the University of California, Berkeley. She received her Ph.D. in physics at the University of California, Berkeley, in 2002. Dr. Millan served on the Academies' Committee on the Role and Scope of Mission-Enabling Activities in NASA's Space and Earth Science Missions and on the Panel on Solar Wind-Magnetosphere Interactions for the Committee for a Decadal Strategy for Solar and Space Physics (Heliophysics). She is currently serving as secretary for the Space Physics and Aeronomy section of the American Geophysical Union (AGU) and is a member of the SSB standing Committee on Solar and Space Physics.

CHARLES D. NORTON is a program manager and principal technologist at JPL at the California Institute of Technology. He is the engineering and science directorate formulation lead for Small Satellites at JPL. His research interests are small satellites for spaceborne technology validation, high-performance computing for Earth and space science modeling, and advanced information systems technologies. He has managed CubeSat flight projects and coled a Keck Institute study "Small Satellites: A Revolution in Space Science." He is a recipient of numerous awards for new technology and innovation, including the JPL Lew Allen Award and the NASA Exceptional Service Medal, and is a member of IEEE (senior level), AIAA, and AGU, holding a B.S.E. from Princeton University in electrical engineering and computer science and an M.S and a Ph.D. in computer science from Rensselaer Polytechnic Institute. Prior to joining JPL, he was an National Research Council postdoctoral fellow.

WILLIAM H. SWARTZ is a principal research scientist at the Johns Hopkins University Applied Physics Laboratory (JHU/APL). He is also associate research professor at JHU. As a member of JHU/APL's space sector, Dr. Swartz works to advance the use of remote sensing for addressing pressing science questions and to enable novel observation systems. He is the principal investigator (PI) of a NASA-funded CubeSat mission to develop technologies and measurement techniques that could significantly advance space observation of Earth's radiation budget. He also conducts research into the response of the atmosphere's chemistry and temperature to solar variability, using both Earth system modeling and observations. Dr. Swartz holds a Ph.D. in atmospheric chemistry from the University of Maryland, College Park, and has previously briefed the Academies' Committee on Earth Science and Applications from Space.

ALAN TITLE is a senior fellow at the Lockheed Martin Space Systems Advanced Technology Center (ATC) in Palo Alto, California. His primary scientific research interest is the generation, distribution, and effects of the solar magnetic field throughout the Sun's interior and outer atmosphere. At present, he has 200 articles in refereed journals. He is currently the principal investigator for NASA's solar mission called the Interface Region Imaging Spectrograph (IRIS). Title was the principal investigator responsible for the Atmospheric Imaging Assembly on NASA's Solar Dynamics Observatory (SDO) launched in 2010, and is a coinvestigator for another instrument on SDO, the Helioseismic Magnetic Imager. He was also the principal investigator for NASA's solar telescope on the Transition Region and Coronal Explorer (TRACE) mission, launched in 1998, and the Focal Plane Package on the JAXA/ISAS Hinode mission launched in 2006. Additionally, Dr. Title serves as a coinvestigator responsible for the Michelson-Doppler Imager (MDI) science instrument on the NASA-European Space Agency Solar and

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Heliospheric Observatory (SOHO), launched in 1995. All of these instruments were built under Dr. Title's direction at the ATC. As an engineer, he designs, develops, builds, and flies new instruments that will gather the data necessary to inform his solar research interests. He led the development of tunable bandpass filters for space-based solar observations, a version of which is currently operating on the JAXA/ISAS Hinode spacecraft. He also invented a tunable variation of the Michelson Interferometer that has been employed on the SOHO spacecraft, the SDO, the Global Oscillations Network Group of the National Solar Observatory as well as other ground-based systems. Outside of his research, Dr. Title has supported activities at the Tech Museum, Chabot Observatory, Boston Museum of Science, the National Air and Space Museum, and the Hayden Planetarium. In addition, his educational outreach funding has supported a yearly summer program for Stanford undergraduates, and the Stanford Hass Center activities that develop science programs for K-12 classrooms. And for two decades, promising students from the Palo Alto High School District have come to work in his laboratory. Among his honors and awards are the 2011 John Adam Fleming Medal, awarded not more than once annually to an individual for original research and technical leadership in geomagnetism, atmospheric electricity, aeronomy, space physics, and related sciences. He received his Ph.D. in physics from the California Institute of Technology. Most recently, he has served on the Academies' Board on Research Data and Information and the NASA Technology Roadmap: Instruments and Computing Panel, and he currently serves on the Aeronautics and Space Engineering Board (ASEB).

THOMAS WOODS is the associate director of technical divisions of the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado in Boulder. His research is focused primarily on solar irradiance variability and its effects on Earth's atmosphere, climate change, and space weather. Dr. Woods is involved with several NASA and NOAA satellite programs. He is the PI of the TIMED SEE and SDO EVE satellite instrument programs at LASP and is also the PI of the SORCE and MinXSS CubeSat missions. He is first author on 49 papers and coauthor on 143 other papers. He obtained his B.S. in physics from Southwestern at Memphis (now Rhodes College) and his Ph.D. in physics from JHU. He previously served on the Panel on Solar and Heliospheric physics for the Academies' decadal survey for solar and space physics (heliophysics).

EDWARD L. WRIGHT is a David Saxon Presidential Chair in Physics Professor at the University of California, Los Angeles (UCLA). At UCLA, Dr. Wright has been the data team leader on the Cosmic Background Explorer (COBE), a coinvestigator on the Wilkinson Microwave Anisotropy Probe (WMAP), an interdisciplinary scientist on the Spitzer Space Telescope, and the PI on the Wide-field Infrared Survey Explorer (WISE). Dr. Wright is well-known for his Cosmology Tutorial website for the informed public, and his web-based cosmology calculator for professional astronomers. A member of the National Academy of Sciences, he has served on the Academies' Beyond Einstein Program Assessment Committee, the committee to study Autonomy Research in Civil Aviation, and the committee to study NASA's planned Wide Field InfraRed Survey Telescope—Astrophysics Focused Telescope Assets program (WFIRST-AFTA). Dr. Wright currently serves on the committee for Review of the Federal Aviation Administration Research Plan on Certification of New Technologies into the National Airspace System. He earned his Ph.D. in astronomy from Harvard University.

A. THOMAS YOUNG is executive vice president, retired, at Lockheed Martin Corporation and former chair of the board of SAIC. Mr. Young was previously the president and chief operating officer of Martin Marietta Corporation. Prior to joining industry, Mr. Young worked for 21 years at NASA where he directed the Goddard Space Flight Center, was deputy director of the Ames Research Center, and directed the Planetary Program in the Office of Space Science at NASA Headquarters. Mr. Young received high acclaim for his technical leadership in organizing and directing national space and defense programs, especially the Viking program. He is currently an honorary fellow of the AIAA and a fellow of the American Astronautical Society. Mr. Young is a member of the NASA Advisory Council. He earned his engineering degree from the University of Virginia and M.S. in management from MIT. Mr. Young's service for the Academies includes current membership on the Committee on Astronomy and Astrophysics and the Committee on Survey of Surveys: Lessons Learned from the Decadal Survey Process. His prior Academies' membership includes the Committee on the Assessment of the Astrophysics Focused Telescope Assets (AFTA) Mission Concepts, the Planning Committee on Lessons Learned in Decadal Planning in Space:

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A Workshop, the Committee on the Planetary Science Decadal Survey: 2013-2022, the Panel on Implementing Recommendations from New Worlds, New Horizons Decadal Survey, the Committee on the Decadal Survey on Astronomy and Astrophysics 2010, and the SSB (vice chair).

STAFF

ABIGAIL A. SHEFFER, *Study Director*, is a program officer for the SSB. In fall 2009, Dr. Sheffer served as a Christine Mirzayan Science and Technology Policy Graduate Fellow for the National Academies and then joined the SSB. Since coming to the Academies, she has been study director on reports such as *Sharing the Adventure with the Student: Exploring the Intersections of NASA Space Science and Education—A Workshop Summary*, *Landsat and Beyond—Sustaining and Enhancing the Nation's Land Imaging Program,* and *The Effects of Solar Variability on Earth's Climate: A Workshop Report*. Dr. Sheffer has been an assisting staff officer on several other reports, including *Pathways to Exploration—Rationales and Approaches for a U.S. Program of Human Space Exploration* and *Solar and Space Physics: A Science for a Technological Society*. Dr. Sheffer earned her Ph.D. in planetary science from the University of Arizona and A.B. in geosciences from Princeton University.

MICHAEL H. MOLONEY is the director for space and aeronautics at the SSB and the ASEB of the Academies. Since joining the ASEB/SSB Dr. Moloney has overseen the production of more than 60 reports, including five decadal surveys, in astronomy and astrophysics, Earth science and applications from space, planetary science, microgravity sciences, and solar and space physics. He has also been involved in reviewing of NASA's space technology roadmaps and oversaw a major report on the rationale for and future direction of the U.S. human spaceflight program, as well as reports on issues such as NASA's strategic direction; lessons learned from the decadal survey processes; the science promise of CubeSats; the challenge of orbital debris; the future of NASA's astronaut corps; NASA's aeronautical flight research program; and national research agendas for autonomy and low-carbon propulsion in civil aviation. Since joining the Academies in 2001, Dr. Moloney has also served as a study director at the National Materials Advisory Board, the Board on Physics and Astronomy (BPA), the Board on Manufacturing and Engineering Design, and the Center for Economic, Governance, and International Studies. Dr. Moloney has served as study director or senior staff for a series of reports on subject matters as varied as quantum physics, nanotechnology, cosmology, the operation of the nation's helium reserve, new anti-counterfeiting technologies for currency, corrosion science, and nuclear fusion. Before joining the SSB and ASEB in 2010, Dr. Moloney was associate director of the BPA and study director for the 2010 decadal survey for astronomy and astrophysics (New Worlds, New Horizons in Astronomy and Astrophysics). In addition to his professional experience at the Academies, Dr. Moloney has more than 7 years' experience as a foreign-service officer for the Irish government—including serving at Ireland's embassy in Washington and its mission to the United Nations in New York. A physicist, Dr. Moloney did his Ph.D. work at Trinity College Dublin in Ireland. He received his undergraduate degree in experimental physics at University College Dublin, where he was awarded the Nevin Medal for Physics. Dr. Moloney is a corresponding member of the International Academy of Astronautics and a senior member of the AIAA. He is also a recipient of a distinguished service award from the Academies.

KATIE DAUD is a research associate for the SSB and the ASEB. Previously, she worked at the Smithsonian National Air and Space Museum's Center for Earth and Planetary Studies as a planetary scientist. Ms. Daud was a triple major at Bloomsburg University, receiving a B.S. in planetary science and Earth science and a B.A. in political science.

DIONNA J. WILLIAMS is a program coordinator with the SSB, having previously worked for the Academies' Division of Behavioral and Social Sciences and Education for 5 years. Ms. Williams has a long career in office administration, having worked as a supervisor in a number of capacities and fields. Ms. Williams attended the University of Colorado, Colorado Springs, and majored in psychology.

JAMES ALVER is a recent graduate of Harvard College with a B.A. in government and a secondary in Earth and planetary sciences. While at Harvard, he wrote for the *Harvard Political Review* focusing on space policy issues

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as well as for the humor newspaper *Satire V*. Mr. Alver combined his interests in space and government during time as the Lloyd V. Berkner Space Policy Intern at the SSB, gaining a deeper understanding of the interaction between scientists, policy makers, and industry. He hopes to use this knowledge for a career in shaping space policy.

THOMAS KATUCKI is a political science major at Grinnell College. He comes to the SSB after interning with the B612 Foundation and working on Asteroid Day in the summer. Mr. Katucki worked on a variety of projects for the board while he served as the Lloyd V. Berkner Space Policy Intern. He has a wide range of academics interests, ranging from international relations to astrophysics.

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Abbreviations and Acronyms

ΔV	delta-V (change in velocity)
AAReST	Autonomous Assembly of a Reconfigurable Space Telescope
ADR	active debris removal
ADRe	active rehabilitation
ADS	Astrophysics Data System (NASA)
AES	Advanced Exploration Systems
AFOSR	Air Force Office of Scientific Research
AFRL/RV	Air Force Research Laboratory's Space Vehicles Directorate
AGU	American Geophysical Union
AIDA	Asteroid Impact and Deflection Assessment
ALASA	Airborne Launch Assist Space Access
AOSAT	Asteroid Origins Satellite
APRA	Astrophysics Research and Analysis program
ASTERIA	Arcsecond Space Telescope Enabling Research in Astrophysics
Astro2010	*New Worlds, New Horizons in Astronomy and Astrophysics* decadal survey
BARREL	Balloon Array for Radiation-belt Relativistic Electron Losses
BRITE	Bright Target Explorer
C&DH	command and data handling
CADRE	Community for Advancing Discovery Research in Education
Cal Poly	California Polytechnic State University
CANYVAL-X	CubeSat Astronomy by NASA and Yonsei using Virtual Telescope Alignment Experiment
CeREs	Compact Radiation Belt Explorer Missions
CINEMA	CubeSat for Ions, Neutrals, Electrons, and Magnetic Fields
CIRAS	CubeSat Infrared Atmospheric Sounder
CIRiS	Compact Infrared Radiometer in Space
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
COTS	commercial off the shelf

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COVE	CubeSat Onboard Processing Validation Experiment
CPOD	CubeSat Proximity Operations Demonstration
CSLI	CubeSat Launch Initiative
CSSWE	Colorado Student Space Weather Experiment
CSUNSat	California State University Northridge Satellite
CubeRRT	CubeSat Radiometer RFI Technology Validation mission
CuSP	CubeSat to Study Solar Particles
CXBN	Cosmic X-Ray Background Nanosatellite
CYGNSS	Cyclone Global Navigation Satellite System
DARPA	Defense Advanced Research Projects Agency
DAVID	Diminutive Asteroid Visitor using Ion Drive
DICE	Dynamic Ionosphere CubeSat Experiment
DNA	deoxyribonucleic acid
DOD	Department of Defense
DOE	Department of Energy
DRIVE	diversify, realize, integrate, venture, and educate
DSL	Discovering the Sky at Longest wavelengths
DSN	Deep Space Network
DYNAMIC	Dynamical Neutral Atmosphere-Ionosphere Coupling Mission
EcAMSat	E. coli AntiMicrobial Satellite
EDL	entry-descent-landing
EDSN	Edison Demonstration of Smallsat Networks
EELV	Evolved Expendable Launch Vehicle
ELaNa	Educational Launch of Nanosatellites (NASA)
ELFIN	Electron Losses and Fields Investigation
ELROI	Extremely Low Resource Optical Identifier
EM	Exploration Mission
EMFF	Electro-Magnetic-Formation Flight
ESA	European Space Agency
ESAS 2017	Decadal Survey in Earth Science that is anticipated in 2017
ESCAPE	Earth Science CubeSat for Advanced Payload Experiments
ESPA	EELV Secondary Payload Adapter
ESTO	Earth Science Technology Office (NASA)
EUV	extreme ultraviolet
FCC	Federal Communications Commission
FIREBIRD	Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics
FWHM	full width at half maximum
GALEX	Galaxy Evolution Explorer
GDC	Geospace Dynamics Constellation
GENSO	Global Educational Network for Satellite Operations
GEO	geostationary Earth orbit
GEO-CAPE	Geostationary Coastal and Air Pollution Events
GNSS-RO	global navigation satellite system-radio occultation
GOES	Geostationary Operational Environmental Satellite (NOAA)
GPS	Global Positioning System
GRIFEX	GEO-CAPE ROIC In-Flight Performance Experiment

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H	hydrogen
HALO	Hydrogen Albedo Lunar Orbiter
HAM	handheld amateur radio
HARP	HyperAngular Rainbow Polarimeter
HeDI	Helium Doppler Imager
HEOMD	Human Exploration and Operations Mission Directorate
HMI	Helioseismic and Magnetic Imager
HOT-BIRD	high-operating temperature barrier infrared detector
IARU	International Amateur Radio Union
IBEX	Interstellar Boundary Explorer
IMAP	Interstellar Mapping and Acceleration Probe
InSight	Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (NASA)
INSPIRE	Interplanetary Nano-Spacecraft Pathfinder in Relevant Environment
IPEX	Intelligent Payload Experiment
IR	infrared
IRIS	Interface Region Imaging Spectrograph
ISARA	Integrated Solar Array and Reflectarray Antenna
iSAT	Iodine Satellite
ISM	Industrial Scientific and Medical
I_{sp}	specific impulse
ISS	International Space Station
ISX	Ionospheric Scintillation eXplorer mission
ITAR	International Traffic in Arms Regulations
IT-SPINS	Ionospheric-Thermospheric Scanning Photometer for Ion-Neutral Studies mission
ITU	International Telecommunication Union
IV&V	Independent Verification and Validation
IXO	International X-ray Observatory
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JPSS	Joint Polar Satellite System
JSpOC	Joint Space Operations Center (U.S. Air Force)
JWST	James Webb Space Telescope
LAICE	Lower Atmosphere/Ionosphere Coupling Experiment mission
LEO	low Earth orbit
LISA	Laser Interferometer Space Antenna
LMPC	Linear Mode Photon-counting CubeSat
LMRST	Low Mass Radio Science Transponder
LunaH-Map	Lunar Polar Hydrogen Mapper
MagCat	Magnetospheric Constellation and Tomography
MagCon	Magnetospheric Constellation Mission
MarCO	Mars Cube One
MCubed	Michigan Multipurpose Minisat
MEDICI	Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation
MEROPE	Montana Earth Orbiting Pico Explorer
MHD	magnetohydrodynamic
MinXSS	Miniature X-ray Solar Spectrometer

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MiRaTA	Microwave Radiometer Technology Acceleration mission
MITEE	Miniature Tether Electrodynamics Experiment
MLI	Multi-Layer Insulation
MMO	Mars Micro Orbiter
MMS	Magnetospheric Multiscale Mission
MRO	Mars Reconnaissance Orbiter
NASA	National Aeronautics and Space Administration
NEA	near Earth asteroid
NOAA	National Oceanic and Atmospheric Administration
NODeS	Network and Operation Demonstration Satellite
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRC	National Research Council
NRO	National Reconnaissance Office
NSF	National Science Foundation
NTIA	National Telecommunications and Information Administration
NuSTAR	Nuclear Spectroscopic Telescope Array Mission
O/OREOS	Organism/Organic Exposure to Orbital Stresses
OCSD	Optical Communication and Sensor Demonstration
OPAL	Orbiting Picosatellite Automated Launcher
PFISR	Poker Flat Incoherent Scatter Radar
PI	principal investigator
P-POD	Poly Picosatellite Orbital Deployer
PreSat	PharmaSat Risk Evaluation (PRESat) nanosatellite (NASA)
PSD	Planetary Science Division (NASA)
Q-PACE	CubeSat Particle Aggregation and Collision Experiment
R&A	research and analysis
RainCube	Radar in a CubeSat
RAVAN	Radiometer Assessment using Vertically Aligned Nanotubes
RAX	Radio Aurora Explorer
RBLE	Radiation Belt Loss Experiment
REPT	Relativistic Electron-Proton Telescope Instrument
RFID	Radio-frequency Identification
ROSES	Research Opportunities in Space and Earth Sciences
SAO	Smithsonian Astrophysical Observatory
SIMPLEx	Small, Innovative Missions for Planetary Exploration
SLS	Space Launch System
SMC	Space Missile Command
SMD	Science Mission Directorate (NASA)
SO/PHI	Polarimetric and Helioseismic Imager
SORCE	Solar Radiation and Climate Experiment
SORTIE	Scintillation Observations and Response of the Ionosphere to Electrodynamics
SRAM	static random-access memory
STEM	science, technology, engineering, and mathematics

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STF	Simulation to Flight
STMD	Space Technology Mission Directorate (NASA)
STP	Space Test Program (DOD)
STRaND	Surrey Training, Research, and Nanosatellite Demonstrator
TBEx	Tandem Beacon-Explorer
TCTE	Total Solar Irradiance Calibration Transfer Experiment
TechEdSat	Technology Education Satellite
TEMPEST-D	Temporal Experiment for Storms and Tropical Systems Demonstration
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TIM	Total Irradiance Monitor
TIR	thermal infrared
TIRFF	Thermal Infrared Free Flyer
TJ3Sat	Thomas Jefferson CubeSat
TRL	technology readiness level
TRYAD	Terrestrial Rays Analysis and Detection Mission
TSI	total solar irradiance
TSIS	Total and Spectral Solar Irradiance Sensor
U	unit, with 1U being about 10 cm × 10 cm × 10 cm
UHF	ultrahigh frequency
ULA	United Launch Alliance
UNP	University Nanosatellite Program
USGS	U.S. Geological Survey
USML	U.S. Munitions List
UV	ultraviolet
VCLS	Venture Class Launch Services
VHF	very high frequency
VLBI	Very Long Baseline Interferometry
WFIRST	Wide-Field InfraRed Survey Telescope
WISE	Wide-field Infrared Survey Explorer
WMAP	Wilkinson Microwave Anisotropy Probe
WoS	Web of Science

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