REPORT IN BRIEF

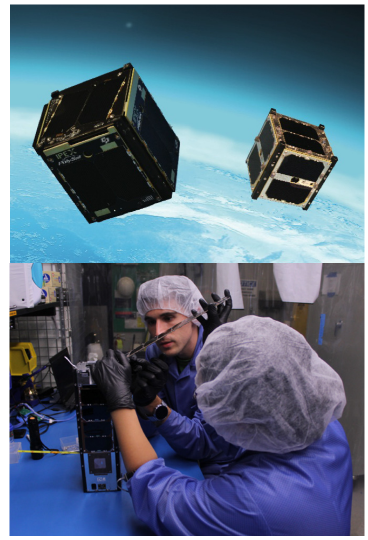
Space Studies Board

May 2016

DIVISION ON ENGINEERING AND PHYSICAL SCIENCES

Achieving Science with CubeSats: Thinking Inside the Box

In the last few years, hundreds of CubeSats – small satellites built in increments of 10 cm cubes – have been launched into low Earth orbit for purposes ranging from education to technology demonstration to scientific data collection. Because CubeSats cost significantly less and are easier to launch than larger satellite missions, nontraditional spacecraft users in academia, industry, and government agencies now have options for accessing space. Recognizing this growing interest in CubeSats, the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF) asked the National Academies of Sciences, Engineering and Medicine to explore the current status of CubeSats and to determine whether they can be effectively used to obtain high priority science data. In *Achieving Science with CubeSats: Thinking Inside the Box*, the Academies conclude that CubeSats are already producing high value science, are enabling new kinds of targeted measurements, and can augment – but not replace – the capabilities of large satellite missions and ground-based facilities. The Academies recommend that NASA and NSF continue to support the use of CubeSats for science without overly restraining the spirit of innovation that characterizes the broad community of CubeSat users. The report also identifies several technology areas derived from science needs that require additional research in order to improve the CubeSat platform, including high bandwidth communications, precision attitude control, propulsion, and the development of miniaturized instrument technology.



Top: NASA-sponsored MCubed and IPEX 1U demonstration CubeSats. Each CubeSat is 10 cm on a side. Bottom: Students are involved in all phases of CubeSat development and flight operations.

Source: NASA/JPL-Caltech (Top), University of Michigan and the Michigan eXploration Laboratory (Bottom)

USING CUBESATS FOR HIGH-PRIORITY SCIENCE

Since 2010, the use of CubeSats for science has grown rapidly with more than 80% of all science-focused CubeSats launched from 2012-2016. Similarly, more than 80% of peer-reviewed papers describing new science based on CubeSat data have been published in the past five years. CubeSats excel at simple, short-duration missions that need to be of comparatively low-cost and missions that require multi-point measurements. Some examples of how high-priority science goals could be pursued using CubeSats include:

- ***The 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. *(Relevant Fields: Solar and Space Physics, Earth Science)*

Read, purchase, or download a free PDF of this report at http://www.nap.edu

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

- ***Multi-point, 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. *(Relevant Field: Earth Science)*

- ***In situ investigations 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. *(Relevant Field: Planetary Science)*

- ***Low-frequency radio science:*** Interferometers made of CubeSats could explore the local space environment and also galactic and extragalactic sources with spatial resolution that cannot be achieved from Earth. *(Relevant Fields: Astrophysics, Solar and Space Physics)*

- ***Investigating 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. *(Relevant Field: Biological Science)*

ENABLING CUBESAT DEVELOPMENT FOR TRAINING AND HIGH-PRIORITY SCIENCE

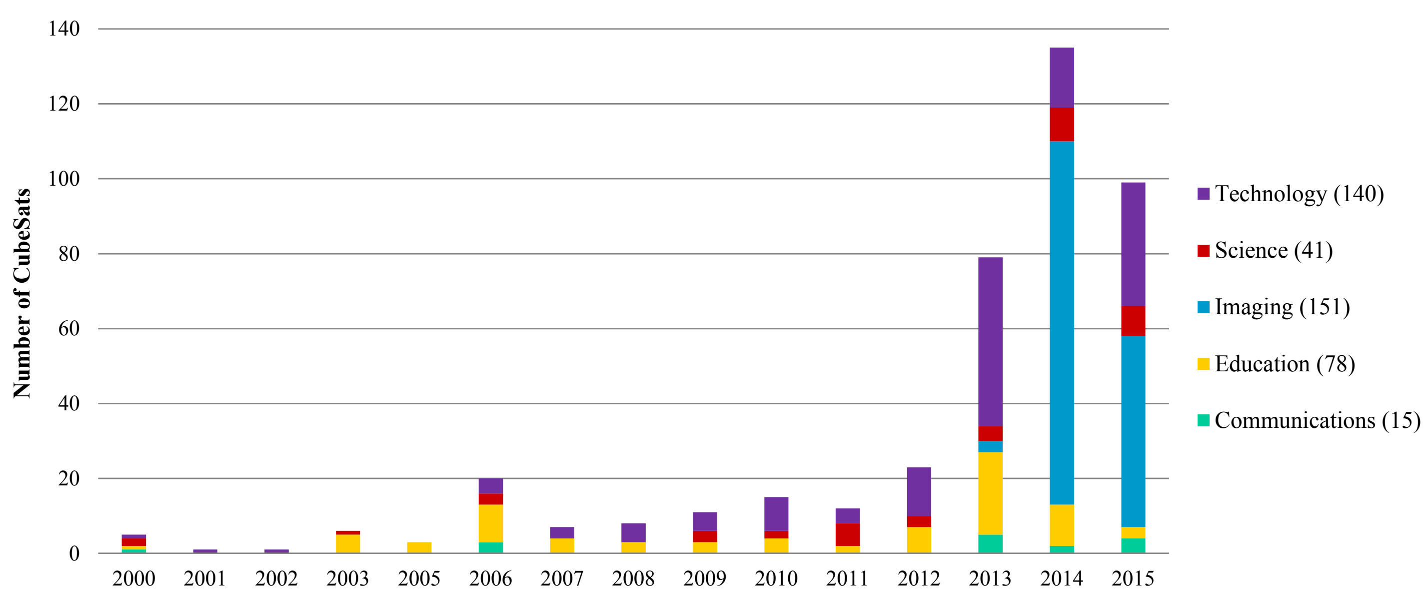
NSF CubeSat Program

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. NSF's pioneering science 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 the end of 2015, NSF has launched 8 science-based CubeSat missions (consisting of 13 CubeSat spacecraft), and has 7 missions (11 CubeSat spacecraft) in development. This program has been successful with regard to both goals; however, other disciplines such as Earth science and astronomy could also benefit from the opportunities that CubeSats provide.

RECOMMENDATION: The 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 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.

NASA CubeSat Programs

Although NASA's CubeSat programs have historically placed greater emphasis on developing new technologies, in recent years NASA has greatly increased the number of opportunities to propose science-based CubeSat missions. As of the end of 2015, NASA has launched a total of 18 CubeSat missions (34 spacecraft) with science and technology objectives, yet the use of CubeSats for science has not reached its full potential. CubeSat activities within NASA programs



The number of CubeSats launched per year by mission type. 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). *Source: Data from M. Swartwout, St. Louis University, "CubeSat Database," adjusted and updated by the committee.*

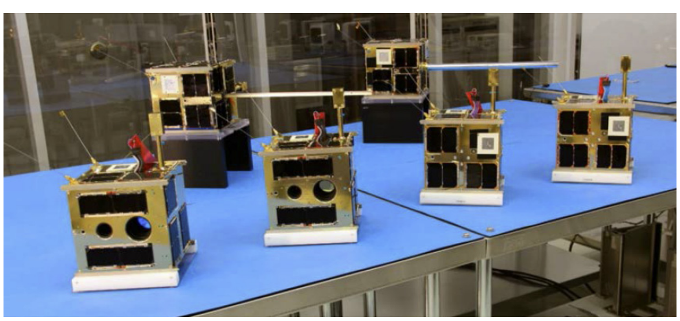
have remained largely independent of one another, but with the growing use of CubeSats for science, this lack of coordination is beginning to impact NASA's ability to communicate a clear strategic vision on the role of CubeSats. The growing interest in the deployment of CubeSats has led to some management challenges that have the potential to stifle the impact that CubeSats can have for science. In addition, because of the disaggregated nature of CubeSat programs at NASA, programs have begun to duplicate efforts in some areas and are not systematically sharing lessons learned.

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 and 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 also important to allow CubeSats to be used for rapid responses to newly recognized needs and to realize the potential from recently developed technology.

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 towards more capable science missions and as the proposed new management structure is implemented.



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. *Source: Space Flight Laboratory of the University of Toronto*

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.

IMPROVING THE CAPABILITIES NEEDED TO LEVERAGE CUBESAT TECHNOLOGY

The capacity to do science with CubeSats strongly depends on the technological capabilities of the CubeSat platforms available to investigators. Due to their geometrical and mass constraints, CubeSats provide a unique innovation platform for rethinking many engineering subsystems, and such development may have important consequences beyond CubeSats for spacecraft of various sizes.

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.

Many high-priority science investigations of the future will require data from constellations or swarms of 10 to 100 spacecraft that 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 for 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 fast pace of technology development, highly engaged academic and commercial communities, and rapid and frequent flight opportunities, allow CubeSat technology gaps to close at a much quicker pace than elsewhere in the space sector. Private industry is an important stakeholder in the CubeSat ecosystem, and one that the government and scientific community can leverage to promote its own cost-effectiveness.

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.

CUBESAT POLICY ISSUES

There are several policy challenges that could constrain the expansion of CubeSats for science applications. Three in particular stand out: the reality and perception of CubeSats as an orbital debris hazard, the complexities and constraints of radio spectrum availability, and the availability of affordable launch opportunities. The CubeSat community has an opportunity to avoid potential future problems by proactively engaging in policy discussions and seeking technological solutions.

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.

GUIDING PRINCIPLES FOR CUBESAT DEVELOPMENT

CubeSats, which provide unique services at low cost and are evolving rapidly to meet the needs of underserved users, share many of the characteristics of disruptive innovations. As is the case with most disruptive technologies, CubeSats began with a threadbare set of capabilities, but the small size and standardized form factor have helped to accelerate innovation and those capabilities are beginning to improve as the technology matures. 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 managing disruptive innovations led the committee to suggest some best practices that can guide the ongoing development of CubeSats are:

- ***Avoid premature focus:*** Although the report 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 towards 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 and not to burden low-cost missions with such enhanced processes, by actively involving CubeSat experts in policy changes and discussions as well as in proposal reviews.

COMMITTEE ON ACHIEVING SCIENCE GOALS WITH CUBESATS: Thomas H. Zurbuchen, University of Michigan, *Chair*; Bhavya Lal, IDA Science and Technology Policy Institute, *Vice Chair*; Julie Castillo-Rogez, California Institute of Technology; Andrew Clegg, Google, Inc.; Paulo Lozano, Massachusetts Institute of Technology; Malcolm Macdonald, University of Strathclyde; Robyn Millan, Dartmouth College; Charles D. Norton, California Institute of Technology; William H. Swartz, John Hopkins University; Alan Title, Lockheed Martin; Thomas Woods, University of Colorado; Edward L. Wright, University of California, Los Angeles; A. Thomas Young, Lockheed Martin Corporation (retired)

STAFF: Abigail Sheffer, Program Officer, *Study Director*; Katie Daud, Research Associate; Catherine Gruber, Editor; Dionna Williams, Program Coordinator; James Alver, Lloyd V. Berkner Space Policy Intern; Thomas Katucki, Lloyd V. Berkner Space Policy Intern; Michael Moloney, Director, Space Studies Board

This study was supported by NASA. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

Copies of this report are available free of charge from http://www.nap.edu.