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# Small Spacecraft Technologies: The Evolution of CubeSat Spacecraft Platforms

**Craig Burkhard**
Craig.D.Burkhard@nasa.gov
NASA Ames Research Center
Moffett Field, CA, 94035
USA

**Sasha Weston**
Sasha.Weston@nasa.gov
Millennium Engineering and Integration,
NASA Ames Research Center
Moffett Field, CA, 94035
USA

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## *ABSTRACT*

*The maturity of small spacecraft technology is indicated by the continued growth in the number of missions, mission complexity, and the expansion of smallsat subsystem capability. The inception of the CubeSat platform has incentivized the space industry to achieve a broad collection of science for less cost, and there is an evolving trend in the overall utilization of the CubeSat platform seen in the last decade. CubeSats' initial purpose was to serve as a platform to demonstrate specific technologies while also serving as an educational platform for students and professional engineers alike. In the ten years since, CubeSats are being designed for more complex science missions around the Moon, Sun, or to deep space, and the projection for 10 years from now is that CubeSats will be performing more complex deep space missions.*

*The progress of overall small spacecraft technology development is captured in the most recent* 2020 Small Spacecraft Technology State-of-the-Art *(SoA) report, the objective of which is to assess and provide an overview on the current development status across all subsystem architectures. The SoA report summarizes the results of a variety of surveys covering device performance, capabilities, and flight history, as presented in publicly available* *literature. The focus of these surveys is on devices or systems that can be commercially procured or appear on a path towards being commercial availability. The work toward the 2020 edition of the SoA report was managed by NASA's Small Spacecraft Systems Virtual Institute (S3VI) and performed by several contractor staff. The S3VI is jointly funded by NASA's Space Technology Mission Directorate and Science Mission Directorate.*

ATTENTION: Abstract should be one paragraph long (**not more than 250 words in total**) and be complete in itself (no reference numbers). It should indicate subjects dealt with in the paper and state the objectives of the investigation. Newly observed facts and conclusions of the experiment or argument discussed in the paper must be stated in summary form; readers should not have to read the paper to understand the abstract. Abstract is not an introduction.

# INTRODUCTION

The last ten years have witnessed a sizeable advancement of the CubeSat platform as it has expanded in both capability for increased mission complexity and physical dimensions to meet more complex needs. The first CubeSats that were built and launched were primarily technology demonstration and educational missions, and now they are used more for Earth science missions and include more diverse CubeSat platforms. In-space CubeSat constellations have been a major contributor to CubeSats' growth as a platform for science advancement. While most of these are in low-Earth orbit (LEO), CubeSats are starting to expand their operations beyond LEO and into deep space. The notable MarCO mission with its two 6-unit (U) spacecraft having reached Mars in 2018, was the first step to bridge the technological gap for CubeSats to operate in deep space. Over the next several years, it is likely that CubeSats will become more advanced to support or perform complex science missions in deep space.

This paper focuses on 1U through 6U platform development with additional information on 12U and picosatellites as those platforms are becoming more utilized. Data for this paper was collected from Nanosats.eu using records as of April 2021 and further references are provided for the various missions discussed. The graphs presented herein are from 2010 through March 2021 and show all 1U-6U CubeSat missions that were successfully launched. The intent is to illustrate the significance of the number, type of CubeSat missions, and the sizes of CubeSats that were designed and launched. Earth science is indicated by studying the physical constitution of the Earth and its atmosphere including: Earth observation, GPS radio data, oceanography, and Earth's magnetic field.

# 1.0 EVOLUTION OF CUBESAT PLATFORMS

The adoption of CubeSats was initially made by the university science and engineering community and is the reason many universities now offer courses and degrees in engineering and other fields related to space. CubeSats' prospects for affordable access to space also quickly became a popular feature for government entities and industry, and the 1U – 3U CubeSat platform range was quickly utilized by all space enthusiasts. A seemingless endless application for CubeSats was quickly identified as more engineers and researchers found more CubeSat utility, making the form factor more diverse and complex. Capabilities such as greater data processing and transmission capacity, propulsion systems, optical communications, spacecraft autonomy, and inter-spacecraft navigation make a simple CubeSat more intricate.

To meet the higher demand, the next stage of the CubeSat design was to make the platform larger which enabled greater CubeSat capability. By 2014, the CubeSat form factor expanded to include 1U, 1.5U, 2U, 3U, and 6U, and by 2016 a 12U platform joined the CubeSat family. As indicated in Figure 1, a major leap in CubeSat utilization and growth in size occurred in the last decade since CubeSats are an established integral part of space access.

As of 2021, the CubeSat spacecraft is a diverse platform that offers engineers, scientists, and researchers more volume, processing power, on-orbit capability, and science/data collection. The advancement of CubeSat systems and components has made even the smaller CubeSat platforms (1U-3U) more useful and advantageous since they were first introduced. Larger CubeSats are being favored as they offer more capability for complicated science and technology demonstrations.

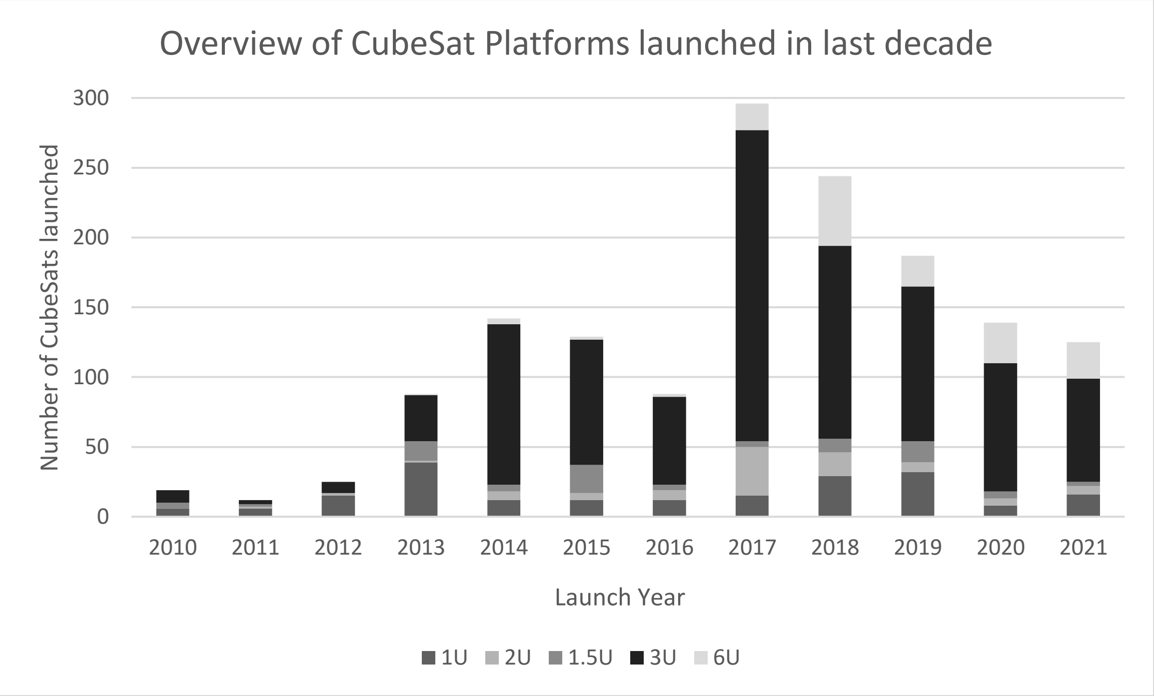

**Figure 1: Overview of launched CubeSat platforms 2010-mid-2021.**

# 2.0 Evolution of CubeSat Missions

Another major shift in the evolution of CubeSats was in the type of missions the CubeSats were being designed for as they became more ubiquitous in both the space industry and their use in LEO environments. Early on, CubeSats were primarily used for technology demonstrations, but we now see their use in scientific missions as well as. Figure 2 illustrates CubeSat mission progression between 2010-2021. Reasons for this increase in science missions using CubeSats include more CubeSats being designed for science missions and more CubeSat designers having emerged in the past five years with a greater focus on CubeSat science collection. A clear trend is that CubeSats are more scientific than they were in 2010. Since then, there has been a concentration in LEO constellations that collect atmospheric data, Internet of Things (IoT) capability, and remote sensing. Another emerging trend is designing CubeSats for missions beyond the LEO environment, such as geostationary and geotransfer orbits, lunar, and deep space.

The growth of scientific CubeSats began in 2011 and skyrocketed in 2014 when Planet Labs released the first of their Doves’ 3U constellation, which consisted of 36% of CubeSats launched and 82% of launched Earth science CubeSat missions that year. The Dove constellation measures optical Earth observation with a 3 - 5m resolution camera, and several constellations of 3U spacecraft remain a prominent contributor to the Earth science missions type with a simple payload. The Low Earth Multi-Use Receiver (LEMUR) constellation is a remote sensing commercial 3U satellite constellation of Spire Global Inc. that is powered by a deployable solar array (1). The first LEMUR spacecraft was launched in 2014 as a demonstration, and beginning in 2015 the first four of the LEMUR constellations were put into orbit. Nine more were deployed in 2016, and as of 2021, 140 3U spacecraft have been launched.

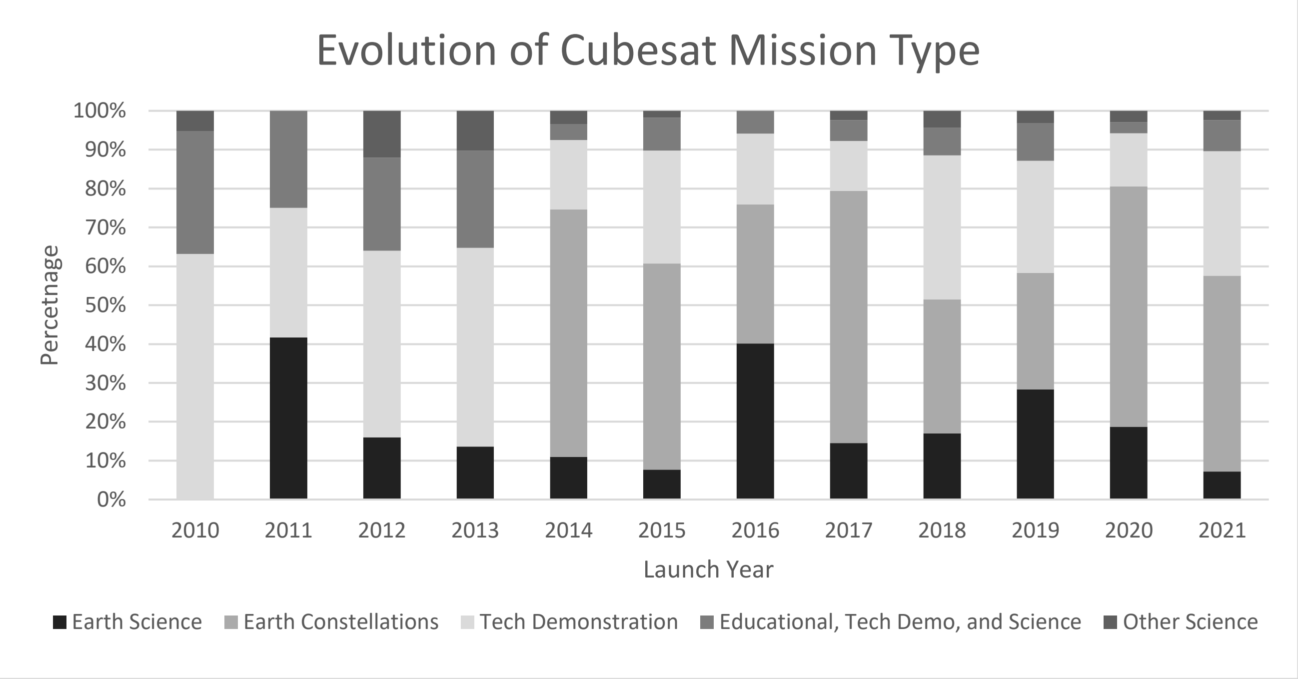

**Figure 2: Evolution of CubeSat mission type 2010-mid-2021.**

There are a number of examples of CubeSats that were launched initially in 2010-2013 where now their multiple CubeSat successors operate in more complicated missions with either a scientific payload, technology demonstration, or both. The Aerospace Corporation has launched 24 spacecraft in its AeroCube series (volumes range from 0.5U – 3U) since 2011. This series has demonstrated innovative propulsion systems, attitude and navigation devices, deorbit systems, optical communications, as well as measure spatial scales of radiation in LEO which validated dosimeters for CubeSats (2-5). The Technical and Educational Satellite (TechEdSat) program is a collaborative effort between students at San Jose State University, the University of Idaho, and engineers at NASA Ames Research Center. Nine TechEdSat CubeSats have been launched since 2011, and their platforms range from 1U – 6U. While the TechEdSat missions have mostly demonstrated technology and serve as educational insight for the students involved, over time their technological development has made significant progress. The TechEdSat team's development of the Exo-Brake has contributed to the Small Payload Quick Return (SPQR) concept, where the active retrieval of small spacecraft, or a payload, is desired. The Exo-Brake successfully deorbits the housed CubeSat between 350 – 100 km and can now be controlled by commands from the ground in order to target a re-entry point (6, 7). Eighteen Prometheus spacecraft have launched since 2013, a few every year to 2021. These have all been on a 1.5U platform. The main objective of Prometheus has been technology demonstration driven to improve CubeSat platform capabilities for low cost (8).

For many, as time progressed, more scientific missions became the CubeSat platform’s main objective with a secondary objective being to demonstrate technology. For other missions, the objective was both to collect science while demonstrating a more complicated piece of technology. By 2021, the number of scientific CubeSats launched magnified seven-fold (due to launch of constellations).

In 2019, the first CubeSats to enter into a geotransfer orbit (GTO) were two 12U spacecraft called Technology Demonstration Orbiters (TDO-3 and TDO-4) and they were to collect space debris tracking data for the United States Air Force Academy. The mission successfully demonstrated an atmospheric modelling thesis (9) is a mssion at the beginning of the projected trend that sees more CubeSats designed for environments beyond LEO.

## 3.0 On the Horizon for CubeSat Missions

CubeSats are now being designed for environments beyond LEO since MarCO’s mission in 2018. There are several upcoming CubeSat missions designed for GTO, geostationary orbit (GEO), lunar, and heliocentric orbits. Expected to launch in 2021, SpectroCube is a 6U European Space Agency (ESA) mission that will measure photochemical changes of organic molecules in a highly elliptical orbit. The organic molecules will be exposed to high solar ultraviolet and energetic particle radiation (10). GTOSat is a 6U that is expected to launch in 2021 that will study Earth’s dynamic radiation belts and collect the first ever data on Earth’s magnetosphere, as well as demonstrate the utility of CubeSats in GEO (11). These combined with the upcoming launch of Artemis I at the end of 2021 will provide the small spacecraft community with the introduction of CubeSat presence beyond Earth since MarCO. Six of the propulsive 6U spacecraft being launched with Artemis I will orbit the Moon and will demonstrate technologies and collect science; the remaining seven will escape into a heliocentric orbit that will also demonstrate innovative small spacecraft technology and send science data back to Earth. The Aerodynamic Deorbit Experiment is a 1U designed at Purdue University that will enter in GTO to characterize the performance of a deployable drag device to accelerate the deorbit of small satellites (12).

### 2.1 Notable CubeSat Missions 2010-2021

This section will highlight a dozen CubeSat missions launched between 2010 – mid-2021 with more attention on the few scientific demonstrations that have occurred on a CubeSat. Note that most of the complex science missions are also a demonstration mission for specific technology used. Please refer to Table 1 for more information on other notable CubeSat missions that are not listed here.

The nature of the Sun, and its influence on the nature of space including the atmospheres of planets, has always been a topic of interest. Understanding this system is helpful in not only understanding more about the universe, but is also crucial in all future space activity. The Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics (FIREBIRD-2) mission is a 1.5U CubeSat dual satellite mission examining the spatial scale and spatial temporal ambiguity of magnetospheric microbursts that first launched in 2013 and then in 2015 (13). This project also contributed to the training and education of a diverse population of university students in all phases of the project.

The study of how the universe works, discovering how planetary systems form, how environments hospitable for life develop, and the search for signature of life on other worlds is the central focus of astrophysics missions. CubeSat presence in this field is scarce as the functionality of this tiny platform is limited to the type of mission it can support. PicSat, a 3U spacecraft launched in 2018 to LEO to observe the transit of the planet Beta Pictoris uses the interferometric instrumentation, integrated optics, and single-mode fiber filtering for the study of stellar environments (14). This CubeSat mission also serves as a technology demonstrator for future interferometric missions. The HaloSat mission, a 6U launched in 2018, had the objective to map the distribution of hot gas in the Milky Way by measuring soft X-ray emissions.

Only a few CubeSats have performed biological demonstrations in LEO. One example includes the *Escherichia coli* AntiMicrobialSat (EcAMSat) mission, a 6U spacecraft that launched in 2017, studied space microgravity effects on the antibiotic resistance in *E. coli*. This is a first step to the future of space exploration as there is an increased risk of opportunistic bacterial infection in space, and there is a strong need for the development of new therapeutic targets will be necessary to treat bacterial infections both here and in space (15).

**Table 1: Notable CubeSat Missions.**

| Spacecraft | Volume | Launch Year | Mission Type | Reference |
|---|---|---|---|---|
| Technology Educational Satellite, TechEdSat-n (TESn), spacecraft | 1U, 3U, 6U | 2012 - 2021 | Educational & Technology Demonstration | (16) |
| Lemur constellation | 3U | 2014-2021 | Earth Science | |
| Prometheus spacecraft | 1.5U | | Technology Demonstration | |
| AeroCube spacecraft | 1U, 1.5U, 0.5U, 3U | 2012-2020 | Technology Demonstration | (17-23) |
| CanX (Canadian Advanced Nanospace eXperiments) spacecraft | 1U –3U | 2008, 2013, 2014, and 2016 | Education, technology demonstration, Heliophysics, Earth Science | (24-26) |
| SporeSat | 3U | 2015 | Biological | (27) |
| AX-1 (Aoxiang Zhixing) | 12U | 2016 | Earth Science, Technology Demonstration | (28) |
| ASTERIA (ExoplanetSat, Arcsecond Space Telescope Enabling Research in Astrophysics) | 6U | 2017 | Heliophysics | (29) |
| HaloSat | 6U | 2018 | Astrophyics, | (30) |
| TDO-3 and -4 (Technology Demonstration Orbiter) | 12U | 2019 | Technology Demonstration, Educational activities, Earth science | (31) |
| NetSat-1-4 | 3U | 2020 | Technology Demonstration | |

| | | | | |
|---|---|---|---|---|
| 13 Artemis payloads | 6U | 2021 | Technology Demonstration, Heliophysics, Lunar Science | |

# CONCLUSION

The size of the CubeSat platform is expanding and their missions are becoming both more complicated and scientific. Future "easy access to space" is the advancement of CubeSat development for more sophisticated and complex science missions in more harsh environments. These complex science missions also require more advancement from some platform capability: greater data processing and transmission capacity, propulsion systems, optical communications, spacecraft autonomy, spacecraft navigation, collapsible/foldable telescopes, thin film solar cells, and inflatable antennas. Because of this, technology demonstrations are perpetual until engineers and scientists can solve these technological gaps, and that is now being researched and developed as more CubeSats are being launched and more are designed to operate beyond LEO. The exposure to GTO, GEO, lunar, and interplanetary space will greatly broaden CubeSat overall capability as more technology is able to be characterized. By 2022, there is expected to be nearly two dozen CubeSats beyond LEO for both demonstrational and scientific purposes, which will govern for even more CubeSat utility. More and more companies, start-ups, academic programs, and other government agencies have the capacity to build and launch a spacecraft. Once "easy access to deep space" is standardized, it is projected CubeSat presence will double over five years.

CubeSat constellations will likely grow in number as they can significantly improve our understanding of the space environment with their ability to capture simultaneous, multipoint measurements with identical instruments across a large area (32). There will also be an improved coordination between spacecraft for inter-satellite navigation and communication which will benefit future complex CubeSat science missions. The current trend of enlarging the CubeSat platform bolsters the idea that they will continue to expand in physical dimensions and scalability for the continuous proliferation of their complex design. When CubeSats were first launched, their main advantage was an affordable way to get to space though now they are a more capable method for space research.

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