The Evolution of CubeSat Spacecraft Platforms

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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. The initial purpose of CubeSats' 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 have been designed for more complex science missions around the Moon, Sun, or to deep space, and the projection for ten 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 2021 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 toward becoming commercially available.

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1.0 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 the CubeSat platform is more diverse. Advancements and interest in CubeSat constellations have been a major contributor to CubeSats' growth as a platform for scientific advancement. While all CubeSat constellations operate 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 beyond Earth. Over the next several years, it is likely that CubeSats will become more advanced to support or perform complex science missions in deep, interplanetary 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 the Nanosats Database using records as of April 2021. 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. For the purposes of this paper, "Earth science" is indicated by studying the physical constitution of the Earth and its atmosphere including, for example Earth observation, GPS radio data, oceanography, and Earth's magnetic field.

2.0 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 aerospace engineering programs. 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. Endless applications for CubeSats were quickly identified as more engineers and researchers found more CubeSat utility, making the form factor more diverse and capable. Advancements in capabilities such as greater data processing and transmission capacity, propulsion systems, optical communications, spacecraft autonomy, and inter-spacecraft navigation have made a simple CubeSat more intricate.

To meet 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 the 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 had become an established integral part of space access.

As of 2021, the CubeSat spacecraft is a diverse platform that offers engineers and scientists more payload 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 more complex science and technology demonstrations. Please refer to the "Complete Spacecraft Platforms" chapter in the SoA report for more information on commercially available CubeSat platforms (NASA, 2021j). There are tables with a vast amount of performance information on a variety of picosatellite to microsatellite platforms and reference missions.

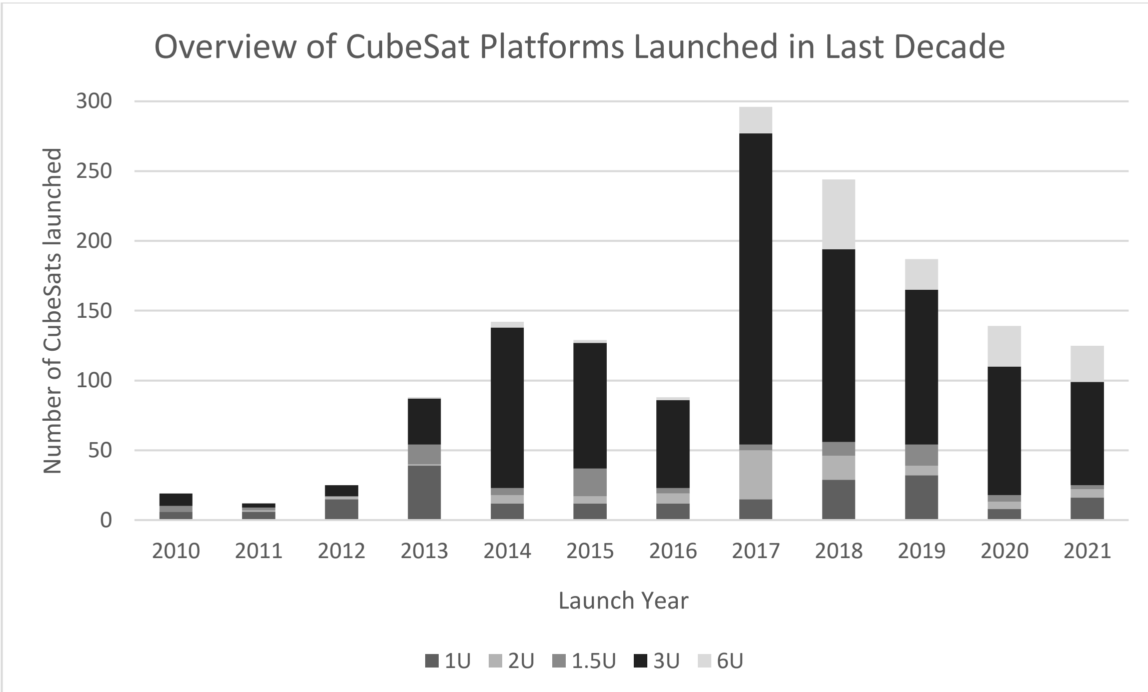

Figure 1: Overview of launched CubeSat platforms from 2010 through mid-2021.

3.0 EVOLUTION OF CUBESAT MISSIONS

Another major shift in the evolution of CubeSats was in the type of missions that 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 from 2010 to 2021. Reasons for this increase in CubeSat science missions include that more CubeSats are in fact being designed for science missions and more CubeSat designers have emerged in the past five years with a greater focus on CubeSat missions where the collection of science data is a key objective. 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, offer 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 (GEO and GTO), lunar, and deep space.

3.1 Rise in CubeSat Constellations

The growth of scientific CubeSats began in 2011 and skyrocketed in 2014 when the first Cubesat constellation was introduced into LEO. Planet Labs released the first of their Doves' 3U constellations the launch of which consisted of 36% of the CubeSats launched and 82% of launched Earth science CubeSat missions in 2014 (according to data on https://www.nanosats.eu/). The Dove constellation measures optical Earth observation with a 3 – 5 m 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 that provides global ship tracking and weather monitoring (Spire Global, 2021). 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 April 2021, 140 LEMUR 3U spacecraft have been launched and are operational[i]. The HawkEye 360 constellation aims to advance the field of space-based radio frequency (RF) geoanalytics using the NEMO nanosatellite platform by Space Flight Laboratories. The third cluster of three nanosatellites were launched July 2021, and each new cluster increased the capacity to collect and track more geolocations with higher frequency revisit times (HawkEye, 2021). RFGeo is the first product released by HawkEye 360 where customers can view data located by the RF signals the HawkEye 360 constellation collects.

CubeSat constellation missions that carry the same payload (or similar function) on all spacecraft typically strive to achieve enhanced coverage and high re-visit frequency services (Wu et al., 2020). This has already been accomplished with broadband Internet, Earth observation, and IoT services, and there are several other companies utilizing this CubeSat constellation service approach. Bringing IoT connectivity to economically unfeasible regions is a large target for companies and are experiencing explosive growth around the world. Previous forecasts of IoT connectivity indicated that by 2020 there would be 30 billion IoT devices, and halfway into 2021 there are 35 billion devices installed around the world[ii]. However, only 60% of the global population with access to the Internet will need to be addressed before IoT can really take off (Johnson, 2021), which is also a motivator for smallsat/CubeSat constellations. An alternate route for a CubeSat constellation is to have different, distributed payloads carried on the spacecraft that can perform an integrated service (Wu et al., 2020). This development path of a CubeSat constellation is more complicated, however allows for greater functionality among the interacting spacecraft to achieve a wide set of goals. Distributed CubeSat constellation missions are gaining more attention for future constellation missions as they are versatile and have a wide range of applications from ground stationless towers to in-space infrastructure services to debris monitoring and collision avoidance (Daniel et al., 2017).

3.2 CubeSat Enabling Technology

For complex CubeSat mission applications to be achieved, known technical gaps need to be solved to optimize CubeSat performance. These enabling technologies include in-space propulsion, inter-satellite link communications, lunar navigation network, high precision navigation and stability control, and on-board information processing. Each of these technical advances are happening at their own rate and all have made considerable progress in the past five years. There have been recent demonstration missions for each of these technology areas and the results have enabled the utility in operational missions. With this, these enabling technologies are expected to be more established in the next five years.

In-Space Propulsion: SmallSat in-space propulsion is known as a major enabling technology for future space exploration. Both chemical and electric propulsion have been demonstrated on larger SmallSats the past few years (examples: GMS-T launched 2021, GPIM launched 2019, UniSat-7 launched 2021). On CubeSats however, the flight heritage is much less though is starting to get more LEO exposure with constellations and single satellite demonstrations. The HawkEye 360 constellation mentioned above employs a Comet thruster head developed by Bradford Space, and the Enpulsion's IFM Nano FEEP was first integrated onboard a 3U Planet Labs Flock 3P' CubeSat in 2018. The Astro Digital Ignis satellite is a technology demonstration on the Astro Digital Corvus-6 6U spacecraft and includes the Apollo Fusion Apollo Constellation Engine (ACE). It is expected to launch in 2021 (Apollo Fusion, 2021). For a complete understanding of the metrics associated with the nominal operating condition for the surveyed propulsion device that is commercially available, please refer to the In-Space Propulsion chapter in the 2021 SoA report (NASA, 2021k).

Inter-satellite link communications: Reliable communication between spacecraft will open many doors for complex science and mission applications. When CubeSat automation is solved, constellations can exchange information to maintain precise positions without input from the ground. Radiometric ranging is a function recently incorporated into CubeSat transceivers, and an example is a SmallSat SDR X-band transceiver. CubeSat Laser Infrared CrosslinK (CLICK) is a technology demonstration of two 3U spacecraft that will advance inter-satellite communication links via laser terminals. CLICK-A will demonstrate a laser downlink, CLICKB/C a laser cross-link. Both CLICK spacecraft use a 3U platform and the payload occupies approximately 1.5U. The CubeSat lasercom module, by Hyperion Technologies, enables a bidirectional space-to-ground communication link between a CubeSat and an optical ground station (NASA, 2020g). Inter-CubeSat transponders may very well become a vital element of eventual deep space missions, since CubeSats are typically limited in broadcasting power due to their small size and may be better suited to relay information to Earth via a larger, more powerful mothership (NASA, 2021l).

On-board computing: High-performance computing hardware to handle the large amount of anticipated data generated by more complex small spacecraft; embedded system software networked for real-time multitasking distributed system software; and software partition protection mechanism. Next generation avionics systems have been identified as a heterogeneous architecture that can handle mixed criticality configurations, meaning they contain multiple processors with varying levels of performance and capabilities. An example of the new generation of a smallsat avionics distributed avionics application is the integration of Field Programmable Gate Arrays (FPGA)-based software defined radios (SDR) on small spacecraft (NASA, 2021m).

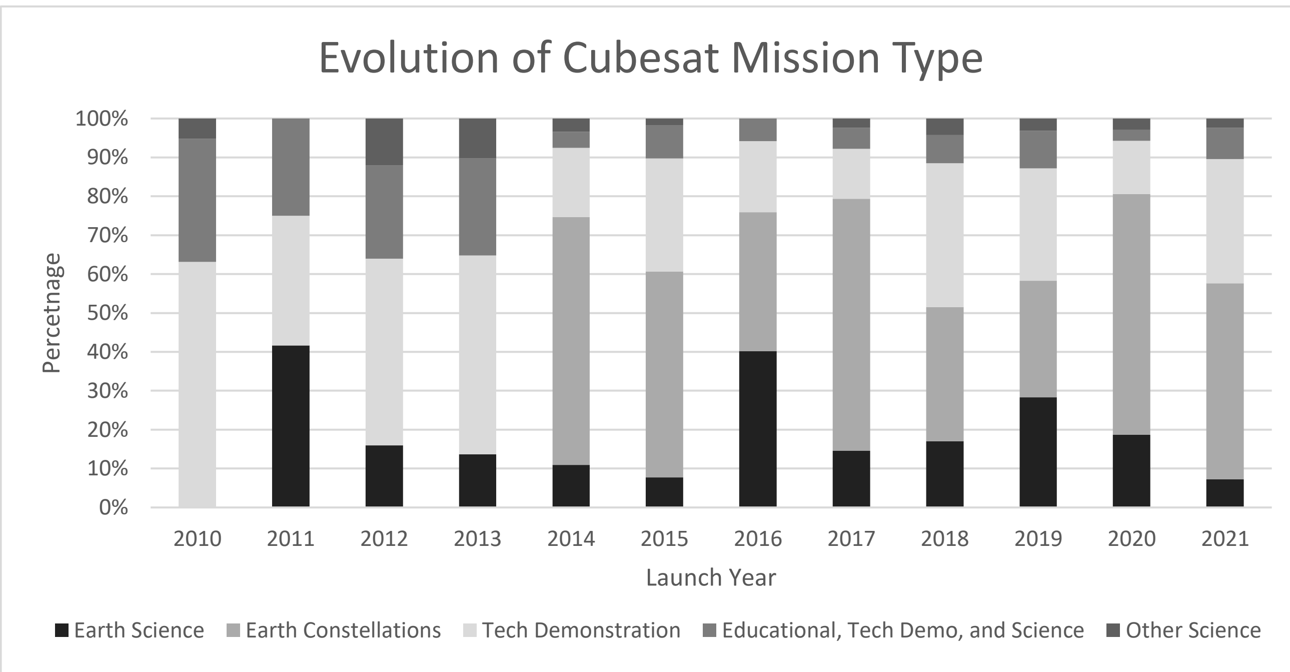

Figure 2: Evolution of CubeSat mission type from 2010 through mid-2021.

3.3 CubeSat Mission Type

There are several examples of CubeSats that were launched initially in 2010-2013 where now their multiple CubeSat successors operate in more complex 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 (Gangestad et al., 2015). The Technical and Educational Satellite (TechEdSat) project is a collaborative effort between students at California Polytechnic State University in San Louis Obispo, California, San Jose State University in California, International Space University in Illkirch-Graffenstaden, France, Smith College in Northampton, Massachusetts, University of Idaho in Moscow, University of California, Davis, University of California, Riverside, and the University of Florida in Gainesville, and engineers at NASA Ames Research Center (NASA, 2021p). 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 (Murbach et al., 2019). Developed and operated by the Los Alamos National Laboratory, 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 (Dallmann et al., 2015).

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).

The first launch of a 12U was in 2016 (Chinese spacecraft AX-1, or Aoxiang Zhixing), and since then only a few have made it into LEO. However, in 2019 the first CubeSats to enter into a GTO were two 12U spacecraft called Technology Demonstration Orbiters (TDO-3 and TDO-4), and they collected space debris tracking data for the United States Air Force Academy. The mission successfully demonstrated an atmospheric modelling thesis and is at the beginning of a projected trend where more CubeSats will be designed for environments beyond LEO (Gargesy, 2021).

3.4 Notable CubeSat Missions 2010-2021

This section will highlight several CubeSat missions launched between 2010 and –mid-2021 with more attention on the scientific demonstrations. 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 (Johnson et al., 2020). 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 (Nowak et al., 2018). 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, which studied space microgravity effects on the antibiotic resistance in *E. coli*. This mission was 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 (Padgen et al., 2020).

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	[18], [19], [22], [23], [25]
LEMUR constellation	3U	2014-2021	Earth Science	[43]
Prometheus spacecraft	1.5U	2013-2021	Technology Demonstration	[19]
AeroCube spacecraft	1U, 1.5U, 0.5U, 3U	2012-2020	Technology Demonstration	[7], [8], [11], [13], [26]
CanX (Canadian Advanced Nanospace eXperiments) spacecraft	1U –3U	2008, 2013, 2014, and 2016	Education, Technology Demonstration, Heliophysics, Earth Science	[39], [45], [48]
SporeSat	3U	2015	Biological	[21]
AX-1 (Aoxiang Zhixing)	12U	2016	Earth Science, Technology Demonstration	
ASTERIA (ExoplanetSat, Arcsecond Space Telescope Enabling Research in Astrophysics)	6U	2017	Heliophysics	[24]
HaloSat	6U	2018	Astrophyics	[35]
TDO-3 and -4 (Technology Demonstration Orbiter)	12U	2019	Technology Demonstration, Educational Activities, Earth Science	[9]
NetSat-1-4	3U	2020	Technology Demonstration	[49]
13 Artemis payloads	6U	2021	Technology Demonstration, Heliophysics, Lunar Science	

4.0 ON THE HORIZON FOR CUBESAT MISSIONS

CubeSats are now being designed for environments beyond low-Earth orbit since MarCO's mission in 2018. There are several upcoming CubeSat missions designed for GTO, 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 (Elsaesser et al., 2020). 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 (Blum et al., 2020). These combined with the upcoming planned 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 (Long and Spencer, 2016).

Another direction the space industry is moving towards is more CubeSat constellations with more improved coordination between CubeSats. Several upcoming CubeSat constellations are 6U and 12U platforms that can house more complex devices that will greatly enhance the reliability of these larger platforms. Omnispace is developing a hybrid space and ground network to provide 5G and IoT services using 200 12U CubeSat platforms (Erwin, 2021). There are future plans for direct-to-satellite 5G non terrestrial network connectivity solutions and is expected to be in service by the end of 2022. The AMBER CubeSat constellation from Horizon Technologies will have six 6U satellites in LEO locate and track vessels worldwide by picking up their RF emissions using a suite of in-house detection sensors and other proprietary technologies (Horizon Technologies, 2020). With higher ambitions, SatRevolution aims to launch a Real-Time Earth Observation Constellation (REC), which will consist of 1,024 6U CubeSats to be launched until 2026. The satellites will be divided into four different wavelengths (nm) groups and aims to have unprecedented high temporal resolution (SatRevolution, 2021).

The Sateliot IoT nanosatellite constellation launched their first demonstration 3U satellite in March 2021, and by the end of 2022 they plan to have 16 operational CubeSats, excluding the demonstration satellites (SatNews, 2021). The goal is to have up to 100 CubeSats at around 500 km that can provide services for the 5G mobile network operators (roaming services for sensors, precision agriculture equipment, clean energy infrastructure, and others). NASA's Time-Resolved Observations of Precipitation Structure and Storm Intensity with a Constellation of SmallSats (TROPICS) mission consists of six 3U CubeSats in a constellation that will increase our understanding of storm processes. These satellites will observe the thermodynamics of the troposphere and provide information on the environmental and inner-core conditions over the entire storm lifecycle. The launch window for TROPICS is first half of 2022 (NASA, 2021).

The combination high spatial and temporal resolution from nanosatellite constellations associated with improvement efforts in sensor quality may represent a trend to replace the era of large satellites for smaller and cheaper nanosatellite (Nagel et al., 2020). Dependable in-space propulsion for nanosatellites will greatly bridge the gap between moderate to complex missions and widen the CubeSat mission application. These technological advances will also improve precise formation flying which can allow CubeSats to work on other applications such as in-space services and synthetic aperture radar. With solutions for inter-satellite communication, CubeSat coordination will greatly improve their ability to communicate with each other for different purposes.

5.0 CONCLUSION

The size of the CubeSat platform is expanding, and CubeSat 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 as well as a expanding launch opportunities for CubeSats and smallsats. 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.

Overall, a group of interconnected CubeSats in low-Earth (and -Lunar) orbit is a very useful capability, and once particular technology is optimized, a constellation of CubeSats/SmallSats will be able to perform a variety of applications. Enhanced Earth observation and sciences include global marine traffic information, environmental monitoring, space weather, atmospheric studies, disaster management, infrastructure, agriculture, and research. 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 (NASA, 2021j). 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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