Overview of CubeSat Technology

Richard P. Welle

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Abstract

A CubeSat is a small satellite designed to be deployed from a standardized container to facilitate launch as an auxiliary payload. The CubeSat Design Specification places rigid limits on satellite dimensions to enable containerization and places a number of restrictions on the contents and function of the satellite to ensure that it poses no risk to the launch. The resulting ready and inexpensive access to space has fostered a culture of risk and innovation that has led to short development cycles and very rapid advances in the capabilities of CubeSats. From the first launch of six containerized satellites in 2000, the cumulative number launched has doubled about every 2.5 years and passed the 1000 mark in 2018. Initially intended to promote satellite development programs in educational settings, the CubeSat

R. P. Welle (✉)
The Aerospace Corporation, El Segundo, CA, USA
e-mail: richard.p.welle@aero.org

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form factor has been enthusiastically adopted for technology-demonstration flights, science missions, and commercial applications.

Keywords

CubeSat · Containerization · Risk · Mission assurance · Rideshare · Standardization

1 Introduction

In a narrow definition of the term, a CubeSat is a satellite that conforms to one of various CubeSat Design Specification documents describing satellites based on single or multiple units of a 10-cm cube. The original CubeSat Design Specification was developed at California Polytechnic State University in San Luis Obispo (Cal Poly) starting in 1999 and is based on the Poly Picosat Orbital Deployer (P-POD) that was developed at the same time (Puig-Suari et al. 2001). Since then, various derivative CubeSat standards have been developed, each based on an alternative deployer, that are more or less compatible with the Cal Poly standard. What all have in common, though, is that the deployer provides a standard interface with a launch vehicle in the form of a closed container that is designed to carry a secondary payload while ensuring minimal risk to the launch vehicle and primary payload. The P-POD is a simple box with a door and a spring mechanism. Figure 1 shows a photograph of a three-unit (3 U) deployer. The door is opened on command by a signal sent from the launch vehicle, and the spring mechanism pushes the CubeSat(s) out of the box with an ejection speed on the order of 1 m/s. This and other CubeSat

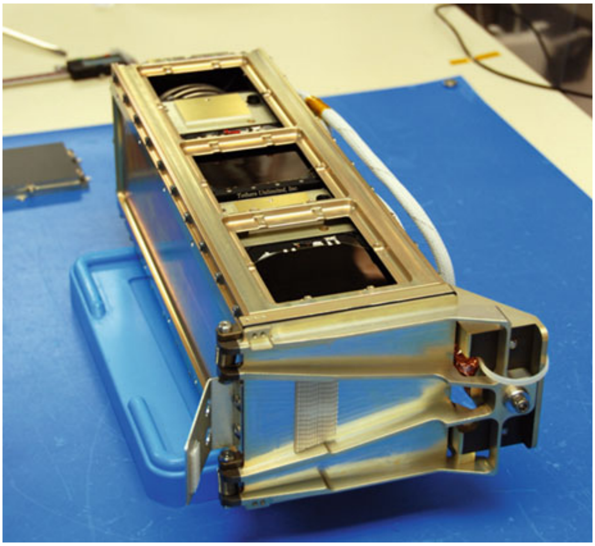


Fig. 1 Photograph of a P-POD CubeSat deployer containing two 1.5 U CubeSats, with access panels removed. (Aerospace Corporation image)

deployers are designed around a standard “unit” volume that is approximately a 10-cm cube. This dimension was selected based on the concept that a volume of 1 liter was a reasonable working volume for an experimental satellite and provides adequate surface area for solar cells on each face (Heidt et al. 2000). While the one-unit (1 U) CubeSat size was prevalent in the first years after the standard was established, many CubeSats today are three units (3 U) or larger. Figure 2 shows a photograph of a 3 U CubeSat with deployed solar panels. The popularity of the 3 U size is a result of that being the size of the most common deployers; the original P-POD was designed to deploy three one-unit (1 U) satellites, with the three satellites configured in a single stack. Although the original intention was to launch three 1 U satellites, a 3 U CubeSat deployer can also carry a single satellite that is 10-cm square and 34-cm-long, two satellites each 17-cm-long (1.5 U), or any combination of satellites that total 34 cm in length.

A somewhat broader definition of the term CubeSat could extend to any small satellite designed to be launched from a closed container. The first satellites fitting this definition were deployed from the Stanford-built Orbiting Picosatellite Automated Launcher (OPAL) in 2000 (Cutler and Hutchins 2000), while the first satellites conforming to the narrower definition of CubeSat were launched in 2003 (Swartwout 2013). While both senses of the term CubeSat refer to standardization of dimensions as well as containerization, the overwhelming majority of containerized satellites launched to date are based on the 10-cm unit cube, and the term CubeSat is most commonly interpreted in this narrower definition. Thus, for the remainder of this chapter, the term CubeSat will be used in the narrower sense, while the broader set of satellites including all those deployed from containers will be referred to as containerized satellites. Although not conforming to the generally accepted scientific usage for scaling prefixes, some additional related terms commonly used in the small-satellite community categorize satellites based on mass rather than physical dimensions and include microsatellite (mass between 10 and 100 kg), nanosatellite (mass between 1 and 10 kg), and picosatellite (mass between 100 and 1000 g). CubeSats can fall into any of these three categories.

Fig. 2 Photograph of a 3 U CubeSat with deployed solar panels. (Aerospace Corporation image)

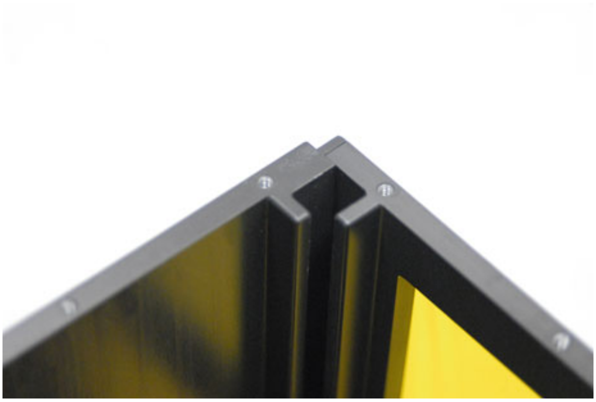
While the small size typical of CubeSats has supported reduced launch costs, the key innovation of the concept, responsible for both the low cost and ready availability of launch opportunities, is the containerization and associated simplification of the launch interface. The original intent of the CubeSat standard was to provide a simple, reliable, and repeatable interface with a launch vehicle to reduce the effort (and cost) of integrating a secondary payload. The goal was to enable inexpensive flight opportunities that could be used by universities for educational purposes, and the majority of early CubeSats were developed by educational institutions for research or training purposes. Eventually the utility of the CubeSat standard was recognized beyond the university, and the form factor was adopted by government laboratories as well as industry, as a vehicle for technology demonstrations, for science missions, and ultimately in commercial applications.

2 The CubeSat Design Specification

The CubeSat is generally defined in terms of the CubeSat Design Specification (CDS), which defines the interface between the CubeSat and the deployer and sets tight constraints on such factors as dimensions, mass, and potentially hazardous materials. The current version of the CDS is available from www.cubesat.org. The original P-POD CubeSat deployer was designed to satisfy several requirements (Puig-Suari et al. 2001). The three key requirements that supported the rapid growth in CubeSat development were the following: (1) the deployer must protect the launch vehicle and primary payload from any interference from the CubeSats; (2) the deployer must have the ability to interface with a variety of launch vehicles with minimum modifications and with no changes to the CubeSat standard; (3) the resulting CubeSat standard should be easily manufactured without using exotic materials and expensive construction techniques. The first requirement ensured that launch providers and primary payload owners could accept CubeSats on a rideshare basis with minimal risk. The second requirement ensured that launch providers would not have to go through the launch qualification process for the deployer more than once and further ensured that CubeSat builders could start projects without having to identify (and pay for) the launch up front – they could be comfortable knowing that a launch opportunity could be found once the satellite development process was sufficiently advanced to be certain of a launch-readiness date. The third requirement ensured that CubeSats could be built, if desired, at a cost commensurate with typical university budgets.

The CubeSat Design Specification developed for the original P-POD has undergone some evolution as experience was gained with early flights (e.g., removing the prohibition on propulsion and adding limitations on magnetic fields), but the basic requirements outlined in 2001 are still satisfied. The latest version of the CDS is available from www.cubesat.org and should be reviewed thoroughly by anyone planning a CubeSat project. The key requirements of the CDS fall into four broad areas: mechanical, electrical, operational, and do-no-harm requirements.

Fig. 3 Close-up photograph of a CubeSat test pod showing the deployer rails on one edge. (Aerospace Corporation image)



Mechanical requirements specify the physical dimensions of the CubeSat (presented in the form of mechanical drawings for each CubeSat size) that allow it to interface properly with the deployer. For most current CubeSat specifications, the mechanical interface is a set of four rails spaced at 10 cm that slide along corresponding rails in the deployer. The four black CubeSat rails are visible on the long edges of the CubeSat in Fig. 2, while the corresponding deployer rails are visible in Fig. 3. The CDS specifies rail dimensions, materials, and surface properties to ensure that the CubeSat will eject from the deployer without binding. The mechanical requirements also set limits on the maximum mass of the CubeSat (on a per unit basis) and limits on the location of the CubeSat center of mass.

Electrical requirements are principally designed to ensure that the CubeSat will remain powered off prior to deployment and include a requirement that there be a deployment switch on the CubeSat that will disconnect all power systems while the CubeSat is in the deployer. Additional inhibits are required to ensure that there will be no inadvertent radio-frequency (RF) transmissions while in the deployer.

Operational requirements include legal requirements (licensing for RF and, if in the United States, licensing for remote sensing), limitations on orbital debris, and start-up restrictions that prohibit actuation of any deployable hardware (such as solar panels) in the first 30 min after ejection of the CubeSat and prohibit any RF transmissions in the first 45 min.

Additional general requirements and testing requirements are designed to ensure that the CubeSat is incapable of doing harm to the launch vehicle and/or primary payload. These requirements include limits on propulsion systems, total stored chemical energy (batteries), materials outgassing, and hazardous materials (including a complete prohibition of pyrotechnics). Testing requirements include random vibration testing, shock testing, and thermal vacuum bakeout (to ensure proper outgassing of components) performed to test levels as specified by the launch provider or P-POD integrator.

Having a standard set of requirements is beneficial to both the launch provider and the CubeSat builder. For the launch provider, the CDS ensures that the CubeSat, as an auxiliary payload, will do no harm. Furthermore, any launch provider can establish the capability to launch CubeSats by qualifying a CubeSat deployer (the P-POD, or its equivalent), without having to delve into the details of each CubeSat that might be launched. For the CubeSat builder, the CDS provides a set of rules that must be met. However, more significant for the CubeSat builder is that the CDS provides for a standard interface that, if met, allows the CubeSat to ride to space on a broad range of launch vehicles with minimal integration effort. This means that a CubeSat complying with the standard will have a selection of ride opportunities at competitive prices and that these ride opportunities will be frequent.

In principle, satellites built to conform with the CDS should be capable of riding on any launch vehicle flying a CubeSat deployer. In practice, launch vehicles come with a variety of launch environments (particularly in the area of vibration loading), and the suitability of a potential ride will depend on whether the CubeSat was built to hold up under the relevant launch environment. While it is possible to build a CubeSat to survive even the most severe vibration environment, for most launch vehicles, such a satellite would be overbuilt. In practice, satellites are often designed for “typical” launch environments rather than extreme environments, possibly leading to rejection of certain launch opportunities that may come with unacceptable environments. Further, some launch providers may occasionally place restrictions on CubeSats beyond the minimum requirements of the CDS. For example, some launch providers may have a complete prohibition on propulsion systems. Other launch opportunities may involve transit through the International Space Station (ISS), in which case the satellites have to be designed and tested to man-rated space systems specifications. Finally, some CubeSat builders find it necessary to build a satellite that does not conform to all aspects of the CDS (e.g., by exceeding the maximum allowable mass or by having a pressure vessel). In this case, the CDS provides a process to request waivers, which are subject to approval by the launch integrator and/or launch provider (and possibly by the owners of other payloads on the launch vehicle).

The CubeSat Design Specification was created with the intention of encouraging flight opportunities for educational purposes. The first CubeSat launch, carrying six university-built CubeSats, took place in 2003. Of the first 100 CubeSats flown (which took until 2012), over 75 were university-built, only three were commercial, and the remainder were built by or for government organizations (NASA and the DoD). However, by 2012, the CubeSat standard began to be recognized by industry as a valuable tool for technology-demonstration flights, and 1 year later, in 2013, the first CubeSat developed for commercial services was flown. The pace of flights of containerized satellites (almost all of them conforming to the CubeSat standard) has continued to accelerate. Since the first flight in 2000, the cumulative number of containerized satellites launched has doubled about every 2.5 years (see Fig. 4). By early 2019, the total number of CubeSats launched had passed the 1000 mark, with just under 300 coming from universities, about 150 from government, and nearly 600 from commercial sources (including over 450 from just two companies, Planet Labs and Spire) (Swartwout 2019).

The CubeSat Design Specification established the defining characteristics of the CubeSat itself: the size, mass, etc., as well as limitations to ensure minimal risk to the

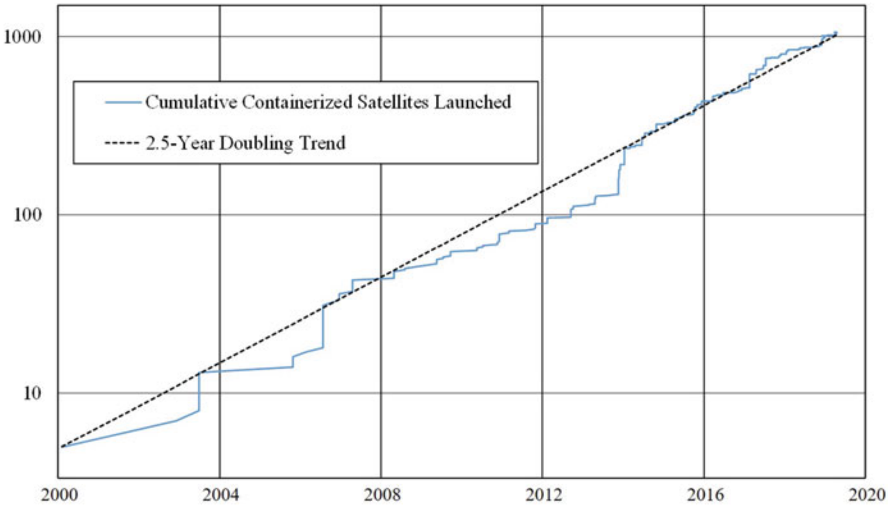


Fig. 4 Cumulative total of all containerized satellites launched as a function of date, compared to a 2.5-year doubling trend. (Aerospace Corporation figure based on data from Swartwout 2019)

host vehicle or primary payload. What was not anticipated was the entirely new approach to space systems enabled by the CDS. A key outcome of the CDS was that the space launch business, at least for kg-class spacecraft, was effectively containerized; the launch provider delivers a box to orbit (the P-POD, or equivalent); and the satellite developer need only design and build a satellite that fits in the box. The CubeSat deployer is analogous to the standardized shipping container that has revolutionize cargo transportation around the world over the past half century by making it possible to pack any cargo into a standardized container and then ship the container to a destination, where the cargo is unpacked. The containers are moved over the road, rail, and ocean transport networks with little regard to their contents, so the transport providers can focus only on efficient transport of the containers without having to develop efficient means of handing all the diverse cargos that might be shipped in the containers. At the same time, cargo owners need only deal with how to pack the cargo into the container, without needing to be concerned about the details of how the container is handled between the point of origin and the destination.

In a similar manner, the CubeSat container provides a standard interface between the launch provider and the satellite. The consequent simplification of the integration process reduces costs for the launch provider and provides a set of standards for the satellite developer which, if satisfied, will allow the CubeSat to ride on any of a number of launch vehicles. Thus, the path to space for a CubeSat is vastly simpler than for traditional satellite programs. It is this ready launch availability, combined with the original goal of the CubeSat as a teaching tool, that leads to a new approach to satellite development. While traditional satellites are built with little tolerance for risk, the low cost of the CubeSat and the availability of high-frequency, low-cost rides to space reduces the cost of a failure and encourages a culture of tolerance to risk, not for the launch vehicle or primary payload but for the CubeSat itself.

3 Risk Tolerance

When the CubeSat was originally conceived as a teaching tool, there was a high value placed on innovation and risk taking. For education purposes, this makes sense; one can learn as much (or more) from a failure as from a success. However, many non-educational programs recognized the potential of the risk-tolerant approach to CubeSats for supporting a program of rapid technology development. For example, technology-demonstration missions can often be flown with a high risk tolerance, particularly when the missions are part of a series of technology-demonstration exercises. Under these circumstances, an anomaly encountered on one flight can serve to inform the design of subsequent flights. Since the development cycle can be very short, a goal of demonstrating a particular technology in space can be applied to a series of flights rather than to a single flight. Under this approach, any single flight can have a high tolerance to risk under the expectation that a series of flights spread over a reasonable time interval will ultimately be able to satisfy all the program objectives.

Similarly, the opportunity to fly a high-risk mission at nominal cost encouraged entrepreneurs to establish programs that required multiple generations of spacecraft designed on a very short cycle, with the understanding that there may be failures on orbit and that any failures would provide lessons leading to improved designs in the next generation of the satellite. In this approach, the success of the program is defined not by the capabilities of the first satellite to fly but by the capabilities of the nth generation of satellite.

This is not to say that all CubeSats can be built using a risk-tolerant approach. For university satellite programs where learning is the primary goal, a risk-tolerant approach is certainly appropriate. For programs focused on technology evolution and/or maturation where the ultimate goal is an operational system or process that may take several years to develop, a risk-tolerant approach will likely be appropriate. However, for programs that are one-off science missions or technology-demonstration missions where the loss of a single satellite will severely impact program success, the tolerance to risk should be much lower, and more traditional approaches to satellite mission assurance must be implemented.

4 Elements of the Risk-Tolerant CubeSat Approach

Many aspects of the risk-tolerant CubeSat approach derive from a goal to keep costs low enough that a satellite failure would not be intolerable. An example of things that CubeSat programs can do to keep costs down is the use of commercial off-the-shelf (COTS) electronics. Traditional satellite programs will use only (or mostly) space-rated (radiation-tolerant) electronics. Typical COTS electronics can tolerate a limited amount of radiation, however, and this limit is rarely reached in low Earth orbit

(LEO) where most CubeSats fly. As such, typical CubeSats will fly exclusively or almost exclusively with COTS electronics. Issues that are encountered due to radiation in one satellite project can be mitigated through elimination of suspect components in subsequent flights, but there is often no systematic effort to evaluate the radiation tolerance of electronic components selected for a flight project.

A corollary to this is that CubeSats are often designed with short lifetimes in mind. For an educational project, the design and build effort provides the majority of the training with an additional gain during initial on-orbit checkout and operations. Beyond that, the marginal value of the satellite for educational purposes is limited. Similarly with technology-demonstration missions, once the technology has been demonstrated (unless on-orbit lifetime is part of the demonstration), there is little marginal value in continuing to operate the satellite. As such, many CubeSats are not designed with lifetimes in excess of 1 year in mind.

Another approach to minimizing costs is to limit the testing regimen throughout the program. In many CubeSat programs, a large portion of the environmental testing can be deferred until completion of the initial satellite build. The overall simplicity of most CubeSats often allows issues encountered late in testing to be corrected quickly because the entire satellite can be dissembled and reassembled in a matter of hours or days. This approach can lead to missed launches if there is insufficient margin built into the schedule to allow correction of issues discovered late in testing. Some CubeSat developers will build an engineering model that is a nominal duplicate of the flight model. Ideally the engineering model will be built before the flight model, with the experience gained through its build and test being available to inform the build and test of the flight model. The engineering model is then available on the ground for testing, software checkout, and anomaly resolution after the flight model is delivered.

Similarly, CubeSat development programs often forgo extensive modeling of spacecraft performance, particularly in the area of mechanical integrity. This can be partially justified in that CubeSats are so small that they become rugged simply by being more compact. Nevertheless, there may still be mechanical issues discovered in testing that could have been caught with careful modeling. However, with CubeSats it may be less expensive simply to expect testing to catch some issues that are then corrected through redesign after testing.

CubeSat developers also often forgo redundancy in the various satellite subsystems; CubeSats typically fly with a much larger compliment of potential single-point failures than traditional satellites. A corollary to this, however, is that the low cost of CubeSats, particularly the marginal cost of building and launching spares, makes it possible to approach redundancy by flying an entire duplicate satellite. Of course, this approach will not mitigate design issues, but it will mitigate workmanship issues, some radiation-induced issues, and operational issues.

An extension of this approach is sequential redundancy where CubeSats are developed as a series. The first of the series is delivered and launched, and the experience gained through the design, build, test, and operations of the first model is then applied to the development of the second unit. Similarly, the design of the third unit is informed by lessons learned with the second unit. In this approach, the success of the program is defined by the success of the first satellite in the series that accomplishes the full mission. Of course, the program goals may evolve as the satellite series progresses, leading to a continuing development effort reaching for ever-advancing goals. The point of the CubeSat Design Specification was to ensure easy access to space at a cost where a satellite failure was not intolerable. The redundant-satellite approach or, even more so, the sequential redundancy approach means that a satellite failure is not necessarily a mission failure.

The sequential redundancy model is used to some extent in all satellite programs involving experienced builders; lessons learned in the build of one satellite are applied to any future satellite where they are useful. However, with traditional satellites the time cycle for this is typically several years long; some complex satellites may be in the development phase for a decade or more and the final design frozen many years before launch. With CubeSats, the development cycle can be measured in months rather than years, so experience builds up rapidly. A related benefit of the CubeSat approach to satellite design is that the fast cycle time typical of such projects means that a team can be kept together through many projects. Thus, a small, dedicated team of engineers can build up the experience of multiple satellite projects, on a timescale short enough that there is not a lot of turnover on the team, and any experience gained by the team is retained.

Although the risk-tolerant approach to CubeSat development can be a valuable tool for advancing the state of the art in CubeSat capability and reliability, it is not applicable in all cases nor, perhaps, even in the majority of cases. The high tolerance to risk is really appropriate in only two circumstances: either a single satellite is being developed in an educational setting where the process of designing and building the satellite has as much or more value than actually flying the satellite or a satellite is being developed as part of a long-term series of satellites where the end goal is a satellite design with capabilities well beyond what can easily be achieved in a single development stage, and the potential for anomalies (or outright failures) in intermediate satellite designs are taken into consideration in the overall plan. The sequential redundancy approach is appropriate if the program goal is either technology maturation for its own sake or the development of a capability that is far beyond the current state of the art and cannot reasonably be achieved in a single design effort.

Although one may be tempted to implement a risk-tolerant approach in the development of a technology-demonstration mission, one must be very careful in this if the technology-demonstration mission is not one of a larger series. Specifically, if a mission has the goal of a flight demonstration of a specific technology and only one flight is planned, then the tolerance for risk is likely to small. The expectations for the mission must be clearly understood, both by the CubeSat developer and by the customer, before assuming that a risk-tolerant CubeSat approach is appropriate.

5 Mission Assurance

The risk tolerance described above is limited in that it applies only to the question of whether the satellite will successfully perform its intended function. The other key aspect of mission assurance is the safety of flight. Safety of flight risks are issues that could potentially harm other mission partners, from the start of launch processing to spacecraft separation on orbit.

Traditional space programs have a low tolerance to risk in either area, so when multiple traditional satellites would ride on a single launch vehicle, they would have had similar approaches to mission assurance. With CubeSats as rideshare, a single launch vehicle may have payloads with widely differing risk tolerances flying together. In response to this, the DoD Space Test Program developed a method for Rideshare Mission Assurance (RMA) that allows multiple satellites with varying risk tolerances to fly on a single launch, while protecting each satellite from risks to on-orbit performance posed by other payloads on the same launch (Read et al. 2019). RMA allows launch partners to accept self-imposed risks to the performance of their own payloads without being exposed to flight safety risks from other payloads.

The objective of the RMA process is to provide mission partners with an assurance that all payloads included on a mission will do no harm to each other or to any operational aspect of the launch. To this end, a set of do-no-harm criteria are defined that parallel similar requirements in the CDS. The principal requirements fall into the categories of launch environments (vibration, acoustic, shock), contamination, debris mitigation, pressure vessels, electromagnetic interference, and electrical inhibits (three inhibits are required to prevent unintentional activation of propulsion systems, any deployable structures, and any transmitters). A more detailed discussion of RMA is provided in (Read et al. 2019) along with a detailed checklist of tests and evaluations needed to ensure compliance with the RMA process.

6 Launch Considerations

Beyond the strict limitation on size and mass, the principal constraint on CubeSat missions is driven by the fact that all CubeSats launched (at least to date) have been as rideshare payloads. Being a rideshare means that the orbital parameters are selected by the primary payload on the launch or, at best, selected by agreement among a number of small payloads. The impact of launching as a rideshare varies depending on the mission. For most educational missions and many tech-demo missions, the orbital parameters are a secondary consideration; particular orbits may be desired, but a range of orbits will still satisfy the mission requirements. In such cases, there are likely sufficient launch opportunities that a ride satisfying the mission requirements will be available within a reasonable wait. In a few cases, a technology-demonstration mission may require a very specific orbit, in which case the wait for launch may be long.

Most operational missions, on the other hand, are likely to have more specific orbital requirements. In this case, the opportunities for rideshare might be insufficient. For missions requiring large numbers of satellites, one option is to design the mission with the intention of building an ad hoc constellation using quasi-random orbits (Gangestad et al. 2015); subsets of the constellation are deployed from multiple launch vehicles going to orbits that are selected based on their relative value to the overall mission of the constellation. An alternative, if the constellation is large enough or has to be distributed over a number of well-specified orbital planes, is to purchase a dedicated launch or launches. While most launch vehicles are designed with payload capacities well beyond anything useful for dedicated CubeSat launches, there are a number of entries in the new generation of small launch vehicles currently under development. Even though most of them will probably never fly, some are likely to make it to market. As of this writing, the Rocket Lab Electron, with a payload capacity in the range of 200 kg (depending on orbit), has already completed ten successful launches.

As the CubeSat industry has matured, the number of launch vehicles capable of carrying CubeSats has grown substantially. In 2018 there were 21 space launches carrying a total of 214 CubeSats, involving 9 different types of launch vehicles. For organizations developing one or a few CubeSats, launch services are typically obtained through a launch broker – organizations that consolidate collections of CubeSats from various developers and act as the interface with the launch provider. Launch brokers work with CubeSat developers to identify launch opportunities and support the launch providers by ensuring that the requirements of the CDS are being met by all the CubeSat developers. One launch option worth noting for US educational and nonprofit organizations is the NASA CubeSat Launch Initiative (CSLI), a program that provides free or reduced-cost access to space for CubeSats from qualifying organizations (CubeSat Launch Initiative). This program has supported the launch of over 80 CubeSats to date.

7 Missions

Although the first launch conforming to the CDS in 2003 included one science mission (Flagg et al. 2004), there was a perception for many years that CubeSats were too small to conduct useful science or other operational missions. In the first decade of CubeSat launches, over 70% were developed either for educational purposes or for technology demonstrations. Over time, however, both science-funding agencies and commercial ventures began to recognize the potential of CubeSats for operational missions. In 2008, the National Science Foundation began supporting CubeSat-based science investigations. In 2013, Planet Labs launched the first of what would become the world's largest CubeSat constellation with the goal of imaging the entire land mass of the Earth every day. In 2015, the National Academies of Sciences, Engineering, and Medicine undertook a study of the potential utility of CubeSats for science missions (National Academies of Sciences, Engineering, and Medicine 2016) and 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, and they enable new kinds of measurements and have the potential to mitigate gaps in measurements where continuity is critical." As of this writing, over one third of all CubeSats launched to date are part of the Planet Labs imaging constellation, and many other science and commercial satellites have been successfully deployed. Of the 214 CubeSats launched in 2018, less than 40% were categorized as educational or technology-demonstration missions.

The most obvious implication of the CubeSat Design Standard is the constraint on mass, volume, power, etc. that derives from the requirement to launch within a small box. This constraint is well understood and, in most cases, can quickly be used to determine whether a given mission can be accomplished using a CubeSat. In general, many missions will be constrained by simple physics; one cannot squeeze a 1-meter telescope into a CubeSat. But one should be careful in applying the physics constraint to any given mission. For example, it is straightforward to demonstrate that a 3 U CubeSat will not provide ground imaging at 50-cm resolution. So if the mission planner starts by assuming that the goal of the mission is imaging at 50-cm resolution, then a 3 U CubeSat is precluded by definition. But one should ask if the resolution is really the mission. Most often the mission involves determining something about the ground being observed: land use, vegetation, cloud cover, water quality, or another parameter. It is worth asking if the actual mission could be better served by lower-resolution, more frequent observations. The requirements should be about the information to be obtained, not about how it is obtained. Similarly, when designing an imaging system at a larger ground sample distance, say 20 m, it is possible to achieve this in a 3 U CubeSat. However, if the mission requirements call for a field of view that is too large, the optics will no longer fit in a 3 U CubeSat, and a larger satellite will be required. If the requirements specify the data to be obtained rather than the satellite field of view, it is possible to explore the trade between a single larger satellite and some number of CubeSats, each with a smaller field of view but flying in formation to cover the same area.

In general, missions that will remain out of reach for CubeSats are those that require large apertures or high-power instruments or those that require multiple instruments on a single platform. Outside those constraints, CubeSats have the potential to continue to expand their role in the space enterprise. An area where CubeSats may excel is in applications that benefit from distributed sensing, where a swarm or constellation of CubeSats can provide measurements with high temporal and spatial coverage, or in communication applications where, again, high temporal and spatial coverage can benefit the user on the ground. This has been demonstrated by Planet Labs with their use of over 100 CubeSats to provide regular daily imaging of the entire land surface of Earth. Similarly, Spire Global has launched over 100 CubeSats that are used for a number of applications including tracking maritime traffic and aircraft and for weather measurements using GPS radio occultation (Bosch 2019).

Although one tends to think of space missions in terms of services provided or mission data returned to Earth, the role of CubeSats in providing training opportunities should not be discounted. When developed as training missions, the risk tolerance can (and possibly should) be high, which will both enhance the learning opportunity and keep the costs down. The continuing importance of this role is illustrated by launch data indicating that about one in seven of all CubeSats launched in 2018 were developed by educational institutions.

Finally, the technology-demonstration mission continues to be an important role for CubeSats, with over 50 technology-demonstration CubeSats flown in 2018. This category of missions includes pathfinders for components or instruments that may subsequently fly on larger missions or prototype CubeSats that may be the basis for subsequent constellations of CubeSats.

8 Supporting Technologies

Like any satellite program, there is a minimum set of basic satellite bus functions that, depending on the mission, are essential to the success of a CubeSat flight. Functions required for essentially all missions include power, communications, and command and data handling (flight computer). Functions required for a significant fraction of missions include attitude control and navigation. Most CubeSat missions can be completed without propulsion (early versions of the CDS actually prohibited propulsion, a requirement that has now been relaxed), but many more complex missions are being developed that require propulsion for orbit maintenance or orbit changes.

The technologies to support these basic bus functions have been evolving rapidly, and any recitation of the current state of the art would quickly become obsolete. NASA's Small Spacecraft Technology Program (SSTP) compiled a report on the state of the art in 2013 and issued a revised version in 2015. Starting in 2016, the report was moved to an online format and is updated on approximately an annual basis (State of the Art of Small Spacecraft Technology).

Some noteworthy trends have been the rapid advance in communications capability and in the performance of attitude control systems. As of 2012, nearly all CubeSats operated with downlink rates of 9.6 kb/s, and a very few had systems with data rates approaching 1 Mb/s (Mission Design Division Staff Ames Research Center 2014). As of 2019, the peak downlink rate reported from a CubeSat reached 1.6 Gb/s (Devaraj et al. 2019). Similarly, the best pointing precision reported for a CubeSat as of 2012 was about 2 degrees (Mission Design Division Staff Ames Research Center 2014). However, by 2019 integrated attitude control systems for CubeSats were demonstrating pointing precisions two to three orders of magnitude smaller; the ASTERIA mission flown in late 2017 achieved about 2 millidegree body pointing in a 6 U CubeSat and 140 microdegree pointing of an imaging payload using a secondary piezo translation stage to control image placement on a focal-plane array (Pong 2018).

Navigation, at least for satellites in LEO, is easily obtained to a precision of 10 m or less using onboard global navigation space system (GNSS) receivers, including GPS receivers. If precise navigation is not required, then satellite operators can rely on the US space-tracking services (18th Space Control Squadron), which publishes regular updates on the orbital parameters of most satellites at a precision of 1–2 km.

The supporting technology that is perhaps the least mature as of this writing is propulsion. While electronic systems scale well to smaller sizes and are based on rapidly-evolving technologies developed for the consumer electronics industry, propulsion systems typically rely on physical phenomena that do not scale well from large to small and use technologies not often applicable in other industries. As such, the options for CubeSat-scale propulsion are limited but are expanding. The simplest systems use cold gas as a propellant; while these can be relatively easy to integrate and are fairly reliable, they can present a challenge in that they will typically require a waiver of the prohibition on pressure vessels and can provide only a very limited delta-v capability. Chemical propulsion systems present multiple challenges: the chemical reactions and heat transfer do not scale well to small sizes, the high thrust typical of chemical propulsion will produce torques on the spacecraft that may be beyond the capacity of the attitude control system, and the propellants will be restricted by the CDS. Several electric propulsion systems scaled for CubeSat applications are in development, using a wide range of propellants. While these systems may ultimately provide very high delta-v capability, the power limitations on CubeSats will limit the maximum thrust of electric propulsion systems, and any orbit changes will be slow. On the other hand, small electric propulsion systems can provide many years of orbit maintenance.

9 CubeSat Industry

At the start of the CubeSat era, there were few or no commercial vendors capable of providing CubeSat-compatible satellite systems, and essentially all CubeSat programs were “home-grown.” Within a few years, existing and newly formed vendors began offering CubeSat-specific systems including flight computers, power systems, radios, sensors, and complete attitude control packages. Thus, it is possible, for example, for a university program to acquire many or all of the satellite systems through commercial vendors and integrate them in-house to produce a complete satellite. Alternatively, the builder can select which satellite systems will be developed in-house and purchase the rest on the commercial market. A few companies were also formed for the purpose of offering CubeSat development and operation as a service. As such, it is now possible for a customer (e.g., a scientist wanting to fly a small instrument) to contract with a commercial firm to provide a relatively complete satellite service such that the customer need only develop and deliver the payload, which is then integrated, tested, launched, and operated by the commercial vendor.

As with the list of CubeSat technology status, the list of companies providing components and/or services continues to evolve, and any recitation of commercial services would become obsolete in short order. As such, the reader is again referred to NASA’s Small Spacecraft Technology Program (SSTP) report on the state of the art in CubeSat technologies (State of the Art of Small Spacecraft Technology).

10 Conclusion

The creation of the CubeSat standard has led to a very rapid proliferation of satellites in the 1–10-kilogram mass range. Initially these satellites were developed primarily for educational purposes, but their potential value in technology demonstrations and in operational missions did not go unnoticed, and the commercial market for CubeSat systems, CubeSat services, and data produced by dedicated CubeSat constellations has expanded rapidly. The cumulative number of containerized satellites launched has been doubling every 2.5 years since the first launch of six in 2000, and the trend shows no sign of leveling off. The range of missions and the fidelity of data produced by these missions have also continued to grow. The creativity of the

CubeSat community has enabled a number of programs that would have been deemed impossible in kg-class spacecraft 20 years ago.

In general, the approach to mission assurance taken by the CubeSat developer community has been much more relaxed than with traditional satellites. For educational and, to some extent, technology-demonstration projects, this tolerance to risk is appropriate. The potential for high-frequency flight opportunities has led to the concept of serial redundancy in CubeSats. This is the recognition that a high risk tolerance for any given flight is acceptable if the flight is part of a series of flights aimed at incremental technology advances; for any given flight in the series, the risk of failure is offset by the potential gains across the series as a whole. This concept of serial redundancy has led to very rapid advances in the capabilities of space systems but is appropriate only for programs involving multiple flights over an extended time period. However, the lessons learned through sequential redundancy can be, and have been, applied to new missions, yielding highly reliable satellites for a broad range of missions.

11 Cross-References

► Commercial Small Satellites for Business Constellations Including Microsatellites and Minisatellites
► Overview of Commercial Small Satellite Systems in the "New Space" Age
► The Smallest Classes of Small Satellites Including Femtosats, Picosats, Nanosats, and CubeSats

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