



www.adeepakpublishing.com

Pradhan, K. K. and Cho, M. (2020): JoSS, Vol. 9, No. 1, pp. 881–896  
(Peer-reviewed article available at [www.jossonline.com](http://www.jossonline.com))



# Shortening of Delivery Time for University-Class Lean Satellites

Kiran K. Pradhan and Mengu Cho

*Laboratory of Space Environment Interaction Engineering (LaSEINE)  
Kyushu Institute of Technology  
Kitakyushu, Fukuoka, Japan*

---

## Abstract

The introduction of the CubeSat standard has led to exponential growth in the number of small satellites launched in recent years. This is evidenced by statistics, which show such growth predominantly for satellites weighing 10 kg or less. Several factors can be attributed with the proliferation of small satellite launches, including the use of commercial off-the-shelf (COTS) components and the acceptance of higher risk during their development stage, both of which have enabled faster delivery of these satellites from concept to launch. Such non-traditional, risk-taking approaches to minimize cost and time required to achieve mission success led to the emergence of a “lean satellite” development and management philosophy, recognizing that it was not the size or the mass that drove the delivery time, but rather, the development philosophy itself. With the concept still in its infancy, the statistical analysis of the delivery time indicates likelihood of developing satellites faster, possibly in less than a year. Also, study of the mission success of the satellites shows that spending more time in building a satellite does not necessarily contribute to making the satellites reliable. Frequency coordination and compliance to safety requirements being some of the key challenges currently affecting the development time, recommendations are proposed herein, derived from the experience gained in development of lean satellites at Kyushu Institute of Technology for future lean satellite projects of universities around the world.

---

## 1. Introduction

When the CubeSat standard was introduced, many might have thought of it as a mere educational tool for universities, which lacked the capacity to provide any real value to small satellite users. About a decade later, the number of small satellite launches per year increased exponentially. The growth observed is predominant for satellites within the 1–10 kg category (Figure 1), most of which are CubeSats. In contrast, only a gradual growth is observed in the satellite

launches per year for those weighing between 11 and 500 kg (Figure 2).

The small satellites, especially the CubeSats, are being widely accepted across all space sectors as a key technology for advancement in the satellite industry. This has led to a paradigm shift in the space sector. A key feature of these small satellites (or CubeSats) is the use of commercial off-the-shelf (COTS) components, which has led to reduction in the cost of developing a satellite. In addition, the notion of failure being

Corresponding Author: Kiran K. Pradhan – [pradhan.kiran-kumar901@mail.kyutech.jp](mailto:pradhan.kiran-kumar901@mail.kyutech.jp)

Publication History: Submitted – 03/19/19; Revision Accepted – 11/18/19; Published – 01/15/20

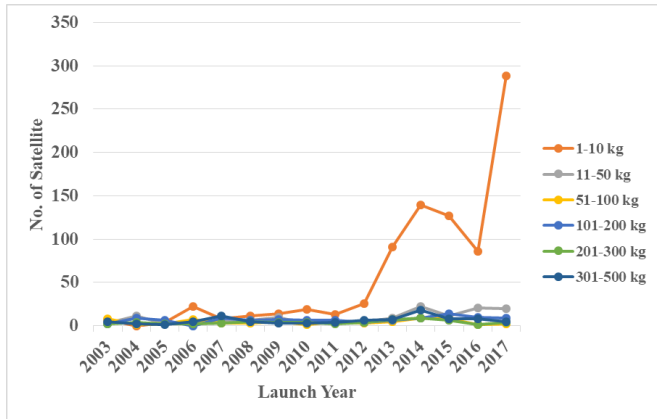


Figure 1. The number of small satellites (500 kg and less) launched per year.

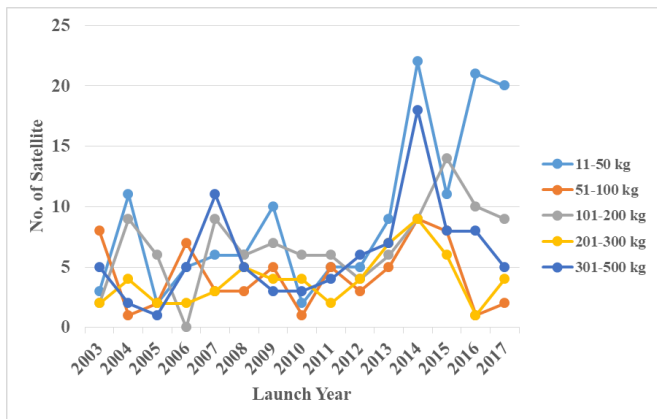


Figure 2. The number of small satellites (between 11 and 500 kg) launched per year.

unacceptable in the traditional approach of satellite development, which led to the space spiral effect<sup>1</sup> (Wertz et al., 2011), has gradually evolved, with satellite developers accepting higher risk in the development process. That, in a way, has led to faster delivery of satellites with a hint of reversal of the space spiral.

Not every small satellite exhibited these characteristics. Notably, the changes were not an outcome of the size or the mass of the satellite itself; rather, it was a new development philosophy that made it possible to build low-cost satellites in short time: a “lean” philosophy that aims to deliver value to end users in minimum cost and shortest time possible by utilizing non-

<sup>1</sup> In the traditional satellite development approach, the cost of developing a satellite was high, and the time required was long. That led to the demand for higher reliability, which, in turn, led to higher cost and subsequently longer schedule of development.

traditional, risk-taking approach to satellite development (Cho, 2017).

As we are in the transitioning phase of this revolution, there are still scope for improvement in this new development approach. Only a handful of studies has been carried out to aid the advancement of the concept. Statistical analysis of the reliability of satellites showed that the infant mortality of the small satellites is the highest (Dubos et al., 2010). An attempt was made to characterize the failure behavior of small satellites through statistical analysis (Guo et al., 2014). A similar study was carried out for CubeSats to harness its full potential as the technology develop. As an outcome, the probabilistic CubeSat reliability estimation tool was proposed (Langer, 2016) to predict the reliability of the system on the ground. A study focusing on failures occurred during the development of a lean satellite (Faure et al., 2017) was carried out to provide a reference to satellite developers to manage their resources to ensure mission success.

The criticality of the reliability of a satellite has been well recognized and efforts have been made to improve the success probability of future satellite missions. Lessons learned from satellite projects have been made available in various papers, but due to lack of an overview in requirements in the development of a CubeSat, a survey result has been published to give an idea on how to get started for those wishing to access space (Berthoud, 2016). While a case for delivery of satellites within 18 months was put forward through best practices and lessons learned from a satellite project (Debes et al., 2011), no study has followed up to indicate the replication of such delivery time or efforts to shorten it. Challenges in progressing a satellite design in a university project have been discussed in Kroeker et al. (2016), and a database of university satellite project maintained in Swartwout (2013; 2016; and 2018) provides an overview on the trend of university satellite launches and their mission success.

While there are different aspects that can be considered for improvement, the key attribute upon which

Thus, the space programs were locked in this loop of ever-increasing cost and longer schedules with demand for high reliability resulting in very few missions.

this research focuses is the faster development of satellites. Although the time required to build a lean satellite is considerably shorter than the traditional satellites, the need for faster development has been felt due to the rapid pace of technological advancement and ever-increasing demand for better services by the public.

Shorter development time means lower cost, which in turn makes it affordable to a wider market. Hence, new technology or concept could be validated or demonstrated more rapidly, with ease. For universities, students can get hands-on experience in building a satellite through every phase of a project life cycle, that is, mission conceptualization to satellite operation. This is not possible if development period is prolonged, as students would graduate mid-way through the project. Short delivery would make it possible for a student to design an experiment and get data from orbit before graduating. More importantly, from a business perspective, if you are not fast, then you miss the opportunity. Hence, being faster means staying competitive in the market.

The purpose of this paper is to study the current trend in the delivery time of the lean satellites and its correlation with the mission success. Through the lessons learned from the development of previous lean satellites, recommendations are drawn for future lean satellite developers. The authors hope that this paper can contribute to the lean satellite community in carefully planning the projects and avoiding some of the common hurdles faced by most of the past projects. Moreover, this study sets the foundation for future research on the lean development philosophy to strive for faster delivery of satellites. However, this paper is first of its kind and there are not many prior studies to which this paper can refer to. Thus, taking account of all the challenges in collecting the data for this research, this study is primarily targeted towards studying university-built satellites.

This paper is divided into five sections. Section 2 discusses the statistics of lean satellite including the methodology of data collection and definitions of the key terms used. Section 3 describes the various satellite projects as a case study and some common challenges faced by lean satellite projects. The recommendations for future projects are discussed in Section 4,

and, in Section 5, the current study is summarized and the future scope is highlighted.

## 2. Statistics on Lean Satellites

### 2.1. Methods and Definitions

A database for all satellites launched since 2003 and weighing 500 kg or less has been maintained at the Laboratory of Space Environment Interaction Engineering (LaSEINE) at Kyushu Institute of Technology (Kyutech) of Japan. The database contains information such as the mass of the satellite, the launch date, basic orbit information, launcher, country of origin, and so on. The information is collected from the launch manifests published online for each rocket launched (Klanowski; Kelso; Donnio; Kulu; Krebs - website publication dates unknown); the laboratory updates the database at the end of each calendar year. As of writing this paper, the latest database available was for the years from 2003 until 2017. As per the database, there were 1,309 satellites launched between 2003 and 2017 that weighed 500 kg or less. Out of that, about 76% of the satellites weighed 50 kg or less (Figure 3). This research focuses on this category as the majority of the satellites that meet the definition of lean satellite falls under this category. The term “lean satellite” will be used to describe this group of satellites from here on, but this study in no way confines the definition of lean satellites to this category. It is used herein as a term of convenience, for ease of conducting the study.

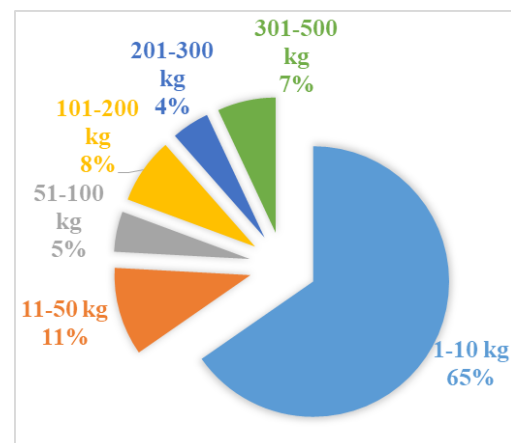


Figure 3. Percentage of number of satellites launched based on mass category.

For the lean satellites identified, additional information is gathered for the purpose of this research. The delivery time and mission status information are obtained mainly through online resources, such as published conference or journal papers (such as SmallSat), conference presentation files (such as CubeSat Workshops), official websites (such as BIRDS) or third-party websites (such as Krebs or EOPortal). If possible, the required information is acquired through direct communications with the persons involved in the satellite project. The information compiled for the university satellites by Swartwout (2016 and 2018), has been a great help in verifying the information and is also a source of data for some of the satellites.

The collection of data was a challenge in itself. Considering the huge number of satellites in the database, it was a daunting task to contact each satellite developer. Fortunately, many of the educational satellites had the information shared online on their website or by some other means. For the rest of the satellite projects, getting in touch with the right person was the biggest challenge, especially for the satellite projects of private and government organizations.

In this research, the “delivery time” of a satellite is defined as the period of time from the kick-off of the project to launch of the satellite. The definition of mission success Levels has been adopted from Swartwout (2016 and 2018). The success Levels are defined below for easy reference:

1. *Level 0 (Manifested)*: Publication of a launch date. (This study does not include satellites that were not launched.)
2. *Level 1 (Launched)*: Lift-off of the rocket. (Launch failures fall under this category.)
3. *Level 2 (Deployed)*: The spacecraft is confirmed to have been released from the launch vehicle.
4. *Level 3 (Commissioning)*: The spacecraft has had at least one uplink and downlink.
5. *Level 4 (Primary operations)*: The spacecraft is taking actions that achieve primary mission success.
6. *Level 5 (Mission success)*: Primary mission objectives has been met. The spacecraft may continue to operate, perform secondary mission, etc.

## 2.2. Statistics Scope

Between 2003 and 2017, 993 satellites were launched that weighed 50 kg or less. This includes satellites from two CubeSat constellation programs, the Flock series and the Lemur-2 series of Planet and Spire, respectively. About 382 CubeSats were launched by the end of 2017 between the two programs. These programs demonstrate the capability of lean satellites as constellations, causing a disruption in the current trend.

Mass production has enabled the companies to produce and launch each batch of satellites in less than six months, which is unprecedented in university projects. To maintain statistical consistency, the current authors have decided not to include these constellation satellites in this study. Figure 4 illustrates the trend in lean satellite launches with and without satellites of the two constellation programs. It can be noted that even without the constellations, the number of satellites launched per year since 2013 is much higher than the previous years, and this truly indicates the paradigm shift in the satellite industry.

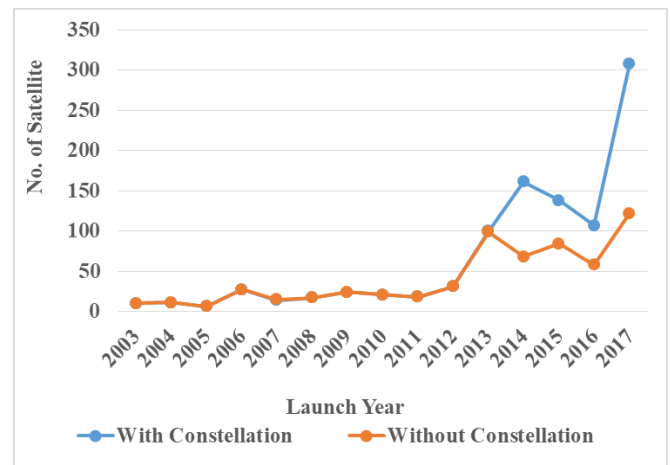


Figure 4. Number of lean satellites with and without CubeSat constellation programs.

## 2.3. Delivery Time

For the lean satellite database, the present authors managed to obtain the delivery time information for 361 satellites (Figure 5). The satellites are categorized in three groups based on the type of organization that

built them. All the satellites built by a university or any educational institute are grouped under the category of “University class”. Satellites developed in collaboration between different organizations having a university as a partner have been placed in this category. Satellites built by a national space agency of a country or any government agency are put into the category of the “Government” class. Likewise, the satellites built by a business entity, startups or any non-governmental/non-educational body have been placed into the “Private” category.

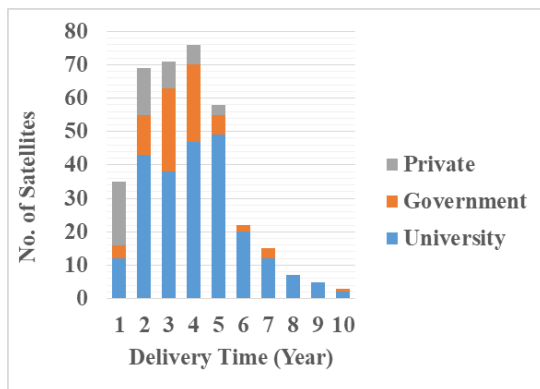


Figure 5. Delivery time statistics of lean satellites (361).

In general, it is observed that the time required for delivery of a lean satellite is shorter compared to traditional, large satellites. Although the time period to qualify as a lean satellite is not clearly defined, and may be a topic for debate, the current authors believe that the target delivery time for lean satellites should be two years or less. Considering two years as the borderline, statistics of Figure 5 show that only about 29% of the satellites have been delivered within two years. The remaining satellites still took more than two years for delivery. Some of the satellites took almost the same time as traditional, large satellites, showing that size and mass are not the key factors contributing to the revolution brought about by small satellites, or CubeSats.

Furthermore, if we look deeper into the statistics, the Private category has about 66% of the satellites delivered within two years, while the Government and University categories have a very low proportion, at 21% and 23% respectively. As stated earlier, achieving delivery time of around two years would be the

minimum objective, while even a period of less than two years seems realistic. On an optimistic side, the authors believe the target should be one year or less for lean satellite delivery time. Thus, the statistics suggests that there is still a room for improvement, especially for the University and Government satellites, since a greater proportion of the satellites have taken more than two years of delivery time.

## 2.4. Reliability/Mission Success

Satellites built faster are not necessarily better; in the realm of traditional satellite engineering, it is believed that building faster is actually worse. Given this, one objective of the current research is to ensure that the reliability of a satellite developed faster is maintained, if not improved. How does the current scenario of success rate look, for the lean satellites? Before looking into the statistics, it should be noted that one of the limitations of this study was to collect detailed information on the missions of each satellite to understand their complexity. Thus, any dependence of the mission complexity to success has not been considered in this research. Not ruling out the fact that there could be a significant impact of mission complexity to the success, the success Levels have been defined as much as possible to be independent of the mission complexity. The emphasis is more on the functionality of the satellite bus, rather than the mission itself.

Figure 6 shows an overview of success Level of 361 lean satellites grouped as per their delivery time. Each satellite was categorized into different success Levels as defined in the earlier section. Success Level 5 consists of those satellites that were able to meet their primary objectives, while Level 1 consists mostly of satellites that did not make it to orbit due to launch failure or some other reason. Other levels contain satellites that performed partially as defined.

Considering satellites with Level 4 or above as the ones achieving minimum success, the success rate statistics show that the proportion of satellites that achieved mission success across the first five categories are almost the same. As it can be seen from Figure 7, the success rate for lean satellites built within one to five years stands at around 60%. With this finding, a proposition can be made that spending longer time in

building does not guarantee a lean satellite better performance. A question arises, then: is it worth spending longer time to develop a satellite? The more time you spend, the higher the cost incurred, contradictory to the aims of a lean philosophy.

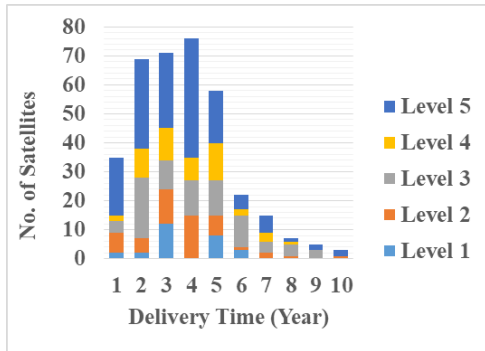


Figure 6. Success rate of lean satellites (361).

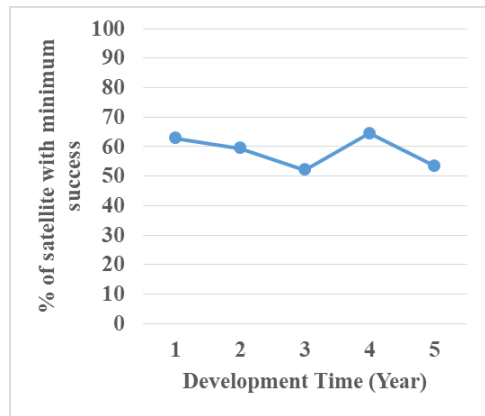


Figure 7. Percentage of successful satellites (309).

With the overall success rate consistent across different categories of delivery time, this study next

looked into the success rate of satellites when segregated by different classes of owners. The data for the Government and Private categories are combined, as the number of satellites in each of the category alone is much less when compared to the number for the University category. Figure 8 represents the proportion of success Levels for different classes of lean satellites. Although the available data for the University class and other two classes of satellites are vastly different, comparing the trend between these groups, we can note that the success rate for the combined Government and Private classes of satellites is about 68%, while that for University class satellites is only about 50%. This might not be surprising, considering that university satellites are usually built by inexperienced students with generally low available funds; however, lack of data on Government and Private projects poses a question on this outcome (Swartwout, 2013).

Looking further into the success Level of satellites based on the different delivery time sets for each category, Figure 9 provides a more detailed view of distribution of satellites among different delivery period and success level, while Figure 10 illustrates the percentage of successful missions, corresponding to their delivery time. For clarity and consistency of the figures, the plots have been limited to one to six years of delivery time for the University class, while for the Government and Private class, it has been limited to one to four years of delivery time.

It is interesting to note that Figure 10(a) represents a completely different trend from Figure 10(b). While it might not be a surprise for the trend in Government

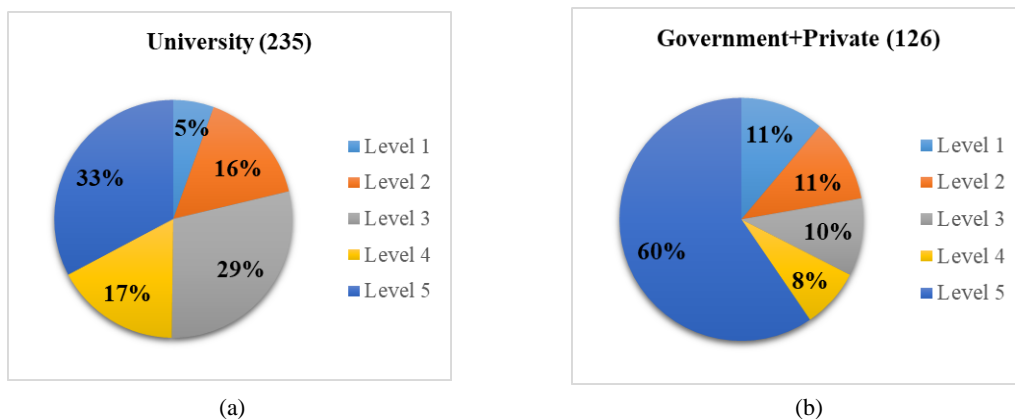


Figure 8. Success rate of lean satellites build by (a) University and (b) Government and Private agencies.

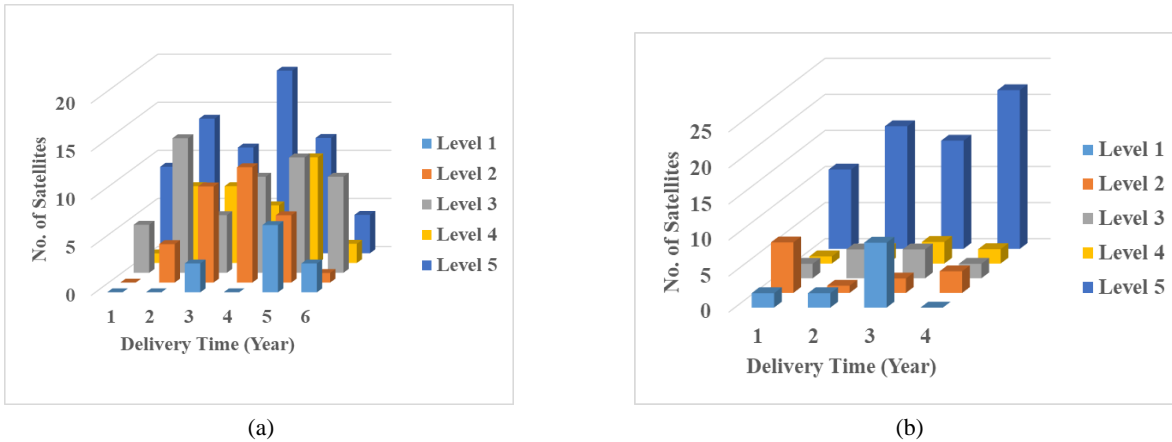


Figure 9. Success rate of lean satellites (a) University class (209) and (b) Government and Private classes (111).

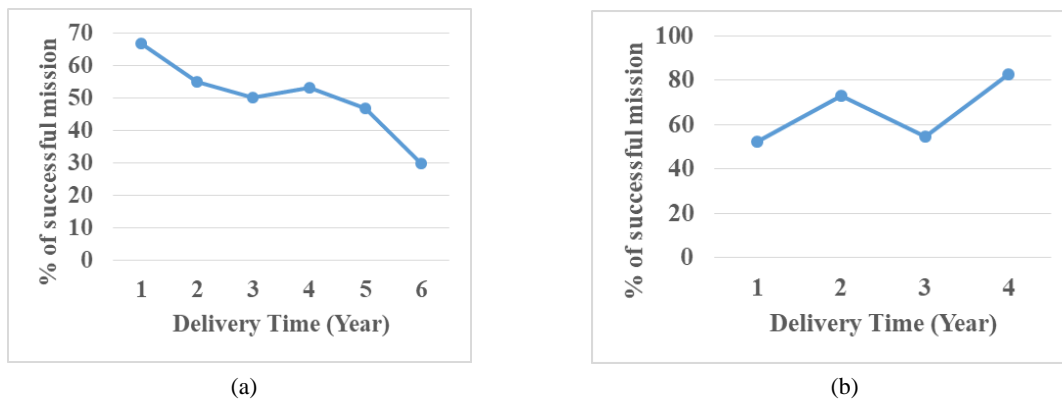


Figure 10. Percentage of successful missions for lean satellites (a) University class (209) and (b) Government and Private class (111).

and Private class of satellites to have a better success rate as the delivery time increases; that is not the case for university-built satellites. It is noteworthy that the success rate of university satellites actually decreases as the delivery time increases.

One key factor contributing to this declining trend in the success rate of University satellites could be the inconsistency in the manpower involved in satellite project. Students usually spend a fixed time in universities—normally between two and four years. Therefore, when a project extends for a long period of time, it is most likely the case that project members get changed midway. While this transition takes place, the handover of responsibilities is not always proper, and most importantly, the transfer of knowledge is very poor (Kroeker, 2016), likely leading to more errors and unexpected delays. Also, the budget available for the project is, in most cases, fixed. Delaying a project

does not guarantee better systems or components, but it might eat away budget margins, leading to a compromised success rate.

### 3. Case Study

By now, readers might have synced with the objective of this research and why we need to strive for a faster delivery of lean satellites. The question that arises is how do we do it? It is beneficial to look into some of the challenges that a project typically faces during its implementation, and how it affects or delays the overall progress of the project. Below, some of the satellite projects of LaSEINE, Kyutech have been considered as a case study for this research. Their development process is reviewed here to understand the challenges and difficulties faced in the course of project implementation.

### 3.1. Lean Satellites of LaSEINE

The first satellite of LaSEINE was launched in 2012. A 30-cubic cm nanosatellite called HORYU-II (Seri, 2013), it was delivered in about two years, and managed to achieve its primary mission objective once in orbit. The team members consisted of a combination of senior-year undergraduate students and Masters-course graduate students.

The success of HORYU-II was followed by another 30-cubic cm microsatellite, HORYU-IV (Faure, 2017), which was developed following lean philosophy, and took a little less than three years from kick off until launch of the satellite. The project members consisted of students and faculty members. The students were mostly graduate students. Both HORYU-II and HORYU-IV were launched as a piggyback payload.

The third satellite of the laboratory was a 2U CubeSat, AOBA VELOX-3, developed in collaboration with Nanyang Technological University (NTU) of Singapore. It took about two and a half years to deliver the satellite, and the project team consisted mainly of undergraduate students. The satellite was launched to the ISS and then released into orbit from JAXA's Kibo module, and managed to achieve success Level 4.

Following success of the HORYU satellites, a CubeSat constellation project was initiated by LaSEINE, again experimenting with the lean philosophy of development. Joint Global Multi-Nation Birds (JGMNB), or simply the BIRDS project (Khan, 2015),

is a series of CubeSat Constellation projects that aim to provide hands-on training to students in all aspects of a satellite project. From mission conceptualization to on-orbit operation of the satellites, each project under the BIRDS program was designed to be implemented within two years.

First in the series was the BIRDS-1 (Monowar, 2017) project, which developed five identical 1U CubeSats. The project team consisted of 15 students guided by faculty members, and took about two years to deliver the CubeSats. Next in the series was the BIRDS-2 (Pradhan, 2018) project, which developed three identical 1U CubeSats. The BIRDS-2 team consisted of 11 students and, similar to the first generation, it took about two years to deliver the CubeSats.

Shortly after the release of BIRDS-2 satellites, SPATIUM-1 (Aheieva, 2018) was launched. A 2U CubeSat project implemented in collaboration with NTU, Singapore. The team consisted of seven members and took about two years for delivery of the CubeSat. The mission success stands at Level 4 at the time of writing this paper.

Table 1 summarizes details about each project of LaSEINE. The launch type indicates whether the satellite was launched as a piggyback payload or whether it was launched to the ISS and then released into orbit. The Development phase shows the different stages that each project underwent to produce the final flight model, while the testing time accounts for the total time spent by each team to conduct key tests at each of the phases represented in person-days. The number of

Table 1. Satellites of LaSEINE, Kyutech

Satellite	HORYU-II	HORYU-IV	AOBA VELOX- 3	BIRDS 1	BIRDS 2	SPATIUM-1
Mass or CubeSat size	7 kg	10 kg	2U	1U (5)*	1U (3)**	2U
Team Size	20	47	53	15	11	7
Launch Type	Piggyback	Piggyback	ISS	ISS	ISS	ISS
Development Phase	STM → EM → EM-2 → FM	EM → EM-2 → FM	EFM	EM-1 → EM-2 → FM	EM-1 → EM-2 → FM	EM-0 → EM-1 → EM-2 → FM
Testing Time (person days)	2289	2573	333	446	493	1254
Number of Missions	5	10	2	6	6	6
Delivery Time (year)	2	3	2.5	2	2	2
Success Level	5	5	4	3	3	4

Note: \*Five identical 1U CubeSats. \*\*Three identical 1U CubeSats.



missions indicates the experimental missions defined for each satellite by the project team.

### **3.2. Challenges in Development for Satellite Projects in LaSEINE**

All of the projects described above were implemented by different students, with varying levels of prior knowledge. Hence, the challenges faced by each team were unique in some ways; there were also common challenges among the projects. For HORYU-II, since it was the first satellite to be launched, there was no heritage in the development process, such as test plan and procedure. As a result, a lot of time was spent on performing different tests to ensure that the satellite survived the launch environment and the space environment. One of the difficulties in the implementation of HORYU-IV was managing a large team, as it was difficult to monitor the task of each member and their progress. Similarly, having many missions made the system complex, and thus hindered progress.

One common issue faced in project implementation is delay in communications or miscommunications when the team has to rely on communication methods such as email or other electronic means. In the AOBA VELOX-3 project, the primary payload was developed in Singapore and the satellite bus and secondary mission was developed in Japan. Most of the information was shared via email, and there usually involved a waiting time to get the response. Even if it is a small clarification and could have been transmitted within a few minutes if communicated face to face, but when communicated over email, the time spent in waiting for response causes delay to the project.

Similar issues were encountered in the HORYU-IV, BIRDS-1 and BIRDS-2 projects while communicating with the vendors/suppliers, one of the reasons being the language barrier. These programs were executed with English being the main language for communications because the majority of the students came from different countries that spoke different languages. While ordering Printed Circuit Boards (PCBs), there were instances when the manufacturer sent some comments seeking clarification on the

design sent to them for fabrication. Such communication happens in Japanese, but usually the person responsible for the design does not speak Japanese. Thus, a Japanese team member had to translate the comments, which usually contained technical terms difficult to translate into English.

For HORYU-IV and BIRDS-2, the delay in response to comments led to delay in the delivery of the boards ordered. In addition, one of the challenges with such communication was that it was handled by only a single person. Most of the time, the other members were not aware of when the emails went out and when or whether any response came in. Moreover, if the responsible person is late checking email, it will also add to the overall delay in the project.

In a constellation project like BIRDS-1 and BIRDS-2, one of the challenges that the team had to deal with was the quality control for the flight models. In the BIRDS program, each member of the team was assigned specific roles/responsibilities, and the team worked towards developing a single engineering model. During the final stages, the team was divided into sub-teams based on their country, and each of the sub-teams worked on their own flight model. Although all the flight models of each project were supposed to be identical, it was difficult to guarantee same quality in performance due to varying workmanship of each sub-team. Hence, during the final assembly and integration, each sub-team faced different issues and delay caused by each of the sub-team added up to the overall delay of the project.

One key cause of delay in the BIRDS-2 project was the error in designing printed circuit boards (PCBs). Two circumstances led to this error. First, the time allocated or available for designing the PCBs were limited. Second, the work was taken up by only one member. Thus, the PCB designer was under pressure and overworked, and because of that, there was a major error in some of the fabricated boards such that it could not be integrated with remaining parts/components. That led to the need to redesign boards, causing lengthy delay in the project. Another reason for such error, also noted in the HORYU-IV project was the lack of a proper double-checking process. Before an

order for manufacturing a PCB was placed, no other member cross-checked the design. Moreover, only one person was familiar with the design of a particular PCB, making cross-checking a difficult prospect.

Safety requirements of the launcher is one of the key aspect of any satellite project, and non-compliance with them can lead to delays in the project, as well. It is crucial to understand the requirements before the start of design phase and review them at regular intervals. Most compliance with safety requirements is verified through various tests, and small changes to the design mean repeated testing for which more time and resources must be spent. There were instances in the BIRDS-2 project where small changes to a sub-system led to multiple vibration tests. Since the testing facilities were available at Kyutech, it was convenient to conduct the test again and again, but if the facilities were located elsewhere, the traveling or transportation of the test article would have made it a lot more tedious and resource consuming.

In the BIRDS-1 project, the batteries of one of the flight models lost its capacity, so in addition to delay in the project due to disassembly of the flight model and replacement of the batteries, the team had to prepare extra documents for completion of safety review. Also, for the HORYU-IV project, an issue with functionality of the satellite and error in integration during the flight model stage led to a second vibration test, as the team had to disassemble the satellite after the first test.

Frequency coordination, an important aspect of any satellite project, is necessary to complete all the administrative procedures and obtain a frequency license before launching the satellite, or else the launch can be delayed. This was experienced by the BIRDS-2 team, where obtaining the frequency license was delayed due to late initiation of the process. Also, due to lack of constant follow-up pertaining to the International Telecommunications Union (ITU) procedures led to delay in publication of Advanced Publication Information (API) that caused the team to miss a launch opportunity. Since it was an ISS launch, the next launch opportunity was just a few months away; in a different scenario, the delay could be for years, or there might not be a next opportunity at all.

Although not critical, other projects faced a few challenges with regard to the frequency coordination. The BIRDS-1 team had to prepare multiple versions of the application document before completing the process. Not fully understanding the requirements for the application could lead to such instances. SPATIUM-1 had a similar case, where the team was unaware of how to proceed with the frequency coordination process. The team did not know where to submit the application, so the documents were initially sent to a wrong office. It took almost a year to complete the frequency coordination process.

### 3.3. General Challenges in Development

One common challenge for university-built satellites is the prior knowledge of project members on satellite engineering. If the members do not have knowledge on systems of a satellite and how they should proceed with the work assigned to them, then the time spent in learning about the systems could lead to a significant delay in the overall timeline of the project. Such challenges were experienced in the BIRDS-2 project, because of which progress in the initial phase was slow. In the BIRDS project, generations of different satellite projects, i.e., BIRDS-1, BIRDS-2, and beyond, overlap by at least one year because the satellite project starts every year and finishes in two years. Students of the former generation are required to mentor the next generation. This arrangement helped to mitigate any significant delay.

In general, it is observed that the learning process should be a combination of theoretical study based on books and hands-on training with actual implementation. Providing hands-on training could be easier, as few senior students can supervise and pass on their experience. The theoretical part may require classroom teaching, which is not always possible depending on the educational resource of the school. Not every university that builds lean satellites has an academic curriculum of space engineering.

The launch opportunity by itself could be a challenge or a factor that could delay the project. Most of the launch services that are currently available are designed for big satellites and are very expensive. The

opportunities available are limited, and not having a confirmed launch schedule means an indefinite timeline that usually leads to slow progress. However, we are experiencing a change in that, as launchers are accommodating more and more lean satellites in every launch. Also, introduction of deployment services from the ISS has greatly increased the number of launch opportunities.

Similarly, one important challenge many lean satellites face is the fact that the satellite projects cannot decide the launch schedule if they choose a launch option of piggy-back or ride-share by a rocket. The satellite project must deliver the satellite in time; otherwise, they miss the launch. For the case of HORYU-IV, which kicked off in June 2013, the launch slot was secured in August 2014. The rocket was launched as planned on February 17, 2016, but developing the satellite within the available time frame was challenging, as there was not much time left for system verification testing towards the end. In such cases, the team has to prioritize and perform key verification tests.

If the launch of a rocket is delayed, which is usually the case, then the satellite projects might have enough time to do all the verification tests. However, once the satellite is in orbit, there might be only a few people left who understand the satellite system to an adequate depth, as some of the students might graduate and leave. During the operation, the project usually encounters many anomalies that need to be resolved via FTA (Fault-Tree- Analysis) or other means, which requires detailed knowledge of the satellite sub-systems. Obviously, if any in-orbit anomaly occurs and is not properly handled, it can affect the mission success rate.

An important aspect of lean satellite is the use of COTS components, which are economical and are easy and quick to procure. However, their use comes with a risk factor, as they are not space graded. Thus, selection of components becomes a challenge. Size, for instance, could be a factor; care must be taken to ensure that the component fits within the margin of the spacecraft volume, especially in the case of CubeSats. The interface of the component should be compatible with the available interface options of the spacecraft bus. Usually, lean satellite buses have low power margins, so power consumption becomes a big factor.

Care must also be taken with regard to the cost of the component, as it can raise the project cost.

Above all, the key question is whether it can survive the harsh launch and space environments. An aspect to consider would be to check whether it has any flight heritage, or whether it has been proven in space, bearing in mind that the performance of the components manufactured in different lots are not always guaranteed to be the same. This could result in performing additional tests on the key components to ensure it survives the launch and space environments. Studies have been carried out to perform tests on a careful selection of components (Sinclair, 2013). With increasing need for reliability of a small satellite, initiatives have been started to address the challenges towards achieving higher reliability (Johnson, 2017). Techniques have also been proposed to assess the behavior of COTS components and any unpredictable errors associated with them (Honghao, 2015).

Another challenge is planning the procurement. These days, many lean satellites, especially CubeSats, rely on components such as EPS (Electrical Power Systems), OBCs (On-Board Computers), and others, provided by commercial vendors. They can be purchased through online shops including CubeSatShop, MakeSat, or others. One has the impression that the online shop products can be delivered in a short time, but the facts are very different; the components are not really “off-the-shelf”. The sales volume is not big enough for the vendor to stock each product, so almost all the components are manufactured on demand. Moreover, due to the fact that the companies that produce the products are mostly small businesses, the company cannot respond to the demand quickly, adding to the risk of delivery delay. The delay of key components affects the schedule of system integration and testing, which directly affects the mission success in orbit, or causes the delay in the overall project schedule.

Finally, university satellite developers often underestimate the importance of obtaining spare components. During the final assembly of the flight model, if a component suffers failure or malfunction, it is very difficult for the satellite developer to fix the problem or replace the broken parts. It must be shipped to the vendor for repair, or another item must be purchased.

Although CubeSat components are low-cost and fast-delivery, some components need a long lead time, on a scale of months. One mistake in the satellite assembly phase could lead to a major delay in satellite delivery.

#### 4. Recommendations

With respect to some of the challenges discussed in the previous section, recommendations are outlined here, so that future university lean satellite projects can avoid encountering similar issues. From the current authors’ perspective, the most critical aspect is the selection of launch method. The CubeSat deployment from the ISS, which started in 2013, provides satellite developers a launch alternative in addition to a piggy-back launch option. This launch method also gives satellite projects an option to choose the launch schedule.

A project team can select a tentative launch window and begin working on their satellite. As the launch window approaches, if the team feels that the satellite development and verification are not fully ready, they can skip the planned launch slot and take another launch slot, with prior notification to the launch provider. This way, it becomes easier to prepare the overall project schedule, including the satellite operation plan right from the beginning, and thus tackle the issues of launch delay. However, the service is available for CubeSats only, and the orbit will be similar to that of the ISS itself. Therefore, the project members need to decide from the beginning whether the mission objectives can be met through such conditions.

Figure 11 plots the delivery time of 303 satellites for rocket launch and 75 satellites for ISS release. When a satellite is launched by a rocket, it takes slightly more time to deliver the satellite into orbit. As illustrated by Figure 11, the peak of curve for ISS release is around two years, while that for rocket launch is four years. Also, there are no satellites that were delivered in more than seven years for ISS release, but there are still a few satellites that took more than seven years for rocket launch.

The next most critical aspect for any project is the frequency coordination process, which no project can avoid. Once the team selects the operating frequency for the satellite, the team needs to understand the procedure involved very well. The process usually starts from the national authorities and then goes up to international administrations. Many steps could be involved with each step taking considerable time. Such procedures usually vary by country, and also by type of frequency selected for use. The procedure for obtaining a license for an amateur band frequency could be very different to that of non-amateur band. Understanding the process well, providing the required information and constant follow up with concerned offices could be key in expediting the process.

Similarly, safety requirements of the launcher are mandatory for all projects to fulfill. Safety concerns are given the highest priority, so no launcher would accept risk if the safety requirements are not fulfilled by the project. As far as possible, it is best to decide on the launcher before beginning the design of sub-

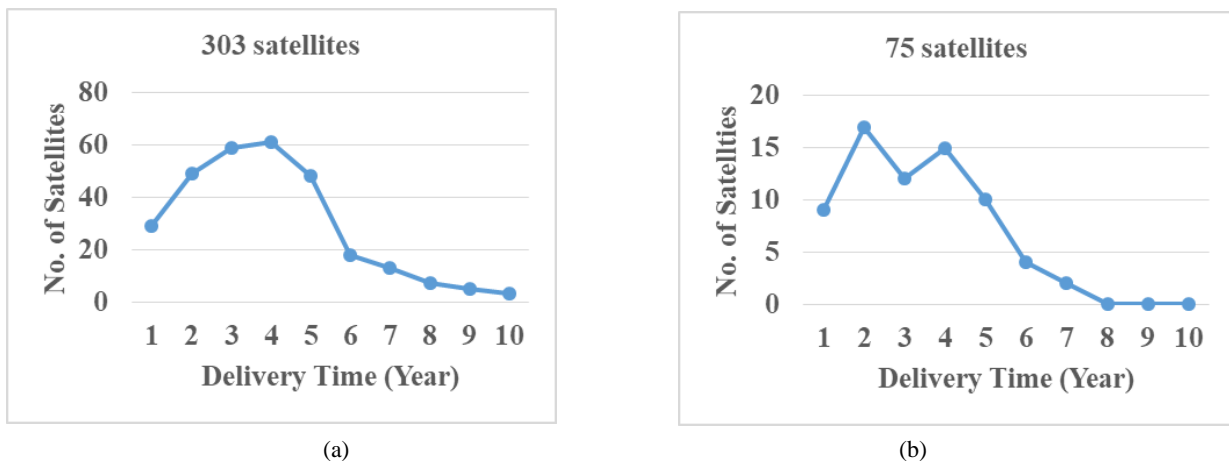


Figure 11. Delivery time of lean satellites for (a) rocket launch and (b) ISS release cases.

systems, so that the requirements are well understood and referred to during the design phase.

It is believed that more time should be spent in performing integrated system-level testing rather than stand-alone sub-system or component functionality testing, especially for a lean satellite project, which typically has a tight schedule (Swartwout, 2013). Performance of a sub-system could vary when tested as a stand-alone system and when it is integrated with other sub-systems, so even after spending a lot of time verifying sub-systems individually, there will be new issues to resolve, which means more time on testing.

One means of overcoming the communication challenges could be to adopt a clearly defined communication means and protocol between the parties. Each party should agree to a medium of communication on which they can be contacted almost anytime and there could be priority assigned to the messages so that the information is shared more efficiently. For instance, lower priority messages could be shared via email, but in urgent cases, the parties should communicate via voice/video call. To ensure that the information is understood properly by the receiving party, proper aids should be used, such as power point presentations with appropriate figures, especially in the cases where a language barrier exists, as in the BIRDS projects.

To overcome a language barrier, one alternative could be to consider overseas manufacturers with common language among the parties. However, additional time in shipment remains a concern, especially if there is a need to send back the components to the vendor for modification or repair. Thus, having a proper communication and response mechanism with the external parties would be more beneficial. Individuals with adequate back up should be identified for translation. In addition, maintaining transparency in communication exchanges is found to be useful aid. As observed in BIRDS-2 and SPATIUM-1 projects, if all the members are copied in the email exchanges, then everyone is aware of the current situation and also, as one or the other member notices the emails received as it arrives, the response time improves accordingly.

To deal with the concern of error in design, especially the PCBs, the obvious recommendation is to

spend more time on the design phase, though it is hard to define what would be adequate time to spend on designing them, or any other hardware. Reserving buffer time while making plans becomes vital. For instance, if it takes about two weeks to fabricate and deliver a PCB, then a minimum buffer time of a week should be added. Similarly, if estimated time to design a board is two weeks then, a minimum one week of buffer time should be allocated. Also, time should be included to double-check the design for possible errors. There should be more emphasis on double-checking, as most of the errors are simple and identifiable if properly re-checked. For an efficient cross-checking mechanism, identifying the person responsible beforehand could make the process smoother. Overall, the idea is to spend an additional day or two in the design phase instead of repeating the whole cycle of designing and fabrication process, which can easily be on the order of weeks or even months.

For constellation projects like the BIRDS program, one effective way of managing the quality of flight models would be parallel assembly and integration of the satellites such that, each team is working on the same step at same time. The person with the most experience should be monitoring the progress of each team, so that any workmanship errors can be identified. It could be argued that the series approach could result in more consistent quality whereby a specialized team works on each of the satellite. But the main purpose of the university projects being education, it is more appropriate to adopt a parallel approach, as all the project members will get the experience and knowledge.

The procurement plan should be developed carefully, and long lead time items, like solar cells, adhesives, etc., that might be space-grade, should be identified as early as possible. The procurement process for those items should likewise be started as early as possible. Adequate budget should be allocated to procure multiple flight components, as a precautionary method. Securing the spare helps in identifying the cause of malfunction found during the test or the flight operation. The spare component can be used as a flat sat model, even if it is not used in actual flight model. Therefore, buying the spare is not wasted money.

## 5. Conclusion

With all sectors of space industry accepting lean satellites as a useful tool, and not just an educational opportunity, it is expected to play a key role in shaping the future of space programs. Faster delivery of satellites would bring more benefits to the space industry and society as a whole.

The delivery time and corresponding mission success information for 361 satellites was compiled for the current study. Analysis of the data showed that the current delivery time statistics are concentrated between two to five years. This indicates that there is a huge opportunity to reduce delivery time, and the target should be less than one year. Interestingly, it was noted that the success rate of the satellite does not necessarily improve as more time is spent in delivery of the satellite. Especially for the university-built satellites, the success rate exhibited a declining trend as the delivery time increased.

The challenges encountered by the satellite projects of LaSEINE and other common challenges were also discussed in this paper. The authors have listed some recommendations deemed to be useful for all future university lean satellite projects, beginning with the selection of launch method, the frequency coordination, and compliance with safety requirements of the launcher, some of the key aspects that a satellite project cannot avoid. Proper management of procurement and maintaining transparency in communications with external parties are other factors to be considered for ease in the development process for lean satellites.

This paper presents an overview on optimal target delivery time for small satellites, issues related thereto, and generic recommendations applicable for all the future lean satellite projects. While following these recommendations might not be adequate to achieve the target delivery time of less than a year, delivery time in small satellite development could still benefit towards that result.

As mentioned in the sections before, the data collection was a challenge to this study. Thus, the data collection method needs to be improved so that more detailed information can be collected for a greater number of satellites. For the future studies, it would be useful to collect specific information on the process of

the satellite development like the tools used for designing and simulations, type of testing and test procedures adopted by the team, the team composition and work distribution, and so on. The project management in itself could have a major impact on the success of the project so it would be interesting to study the approach of each project team. Managing various tests for the satellite in a short time, ensuring timely procurement of components, and making key decisions considering the trade-offs are some of the key aspects that could be considered.

Another short-coming of the current study is that the complexity of the various satellite missions is not taken into account; nor is the great diversity among the satellites. Therefore, future study could also look into categorizing the satellites based on their Level of complexity, and analyzing them separately. Finally, this study only emphasizes university-built satellites, so another aspect of future study would be to put additional efforts in collecting data for private- and government-built satellites. Comparing the statistics and case study among all sectors of the industry would provide a more holistic idea on the development issues. Accordingly, specific recommendations can be put forward to improve overall process of satellite project implementation across all sectors.

## Acknowledgements

The authors would like to thank the project manager and members of the HORYU-IV, AOBA VELOX-III, BIRDS-1, BIRDS-2 and SPATIUM-1 projects for providing valuable information for this research. The authors also express deep gratitude to the faculty and student member of LaSEINE for providing guidance and support in conducting this research.

## References

- Aheieva, K. et al. (2018): Global Mission for 3-D Ionosphere Mapping via CubeSat Constellation, in *Proc. 69th IAC*, Bremen, Germany, October. Paper IAC - 18, B4, 7, 10, x45295.
- Berthoud, L. and Schenk, M. (2016): How to Set up a CubeSat Project – Preliminary Survey Results, in

- Proc. 30th Ann. AIAA/USU Conf. on Small Satellites*, Utah, US. Paper: SSC16-XIII-3.
- BIRDS, LaSEINE, Kyutech (date unknown): “BIRDS Project.” Available at: <https://www.birds-project.com/> (accessed December 20, 2018).
- Cho, M. and Graziani, F. (2017): Definitions and Requirements of Small Satellites Seeking Low-Cost and Fast-Delivery, IAA, 978-2-917761-59-5. Available at <https://shop.iaaweb.org/?q=catalog/3&page=3> (accessed December 20, 2018).
- CubeSat Workshop, Cal Poly State University “CubeSat Developers Workshop”. Available at: <http://mstl.atl.calpoly.edu/~bklofas/Presentations/DevelopersWorkshop.html> (accessed December 20, 2018).
- Debes, J., Howard, N., Harrington, R., Cobb, R., and Black, J. (2011): Rapid Build and Space Qualification of CubeSats, in *Proc. 25th Ann. AIAA/USU Conf. on Small Satellites*, Utah, US. Paper: SSC11-VII-7.
- Donnio, J. P.: “The Satellite Encyclopedia”: Available at [https://www.tbs-satellite.com/tse/online/sat\\_astra\\_1d.html](https://www.tbs-satellite.com/tse/online/sat_astra_1d.html) (accessed April 4, 2018).
- Dubos, G. F., Castet, J.-F., and Saleh, J. H. (2010): Statistical Reliability Analysis of Satellites by Mass Category: Does Spacecraft Size Matter?, *Acta Astronautica*, Vol. 67, pp. 584–595.
- EOPortal, ESA “Earth Observation Portal”. Available at: <https://directory.eoportal.org/web/eoportal/home> (accessed December 20, 2018).
- Faure, P., Tanaka, A., and Cho, M. (2017): Toward Lean Satellites Reliability Improvement Using HORYU-IV Project as Case Study, *Acta Astronautica*, Vol. 113, pp. 33–49.
- Guo, J., Monas, L., and Gill, E. (2014): Statistical Analysis and modelling of Small Satellite Reliability, *Acta Astronautica*, Vol. 98, pp. 97–110.
- Honghao, W., Huiquan, W., and Zhonghe, J. (2015): Bipartite Graph-Based Control Flow Checking for COTS-Based Small Satellites, *Chinese J. of Aeronautics*, Vol. 28(3), pp. 883–893.
- Johnson, M. A. et al. (2017): Increasing Small Satellite Reliability – A Public-Private Initiative, in *Proc. 31st Ann. AIAA/USU Conf. on Small Satellites*, Utah, US. Paper: SSC17-WK-03.
- Kelso, T. S. “Celestrak”. Available at: <http://celestrak.com/satcat/boxscore.php> (accessed April 4, 2018).
- Khan, A., Maeda, G., Masui, H., JGMNB Project member, and Cho, M. (2015): Five-nations CubeSat Constellation; An Inexpensive Test Case for Learning and Capacity Building, *3rd IAA Conf. on University Satellite Missions and CubeSat Workshop & International Workshop on Lean Satellite Standardization*, Rome, Italy, November.
- Klanowski, P. C. “Satellite News Digest”. Available at: <http://www.sat-nd.com/> (accessed April 4, 2018).
- Krebs, G. “Gunter’s Space Page”. Available at: <https://space.skyrocket.de/index.html> (accessed December 20, 2018).
- Kroeker, E., Ghosh, A., and Coverstone, V. (2016): Building Engineers: A 15-Year Case Study in CubeSat Education, in *Proc. 30th Ann. AIAA/USU Conf.*, Utah, US. Paper: SSC16-XIII-07.
- Kulu, E. “Nanosats Database”. Available at: <https://www.nanosats.eu/> (accessed April 4, 2018).
- Langer, M. and Bouwmeester, J. (2016): Reliability of CubeSats - Statistical Data, Developer's Belief and the way Forward, in *Proc. 30th Ann. AIAA/USU Conf. on Small Satellites*, Utah, US. Paper: SSC-X-2.
- Monowar, M., BIRDS Project Team, and Cho, M. (2017): BIRDS Project: Development and Operation Summary of a CubeSat constellation Project, in *Proc. 68th IAC*, Adelaide, Australia, September. Paper: IAC-17, B4, 9- GTS.5,3,x40295.
- Pradhan, K. K. et al. (2018): BIRDS-2: Multi-Nation CubeSat Constellation Project for Learning and Capacity Building, in *Proc. 32nd Ann. AIAA/USU Conf. on Small Satellites*, Utah, US. Paper: SSC18-WKIII-04.
- Seri, Y., KIT Satellite Project, Masui, H., and Cho, M. (2013): Mission Results and Anomaly Investigation of HORYU- II, in *Proc. 27th Ann. AIAA/USU Conf. on Small Satellites*, Utah, US. Paper: SSC13-X-8.
- Sinclair, D. and Dyer, J. (2013): Radiation Effects and COTS Parts in SmallSats, in *Proc. 27th Ann. AIAA/USU Conf. on Small Satellites*, Utah, US. Paper: SSC13-IV-3.

- SmallSat, Utah State University “Small Satellite Conference”. Available at: <https://digitalcommons.usu.edu/smallsat/> (accessed December 20, 2018).
- Swartwout, M. (2013): The First One Hundred Cube-Sats: A Statistical Look, in *JoSS*, Vol. 2, No. 2, pp. 213–233.
- Swartwout, M. and Jayne C. (2016): University-Class Spacecraft by the Numbers: Success, Failures, Debris. (But Mostly Success), in *Proc. 30th Ann. AIAA/USU Conf. on Small Satellites*, Utah, US. Paper: SSC-XIII-1.
- Swartwout, M. (2018): Reliving 24 Years in the Next 12 Minutes: A Statistical and Personal History of University-Class Satellites, in *Proc. 32nd Ann. AIAA/USU Conf. on Small Satellites*, Utah, US. Paper: SSC18-WKVIII-03.
- Wertz, J. R., Everett, D. F., and Puschell, J. J. (2011): *Space Mission Engineering: The New SMAD* (1st ed.), California, US: Microcosm Press, p. 3.