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University CubeSat Project Management for Success

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ABSTRACT

CubeSats have been developed by many different institutions since they were introduced by California Polytechnic State University and Stanford University in 1999. Given the 40% failure rate of university missions, it is important to discover what project arrangements may give the CubeSat the best chance of success. The aim of this paper is to offer those wishing to start a CubeSat program some indications of what successful project management at a university may look like. This paper provides case studies of 3 universities who have launched more than 4 satellites: University of Michigan, the Montana State University, and Aalborg University in Denmark. The information was gathered by asking supervisors from these teams a series of questions relating to project management. These included team structure, continuity, how the students organize themselves, how much of the work is embedded in the curriculum, how new students were integrated and how documentation was used to manage the project. The different methods of organization used in the different programs were described with their unique features. After this, both the variation and the common elements were identified. It is hoped that this research will contribute to successful CubeSat projects in universities worldwide.

Keywords

CubeSat, Success, Project Management, Higher Education, Lessons Learned, Universities.

INTRODUCTION

CubeSats were introduced by Robert Twiggs from Stanford and Jordi Puig-Suari from California Polytechnic as an educational project for engineering students[1]. The aim was to give students a practical experience of designing, building and testing a real satellite. The CubeSat standard has since spread around the world and is now used not only by universities, but by space agencies and industry as well. The latter can draw upon funding, full time staff and standard industry project management techniques. Developing a CubeSat in an educational context frequently means working outside of these support structures.

Previous Work

A summary of the educational reasons why CubeSats are interesting to universities includes: the opportunities to innovate, to experiment, to collaborate and to get practical experience of building spacecraft [2]. Several Universities who are already using 'Problem-Based Learning' philosophies have adopted CubeSats as a project which equips students with technical skills, develops their ability to collaborate and their program management skills [3–5]. Other Universities use a CubeSat concept to introduce new concepts like circuit design, in an exciting, practical way [6]. Other work has involved looking at knowledge building, communication and cultural aspects, and challenges faced by students building a CubeSat ground station [7]. The value of a CubeSat program has been assessed quantitatively in terms of improvement related to five key learning objectives [8]. Research in tandem with industry has established that CubeSat projects provide students with the experience of meeting challenging schedules, managing subcontracts, motivating a team and interacting with a customer which prepares them for work in the aerospace industry[9]. Despite the launch of almost 300 academic CubeSats at the time of writing[10] and whilst it has almost become a rite of passage to write a 'lessons learned' paper on a university CubeSat mission, less has been written on the subject of the project management set up of a CubeSat project within an academic context.

Most 'Lessons Learned' papers cover technical aspects, and some also include some project management and lessons learned [11–14]. For example, a review of small satellite trends 2009-2013 found that university satellites take an average of 3.8 years to develop (compared to 1.7 years for commercial entities [15]). Some detailed advice on less frequently covered topics such as integration can also be found [11,16]. Other advice to future CubeSat program leaders includes: aiming for a short flight duration (< 90 days), leaving sufficient mass and power margins and performing rigorous functional and environmental testing as well as pre-flight demonstrations[17]. Venturini et al. [18] have performed an excellent review of mission assurance aspects and invaluable advice is provided in this work, including many examples of anomalies. For those needing practical advice on aspects of the NASA CSLI initiative, CubeSat 101[19] gives a thorough preparation. However, there has been little work on project management of student cohorts.

In previous work, Berthoud and Schenk carried out a survey among 40 CubeSat groups, between September 2015 and March 2016[20]. This information was used to illustrate trends of initial university CubeSat projects The themes which emerged from these groups placed an emphasis on: planning, learning from other groups, student continuity, documentation and project management, integrating the project within the curriculum, mentoring, software development, simplicity and testing. Experience gathered from these groups shows that at the beginning of a project, time needs to be spent on the planning and setting of objectives and requirements. This has to be balanced against maintaining motivation and enthusiasm in the students. Continuity with a transient unpaid workforce is a challenge, with groups using graduate students or keeping the program to two years in duration as solutions, as well as documentation and innovative project management techniques such as spiral and AGILE models used in the software industry. Given the level of challenge posed by these issues, there is scope for further exploration of management models which lead to successful and sustainable outcomes. This study was initiated in order to provide those starting out on the university CubeSat journey with case studies of three teams who have successfully launched a series of CubeSat missions.

NOMENCLATURE

For the purposes of this paper, we define a **university-clas**s space mission as one where the training of the students was as least as important as the other science/technology objectives. In other words, students were involved in major design decisions, assembly, integration, test and operations. They were not merely observers but active participants in the process.

Not every mission that originates at a university is a university-class mission, nor does exclusion from the category imply that a mission lacked educational value. Also, though we use the term "university", this category covers every type of academic program, from K-12 to postgraduate training.

Furthermore, we observe that not all academic programs are equal: a small school building its own program from scratch does not have the same prospects as a top-tier university operating under the support of its national government. We attempt to distinguish between these programs by defining subcategories of university programs: **flagships** are the universities that are designated by their national governments as being a focal point for the development of national capabilities in spaceflight; these schools enjoy the resources of national attention, with the challenges that come with high expectations of performance. By contrast, **independent schools** are pursuing a spacecraft program out of the specific interests of the participants. As will be shown, we further subdivide the independents into **prolific** (those that have flown 4 or more separate missions) and **regular** independents.

In this paper, we are interested in the experiences of the prolific schools, to provide guidance to the regular independent schools, so that more of them can become prolific. By the end of 2018, 428 university-class missions had been flown, of which 291 had been CubeSats (Figure 1). As indicated in Figure 1, during the

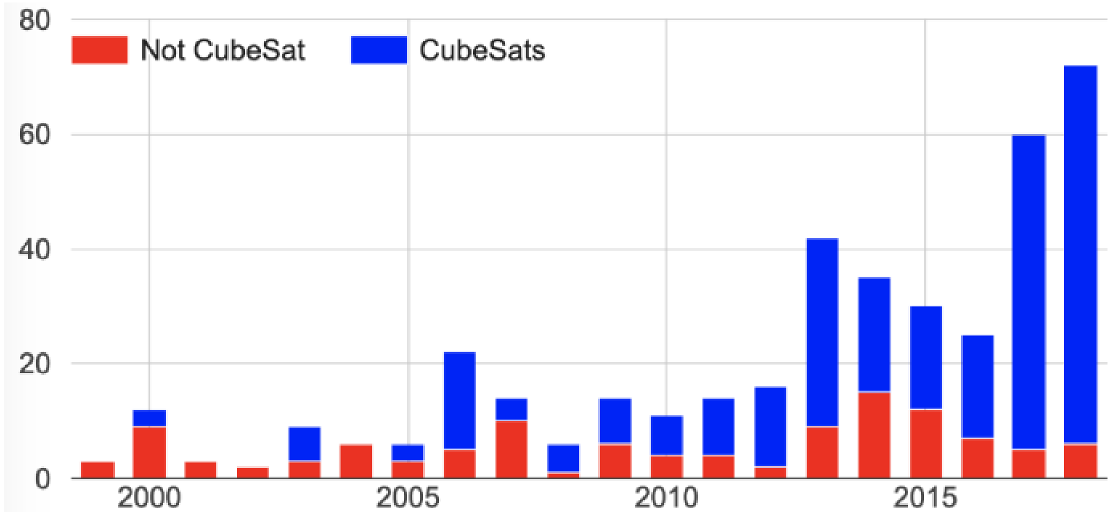

Figure 1: Count of University-class missions launched each year since 1999

past decade, the majority of university-class missions have been CubeSats[21]. CubeSats are the platform of choice for new academic programs; for these reasons, our paper emphasizes CubeSats and CubeSat mission success.

MEASURES OF SUCCESS

Within the framework of an academic program, we consider two measures of success: the performance of an individual space mission, and the sustained performance of the university[22]. Certainly, the former significantly impacts the latter. But the latter is, in our opinion, the goal of an academic CubeSat program: developing and flying multiple spacecraft over a period of years, and thereby providing educational opportunities to multiple "generations" of students.

With regard to this latter measure of success, we note that the 428 missions were developed by 192 academic programs. This is an average of 2.2 missions per university. However, as shown in Figure 2, more than half (106 of 192) of the programs have flown only one space mission each, and three quarters (148 of 192) have flown only one or two missions.

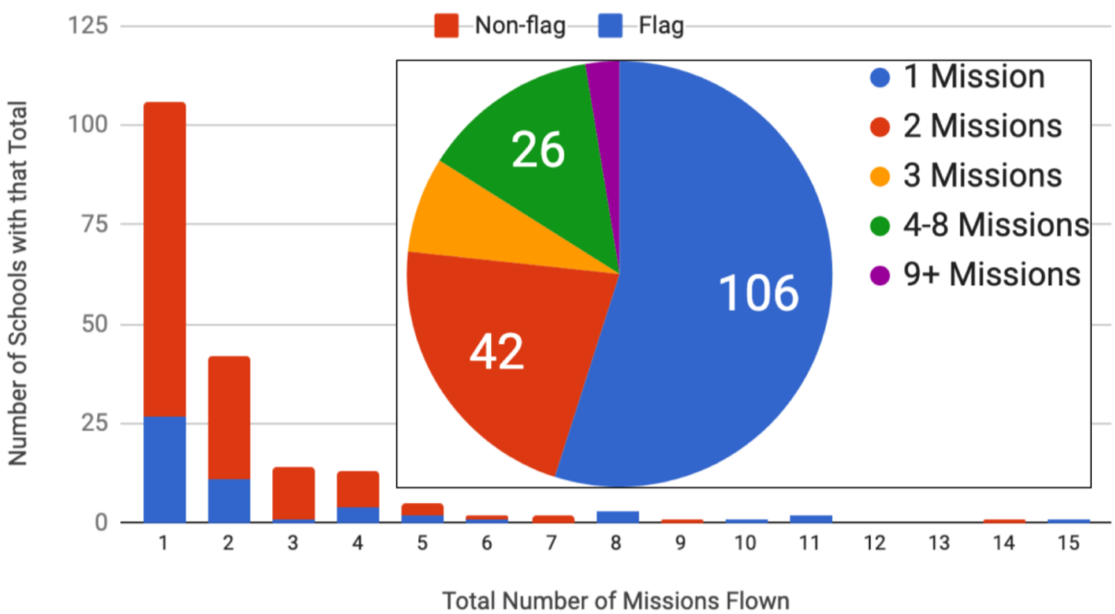

Figure 2: Count of academic programs that have flown a given number of missions. For example, a school that has only flown one mission is counted in the first column. A school that has flown three missions is counted in the third column (but not in the first two columns). **Inset: Count of schools that have flown a number of missions**.

Regular independent programs are strongly represented in the count of 1-2 missions. In terms of total count, nearly half of all university-class missions ever flown (197 of 428) were produced by just 31 universities worldwide, each of whom has flown at least 4 missions. We use the 4-mission threshold as our definition of **prolific** universities. As can be surmised from Figure 2, there are 17 prolific independent universities.

At the risk of repeating, it is worth noting: of the 140 independent schools to launch a spacecraft, 79 of them (56%) have only flown once, and another 22% (31 schools) have flown only twice. How can a university program "graduate" from the ranks of the one-and-done schools to the prolific independents? That is a focus of this paper; for now, we will observe that learning from failure appears to be an important part.

In Figure 3, we tabulate the mission status of every university-class mission flown. We use a 0-5 scale, where 0 indicates that the mission was never released on-orbit (i.e., launch failure) and 5 indicates that all mission objectives were accomplished. As indicated in Figure 3, about one-third of all university-class missions do not meet their minimum mission objectives.

Next, we observe only the prolific independent universities, tracking their mission success in five-year increments beginning in 1999.

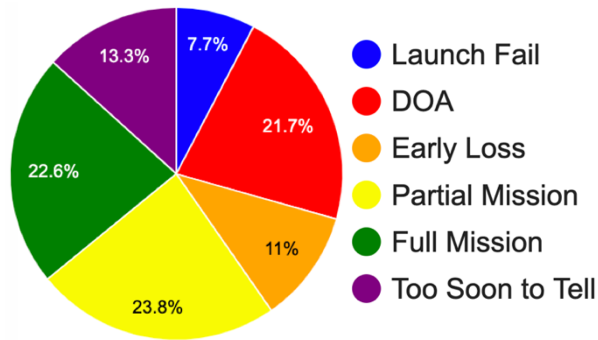

Figure 3: Mission Status, all university-class missions

As shown in Figure 4, the success rates of prolific schools has improved. By contrast, the failure rates of the regular independents has exceeded 33% across every 5-year block (Figure 5); it was only below 50% in the most-recent block, but that is pending the outcome of a host of missions launched in late 2018.

We draw two conclusions: first, that the success rate of any first-time program is quite low. Second, that the difference between prolific and regular independent programs appears to be a matter of perseverance and learning from mistakes, rather than initial success. Therefore, we believe the prolific universities could provide useful general lessons learned that can be applicable to other academic programs.

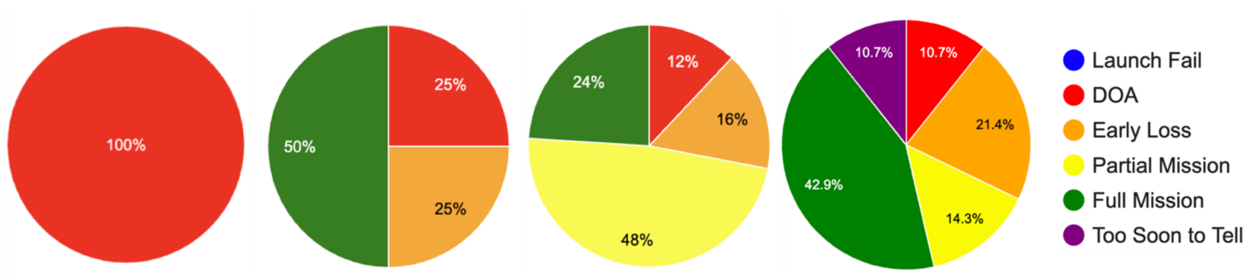

Figure 4: Mission Status, prolific independent universities in 5-year cohorts. From left: 1999-2003, 2004-2008, 2009-2013, 2014-2018

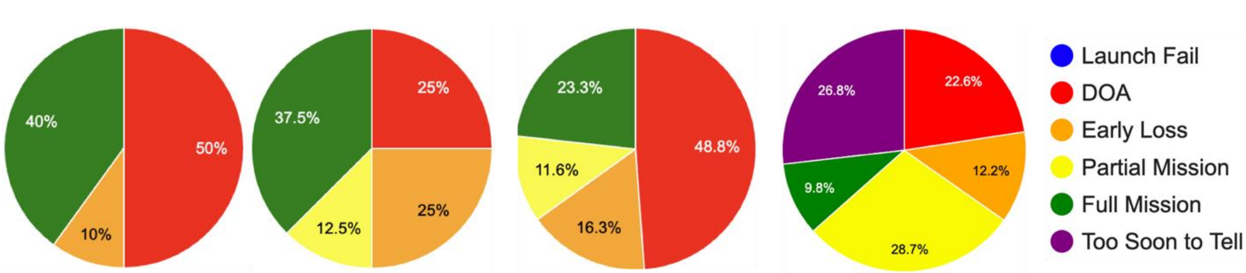

Figure 5: Mission Status, regular independent universities in 5-year cohorts. From left: 1999-2003, 2004-2008, 2009-2013, 2014-2018

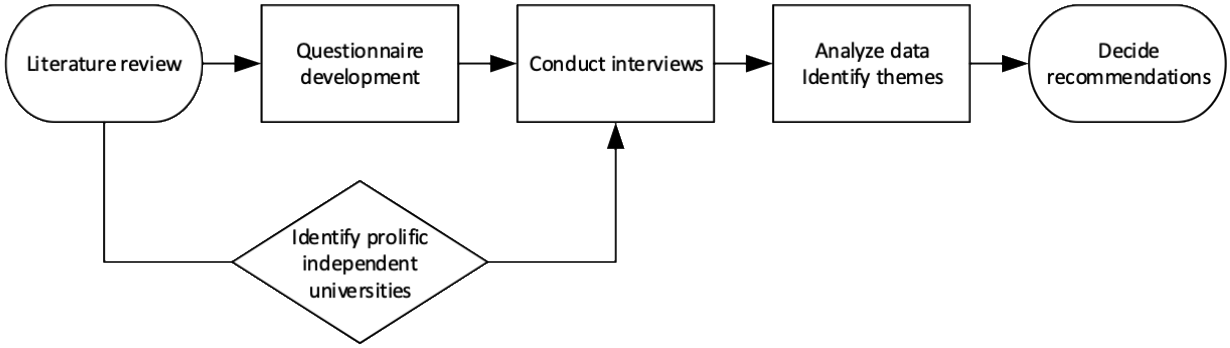

Figure 6: Workflow for this research

Paper Overview

The background section has covered an introduction to previous relevant work, whilst the materials and methods section describes the process of gathering the data. The results section is split into information gathered for each of the three case studies. For each of these the major question areas are addressed. The discussion examines underlying themes and the commonalities and differences between the projects. The conclusions summarize the key points and lessons learned.

MATERIALS AND METHODS

The workflow for this research is illustrated in Figure 6. Initially a literature review was conducted to identify useful previous studies. This work is described in the previous section. This research also helped the development of a questionnaire that was used to interview the Universities How were the Universities in this paper selected? In previous work[23], 12 independent schools were considered to be prolific. Since that publication, the number has grown to 17 (see **Appendix B**). Achieving significant numbers of CubeSat builds without government investment is an indication of perseverance, internal capabilities and a successful project management structure. As such, these universities are of particular interest to any school or university running, or wishing to run, a CubeSat program. An insight into these CubeSat approaches offers the community a unique opportunity of seeing into the internal structure of successful programs. This paper provides case studies of three of these groups. The case studies come from groups in the US and Europe, including the University of Michigan and Montana State University in the US, and Aalborg University in Denmark. The groups have all built 1U to 3U CubeSats with a mix of Technology Demonstrator and/or Science Experiment payloads. The information was gathered by asking the CubeSat program supervisors for each university a series of questions relating to project management. The set of questions used are given in **Appendix A**. This took the form of a semi-structured interview where follow up questions could be asked for elucidation of some of the ideas. The questions asked were designed to tease out some of the practical project management issues that those setting up a CubeSat project in a university context will face. These included team structure, continuity, how the students organize themselves, how much of the work is embedded in the curriculum, how new students were integrated and how documentation was used to manage the project. Supervisors were interviewed instead of students, as they have a continuity of view over the length of the program. The interviews were then thematically analyzed.

RESULTS OF CASE STUDIES

1. AALBORG UNIVERSITY, DENMARK

Context

Aalborg University (AAU) is a Danish public university founded in 1974 with campuses in Aalborg, Esbjerg, and Copenhagen. It has 20000 students with 3800 staff across the three campuses. Aalborg University differentiates itself from the older and more traditional Danish universities with its focus on interdisciplinary, studies and a pedagogical structure centered on real life projects delivered through a problem-based learning philosophy. The Danish degree system consists of 3-year bachelor's, 2-year master's and 3-year PhDs. Aalborg started building its first CubeSats in 2001 and is currently building its 6th CubeSat, AAUSAT-6, which will be launched in 2021. The aim of the project from the supervisor's point of view is for the students to become better engineers and because they enjoy spacecraft design. The projects are always kept to 1U for simplicity and for financial reasons and to keep them within a shorter timescale. They are aimed at 2 years in length to keep the same students involved, but sometimes due to launcher delays can stretch to 3 to 4 years. The launches are financed partly by the university but also with donations from industry.

The CubeSat projects are driven from the Automation and Control section of the Institute of Electronic Systems. This institute has approximately 170 staff and 600 students. The CubeSat projects have 2 staff spending 10-20% of their time on the project. Students come into the project typically in their 2nd year of a bachelor's degree with a curricular project related to the design and prototyping of some aspect of the CubeSat e.g.: a part of the power subsystem or an antenna design. These projects have to fit within the project structure which consists of a half year project which takes up 50% of their time (the rest will be spent on courses) with reporting half yearly and an emphasis on developing their building/craftsmanship skills, as well as their research/design work. . The curricular projects have their emphasis on designing and prototyping to ensure something works, but occasionally the payload may be a bit more exotic and employ untested techniques. At any one time there can be between 5 and 20 students working on the satellite with a mix of 2nd to 5th years. Up to 5-8 staff from other disciplines outside the Electronic systems department have supervised curricular projects in e.g.: software or mechanical engineering. No PhD students are involved, nor are any research assistants or other paid staff. The students are typically half from the bachelor's and half from the master's degree. Mechanical and Electrical technicians can be requested for particular tasks to be achieved in the institute workshops, but none are dedicated to the project. The curricular projects typically involve the first stages of the design up to a prototype, but for the build and test phases, it is up to the students to run the project as an extra-curricular project. There are some students who come in just for the curricular project, others who come in and stay for the duration of the satellite build. Some of the students work 24/7 getting the satellite ready and others may participate for just a few hours occasionally. Some students may choose to do projects on different aspects of the satellite, as they progress through their degrees. The problem-based learning approach facilitates this process.

Leadership and Communication

The students are encouraged to take full responsibility for the satellite. The philosophy of the supervisors is that if they are going to spend a significant proportion of their own extra-curricular time building and testing the satellite, then they need to have ownership of the project. This means that they make all the major design decisions. There is no student society running the satellite projects, but just an informal structure with points of contact for each subsystem. The supervisors have never been to a launch as they consider that the students are responsible and can take the project forward themselves, with appropriate guidance. There is no direct leadership structure for each satellite, although frequently a natural leader for each subsystem emerges as the project progresses. Competitive teams are not used as a way of progressing the project, more a spirit of collaboration is encouraged. As part of the Aalborg philosophy of developing maker skills, students are encouraged to make the whole satellite, buying in as few pre-made subsystems as possible. They do all the soldering, building and testing themselves. They have support from local industry who provide some knowledge and facilities e.g.: a shaker table and a crash course on space soldering. They hold meetings once a week with the supervisors and other sub-meetings are sometimes organized at this meeting. The meetings are held after hours in order that there are no clashes with the curriculum. The students have access to a space laboratory and to their own workspaces very near to the supervisors' offices and are encouraged to ask questions at any time.

Transfer of Knowledge

Reviews are held, but there is no strict review process. For curricular projects, students have to prepare reports. They typically work in groups on a project, each taking an aspect of a subsystem e.g.: for power, one may take the charging system, one may take power distribution and another the solar input system. But overall as this is an extra-curricular project it is challenging to ensure that the students document their work, as they want to be building and testing, not documenting. Students are encouraged to record what they have done in the critical schematics and software which are all stored in one place in a GitHub™ repository. Here they also have access to all the previous projects. More rigorous documentation was required of the students during AAUSAT-4 and AAUSAT-5 which were supported by the European Space Agency 'Fly Your Satellite' scheme [24]. However, students were unwilling to prepare this level of documentation in their spare time. Key schematics and source codes were regarded as essential, but subsystem analysis documents and hardware descriptions soon superseded the documents. Instead of documentation for software such as user manuals, commenting of the codes via software such as Doxygen™ was used instead. All students who are passing on their work to new students are willing to spend time to explain the project. Occasionally those who have already graduated return on an evening to explain or solve a problem. Students sometimes use social media software to communicate, but this is usually to send announcements and is rarely about technical issues. They are more likely to sit together in the Lab or round a table to solve a problem. There is one single source means of communication and that is the GitHub™ repository which has excellent version control. Over the evolution of the CubeSats, the group has standardized the mechanical, electrical and communications interfaces in order to promote flexibility and independence of the modules. For example, the modules need to be mechanically PC/104 compliant, all communication is through a Canbus using a CubeSat Space Protocol overlay and one or two power channels are allocated for each subsystem. This is described in a document, and there is also the Launcher interface document which also must be adhered to. A 'flatsat' with these interfaces is used for end-to-end hardware testing.

Lessons learned

For those starting out, the Aalborg supervisors recommend to keep it simple, to reach out to the community and invite someone with some experience to visit to advise, to encourage the students to build their prototypes fast and often, to use any means possible to enable testing, such as High Altitude Balloons and to give back to anyone who helps them by giving talks at local industry places, radio amateur societies and similar.

2. MONTANA STATE UNIVERSITY, US

Context

Montana State University (MSU) is a public land-grant research university in Bozeman, Montana. MSU offers baccalaureate degrees in 51 fields, master's degrees in 41 fields, and doctoral degrees in 18 fields through its nine colleges. More than 16,900 students attend MSU and the university faculty number 602 full-time and 460 part-time members of staff. The US degree system consists of 4-year bachelor's, 2-year master's and 4-5 year PhDs. MSU started building its first CubeSats in 1999 and is currently building its 10th and 11th CubeSats, IT-SPINS, which will be launched in 2021 and REAL, for launch in 2023. The aim of the program from the supervisor's point of view is threefold: to conduct focused scientific missions; experiential training of university undergraduate and graduate students and to further the development of small satellite capabilities. As small satellite technology was not well developed when MSU started building satellites, it was an interesting technical challenge to make them more sophisticated. The projects vary from prototyping to payloads to satellites of 1 to 6U in size. Most projects take 2-3 years and some involve buying in of components, depending on the primary purpose of the project, who the funder is and the schedule. The launches are financed by grant funding or as part of NASA's ELaNa scheme.

Participants

The project is cross-disciplinary involving students and faculty campus-wide but is administered from within the Physics Department. Lead Faculty and the Space Science and Engineering Laboratory (SSEL) staff all have appointments through the Physics Department. However, different departments in the university have also participated at different times, depending on the project, including graphic design, all engineering departments, computer science, math, biology and chemistry. At any one time typically 2-3 full time staff engineers and 2-4 faculty members (small percentage of their time) will be working on the project. The full-time staff engineers are paid by grant money. The student head count at any given time has varied from 3 to 30 students. The project leaders suggest that for their projects, between about 10 and 15 students are optimum in order for students to engage in a substantial manner. The leaders have found that a substantial engagement promotes ownership of the project. Once they have demonstrated their commitment, undergraduate students receive hourly wages for direct project involvement that does not otherwise result in academic credit hours. Typically, 1-2 PhD candidates and 1-3 MSc candidates will be working on the projects at any one time. PhD students are typically Physics PhDs who are planning to become experimental space scientists. Their hardware involvement is frequently associated with conducting project management and development oversight, development of a scientific payload, as well as satellite operations for the retrieval of science data after launch. PhD students generally focus their specific thesis research on analysis, and interpretation of measurements from operational and past missions and the publication of these results. In that way, earning their degree is not dependent upon the successful launch and operation of their hardware project. Colleagues from government labs, other universities, and industry also serve as reviewers for most major milestone reviews or act as "red team". A strict system of reviews is run (albeit cut down compared to industry spacecraft development) as students need a firm knowledge of what it takes to run a program, so it is helpful for them to gain a knowledge of system engineering.

Leadership and communication

For government-funded scientific missions, the Principal Investigator (usually an MSU staff member) is the ultimate lead; with students serving as leads at the subsystem levels. For more student-based projects, typically the project lead might be a graduate student or a very senior, highly experienced undergraduate student. In these instances of students serving as project leads, the student is closely mentored and supervised by senior staff. Full time staff members are constantly mentoring students, but students run the meetings. Frequent all-hands meetings are held to aid progress, typically weekly during the academic year. But because the program is being run 12-months of the year, during summers the weekly project meetings are supplemented with all-hands stand-up meetings at the beginning of each workday. During the summer, subsystem meetings are also generally held on a weekly basis.

Transfer of Knowledge

In order to transfer knowledge everything is highly documented and kept accessible and succession typically passes from the graduating student to the individual who has been working most closely with the departing student who also has demonstrated capability. The succession of students is strongly aided by the laboratory philosophy of having individual students involved for several years, resulting in a continuous ladder of experienced up-and-coming students. The project has curricular form sometimes for example, through senior capstone projects or undergraduate research credits. Because the program is structured as an extracurricular research laboratory, SSEL staff do not typically teach formal courses. Embedding projects into the curriculum might be completely appropriate for an Aerospace Engineering degree program but is more challenging for a Physics program. The majority of the work on the projects is extra-curricular. The relatively small fraction of students who persist in being involved in the project, really want to be there and they recognize that documentation is needed and are usually willing to prepare it. During academic year, all students have courses at different times, so students are working on their own schedule except for the all hands meeting or subsystem meetings. They are encouraged to participate at a level of 10-15hrs a week (with flexibility for exams). Typically, 50% or less will participate for several years. During summer, there are core hours for involvement as for most professional workplaces. In terms of version control, software is maintained through a version control system from CDR onwards, but other project documents are also stored on GitLab which has a very useful issue tracking facility. SSEL has a laboratory with 12 workstations and a server, the ground station used mostly for the more student-focused projects. Industry documentation such as interface documents are produced for each project and the project is not allowed into the lab until documentation says that it is ready.

Lessons Learned

Getting participants to document almost everything is essential and also most problematic. The supervisor believes that having a system engineering approach right from day one is critical. They encourage staff and students to ensure that they have developed a full mission requirements document library. This document set starts with the succinct mission statement and sets down all top-level requirements which then are flowed down to specific implementation requirements and finally to implementation itself. Once in hand, this document suite controls what is being built. It places clamps on requirements creep, and sets up road blocks to statements like: “What if we just....? Why don’t we add ....? Wouldn’t it be neat if we...?

The supervisor recommends modelling the entire satellite in as much detail on the computer as possible (e.g.: electrical schematics, CAD and software) before going into the laboratory. Although breadboarding and proof of concept work can also useful and necessary. A rule of “4 hands, 4 eyes”, are used on flight hardware. The team of two are constantly checking each other at every step, as well reading procedures and documenting step-by-step progress. A flight-like engineering model to work on any problems on the ground is absolutely invaluable for testing after launch. Testing has been found to be critical: ground testing, day in the life testing, subsystem testing, hardware in the loop testing etc., all hardware should be tested as soon as it is finished or received.

3. UNIVERSITY OF MICHIGAN, US

Context

The University of Michigan is a public research university in Ann Arbor, Michigan. It has 6200 staff and 45000 students. The university started building CubeSats in 2007. The University of Michigan runs two CubeSat programs based in two different laboratories. This study coves the Michigan eXploration Laboratory (MXL), which has 6 satellites in orbit and has delivered parts for several others. The aim of the project from the supervisor's point of view is twofold: to develop and demonstrate new methods for space exploration, utilization and stewardship, and to provide an educational/motivational tool for students.

Participants

MXL is based in the Aerospace Engineering department, with one full-time faculty member leading the student team. MXL operates as a research laboratory, where students are recruited and work out of the lab. Some work is done in collaboration with various student organizations on campus, but the main responsibility for completion rests within MXL. Several funded graduate research assistants form the backbone of the project team, assisted by several undergraduates paid hourly. However, the number of active and funded students is fluid, based on the phases of the project and available research support. Generally speaking, students begin as volunteers, and as they demonstrate their commitment and capabilities, they shift into roles of greater responsibility. Some class credit is available for parts of the project. Ideally, for each task there is one student leading the work, with another in training, and another 1-2 students available as backups as exams and other schedule constraints arise. In addition, 2-3 PhD students are indirect participants, serving as project advisors (and institutional memory) and emergency help. However, owing to the different expectations on MS and PhD students, the PhD students must focus their efforts on research outside of the CubeSat build project, and thus the work falls to MS graduate students. When available, program alumni serve ask external reviewers for the project. The supervisor has worked in university spacecraft projects where the work was all course-based and where it is all research-based; both have limitations in finding the balance between student recruiting/training, retention and completing the work.

Leadership and Communication

The MXL director leads all CubeSat missions, although two graduate students are responsible for most of the day-to-day activities: the project manager and chief engineer. The MXL director selects those students. As noted above, there is typically a primary student and an "understudy" for each of these roles, so that a student is always prepared to step into the leadership role. The PhD students help with the transition process. Still, managing transition proves to be a challenge.

Transfer of Knowledge

MXL uses Redmine for reporting and documentation, and Slack for more immediate communication. Weekly standup meetings are held among the primary participants to manage the project; these are daily during the summer. At the end of each semester, a report is generated to capture the major concepts, plans and progress for the laboratory. Major milestones are documented via a "tech memo". Redmine is used for the day-to-day tasks and updates. Google documents are also used. MXL places a strong reliance on the use of ICDs. Version control is managed through commonly available applications. MXL has had to manage knowledge transfer over 12 years and several cohorts, and that is mainly managed through the understudy process discussed above; ideally, a student starts early in the academic career as an apprentice, gaining knowledge and capabilities over time before they have to take on a leadership role. While it would be ideal for key skills/technical knowledge to be mapped to specific courses, this is not done; as with most other universities, the engineering curriculum is not constructed to directly support CubeSat design, integration, test and/or operations.

DISCUSSION

A discussion based on each of the aspects in the interviews is covered and then an attempt is made to synthesize the information in order to produce some characteristics. The information is qualitative, but there are enough common aspects between the case studies to begin to start this process. This work is necessarily limited by its focus on only 3 case studies. It is questionable whether it is possible to begin to construct an empirical formula for a successful program based on only three case studies. These programs are all extremely successful in their own contexts and it is not necessarily possible to mix and match aspects of each program, as there may be correlation between some of the aspects. For example, Aalborg always build a 1U satellite and always from scratch, they prefer to keep to 1U in order to enable this building from first principles, to limit scope creep and costs. The larger more complex CubeSats built by the other Universities may necessitate buying in of components to achieve a launch date or for specialist equipment. The themes follow those under which the results have already been grouped: context, participants, leadership and communication, transfer of knowledge and lessons learned.

Context

In terms of the contexts of the Universities, the sizes of the Universities vary from 17000 to 52000 students and vary from the more traditional to the more progressive. All of the Universities offer programs through the spectrum from Bachelor to PhD. The CubeSat projects have all been going for more than 10 years. The motivation to build the CubeSats from the staff all include experiential training of students and enthusiasm for space exploration, but may also include other aims, depending on the discipline. The CubeSats are all housed in different disciplines, from physics to electronics systems and aerospace engineering. But all had their own laboratory as a focal point for students to build and test their satellites. All also had their own ground station for operation of the satellites. The size of the CubeSats varied from 1U to 6Us, but all programs started with simple 1U satellites. All programs aim for a 2-3-year turnaround for each project which sometimes stretches to 4 years due to launch delays. Some of the projects involve buying in of components, others build from scratch. Funding for components and launch comes variously from research funding, industry donations and internal university finances and sometimes a mixture. Both of the US Universities have benefited from the NASA ELaNa scheme and Aalborg has partaken in the ESA ‘Fly Your Satellite’ program, both of which offer free launches; however, they have not always done this and have sometimes had to find their own funding for launches.

Participants

All the case studies have 1 or 2 central staff who look after the CubeSat program, typically spending 10-20% of their time on it. Some have more staff who are funded by research grants to work on the CubeSats in a professional context. Other staff participate on a year to year basis depending on the project. The numbers of students on the projects vary from 3 to 40 at one time. Typically for all the projects, the numbers of students dwindle as the CubeSat progresses to the testing and launch preparation stage where large numbers of hours and focus are needed. The students involved offer anything from a few hours per week to full time round the clock participation during the flight preparation and initial operations. They can be early years undergraduates, but all the case studies have higher level master's students leading the projects. One common feature of all the Universities studied here the fact that the more experienced students are assisted by one or more students at a lower level in their studies. This enables knowledge to be passed on from year to year. Students in all Universities seem to be quite willing to spend time passing on their knowledge. In two of the case studies, PhD students in the early years of their PhD are involved and are a good way of stewarding the institutional knowledge of the project. All the case studies involve external participants in some way, sometimes as reviewers (alumnae are often requested to return), sometimes as sponsors, or for help in training students e.g.: in soldering. The question as to how much of the project is part of the curriculum is a challenging one: Aalborg offers projects on the CubeSats as part of the course and these typically involve designing and prototyping, but then the rest of the project is extra-curricular. Montana and Michigan have curricular projects and then involve students in an extra-curricular capacity, paying volunteers who have demonstrated commitment whenever they can.

Leadership and Communication

None of the case studies examined have a student society running the program, although this has been seen to be successful in other Universities, such as CalPoly. But a key common point is that the students are encouraged to take full responsibility for the satellite. Ownership of the project motivates the students to spend their extra-curricular time building and testing the satellite, having a short turnaround time also helps with student motivation. In all the Universities, the students are allowed to make key design choices, but are closely mentored by staff. All the case study Universities have a weekly 'standup' progress meeting to review the week's work and to plan next steps. These are frequently outside of curricular hours in order that timetable clashes can be avoided. Subsystem meetings are held by the students in addition to the weekly meetings. In the summers, more frequent meetings are held. Sometimes the students who lead are picked by the supervisors and sometimes they emerge naturally, but there is no consistency in how the projects are led. Some are also led by Principal Investigators within the Universities.

Transfer of Knowledge

All participants mentioned that transfer of knowledge, and especially documentation, is a real challenge in a university environment. Whilst the Universities studied here had good systems for passing on knowledge through students teaching each other, there was no consistency in either their reviewing system or adherence to documentation. There was agreement that, whilst it is ideal to have a proper system engineering process, it can be difficult to motivate the students to prepare documentation when they are working outside the curriculum. A central repository of documents, interfaces, schematics and code for students, such as GitHub™ or GitLab™, was used as a 'single source of truth' by all teams. This contained much of their legacy documentation and enabled new students to benefit from previous work by other students in their university. Other means of tracking issues and version control such as svn™, Redmine™ and Doxygen™ were also used. In one team social media tools were used by the student team to communicate with each other, but others used the physical proximity of working in a common space laboratory and the weekly standup meetings. All of the teams emphasized the importance of Interface control documents (ICDs) and attributed some of their success to the use of these for mechanical, electrical and communications interfaces (as well as Launch).

Lessons Learned

Many useful ideas were suggested by the teams as lessons learned. For example, having 2 students always working together on flight hardware allows a higher level of monitoring and safety. All means to enable testing were recommended, including the use of high-altitude balloons and 'Flatsat' or hardware-in-the-loop systems for pre-launch testing and for problem solving after launch. As has been covered in previous work, testing systematically, including component level, subsystem and system level testing is considered essential by all teams. All teams had experienced anomalies of many different types with their systems and were adept at recovering from them, where possible. A thorough survey of different types of anomalies has already been covered in the literature.

WHAT MATTERS?

Is there a project management formula for a successful program? Even if the case study teams have common characteristics, how can we assume that these characteristics are contributing to their success? It is of such interest to the CubeSat community, that despite this, we have attempted to assemble some characteristics of successful teams in terms of CubeSat project management. From the evidence so far, the following are proposed as characteristics common to all three case studies in this work:

Characteristic #1: One or two highly motivated staff leading

Previous work has indicated that experience of the staff may predict the success of the missions, but all staff start as CubeSat neophytes, even if they have industry experience to apply. It may be that a measure of persistence and long-term planning for multiple missions are also a factor. All case study teams also included other staff who supervised curricular projects and acted as PIs if they had an interest in a particular aspect of the mission.

Characteristic #2: A design-build-test cycle of 2-3 years

All teams mentioned the importance of maintaining student motivation and that this is challenging in the frame of a satellite build. They have achieved this by involving younger students early who can follow a program from their early years to build and test in their last years at university. Launch delays sometimes frustrated this effort to enable these students to see their work launched. Often, to achieve this development cycle, missions need to be streamlined (descoped).

Characteristic #3: A core of passionate students

The students from 2nd year bachelor's to final year master's students were included in all teams. A system of training up new interested students, where the older students work with younger students who are gaining familiarity with the skills and the project, was common to all programs. The younger students then take over as they progress through their course/s.

Characteristic #4: A mix of curricular and extra-curricular work

Each of the case study teams integrated both curricular work and extra-curricular work into the projects with the core of passionate students coming in to do extra-curricular work and others participating just for credit or with less time commitment.

Characteristic #5: Regular face-to-face contact

Regular weekly meetings outside of curriculum hours were a common feature of the case studies, who used these to ensure regular reviewing and planning occurred.

Characteristic #6: Use of a version-controlled repository

All teams used a central repository with the facility for version control and commenting, such as GitHub/Lab™ for their key schematics, documents and codes.

Characteristic #7: Testing, testing, (do we have to say it again?) testing

This has been pointed out in much of the previous literature, but at the risk of repeating, we are going to say it again here, as all the case study teams have emphasized it. FlatSats and high-altitude balloons were cited as means to enable this testing, as were a ground station and a Satellite Laboratory.

In terms of what doesn't matter, there are a few interesting conclusions: the discipline that hosts the program was different in each case, the size of the CubeSat varied for each case study and indeed within the case studies, although all started with 1U satellites; funding could be research-based or industry-donated or university-financed or a mixture of all of these, but does not need to be substantial. There is no magic total for the number of students involved and PhD students were not always used by the teams. Paying committed student volunteers was optional, but desirable if funding allowed. Different tools were used to communicate between the teams, as long as a central repository was established. Reviewing could be 'light touch' or systematic, but formed helpful deadlines.

FUTURE WORK

Future work would extend this study to other prolific independent teams to see if the characteristics identified still hold up when the sample size is extended. The case studies have been selected on their ability to launch a series of satellites independently from major government funding. These were considered by the authors to be of most use to other international CubeSat teams as they have built sustainable programs on limited funding. It is arguable whether it would be possible, or indeed of interest, to select teams purely on their mission success. It would be highly desirable to extend the case studies to different parts of the world with different educational systems and the authors would welcome contact from non-European and non-US Universities who have launched more than 4 satellites without significant government funding.

CONCLUSIONS

University-class missions are a relatively small element of the overall secondary launch market, but their significance is outsized. University-led spacecraft programs are an important source of recruitment and training for engineers and scientists entering the workforce. While the failure rate of university missions is too high, the high rates are concentrated with "one-and-done" independent schools; schools that produce multiple spacecraft see significant improvements in success.

In this work, case studies of 3 outstandingly successful groups who produce multiple spacecraft have been presented to provide information for those starting out on the CubeSat journey. The groups were asked a series of questions relating to their programs. They were also asked about how they managed and scheduled the project across multiple cohorts of students. Seven characteristics have emerged as common to all three case studies including motivated staff and students, a constrained turnaround cycle, a mix of curricular and extra-curricular work, regular meetings, a central repository for information and an emphasis on testing. Other factors were interesting in their absence including size of CubeSat, funding model, types of communication, payment of participants, use of PhD students and an ideal number of students.

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APPENDIX A

Why are you doing the CubeSat projects?

Is the project housed in one dept or across disciplines?

How many staff /students are working on it at any one time? Is there an optimum number of students to be involved?

Is anyone paid to work on the project, e.g.: staff, research assistants, interns?

How many MSc and PhD students do you have on build/test priorities eg for PhD students?

Do you involve industry at all in the project management? E.g.: reviews

Who leads it? Do you let the students choose their system engineer/project leader?

How do you manage turnover for leaders?

Do the students run it via a society?

Have you embedded the project in the curriculum via research/team projects?

How do you run the communications between students? and between students and staff e.g.: weekly meetings? Meetings? Software? Documents?

How is your information captured?

Do you use industry type documentation such as interface documents? ICDs, NCDs (give credit?)

How do you manage version control?

How have you managed and scheduled the project across multiple cohorts of students? When and how does the transfer of knowledge happen?

How do the students communicate about the project?

How is this different to how you started?

What have been the biggest lessons learned you have learned from the program so far?

What advice would you give to those starting out on a CubeSat project?

APPENDIX B

Below is the list of every university to build its own spacecraft along with the first launch date and the total number of missions; the flagships are highlighted in yellow, the prolific independents in green.

	School	Nation	First Launch	Total
1	University of Melbourne	Australia	1/23/1970	1
2	University of Surrey	UK	10/6/1981	4
3	Weber State	USA	4/29/1985	3
4	Technical University of Berlin	Germany	7/17/1991	15
5	Korean Advanced Institute of Science and Technology	South Korea	8/10/1992	4
6	University of Bremen	Germany	2/3/1994	1
7	National University of Mexico	Mexico	3/28/1995	2

8	Technion Institute of Technology	Israel	3/28/1995	2
9	Universidad Politécnica de Madrid	Spain	7/7/1995	2
10	Russian high school students	Russia	10/5/1997	1
11	US Air Force Academy	USA	10/25/1997	6
12	ESTEC	Europe	10/30/1997	4
13	LASP	US	2/26/1998	4
14	University of Alabama-Huntsville	USA	10/24/1998	2
15	Naval Postgraduate School	USA	10/29/1998	2
16	University of Stellenbosch	South Africa	2/23/1999	2
17	Arizona State University	USA	1/27/2000	2
18	Stanford University	USA	1/27/2000	3
19	Santa Clara University	USA	2/10/2000	3
20	Tsinghua University	China	6/28/2000	4
21	King Abdulaziz City for Science & Technology	Saudi Arabia	9/26/2000	11
22	University of Rome "La Sapienza"	Italy	9/26/2000	10
23	Umeå University / Luleå University of Technology	Sweden	11/21/2000	1
24	US Naval Academy	USA	9/30/2001	8
25	Aalborg University	Denmark	6/30/2003	5
26	Technical University of Denmark	Denmark	6/30/2003	2
27	Tokyo Institute of Technology	Japan	6/30/2003	5
28	University of Tokyo	Japan	6/30/2003	8
29	UTIAS (University of Toronto)	Canada	6/30/2003	4
30	Universidade Norte do Paraná	Brazil	8/22/2003	1
31	Mozhaiskiy Space Engineering Academy	Russia	9/27/2003	2
32	New Mexico State University	USA	12/21/2004	1
33	Norweigan Universities	Norway	10/27/2005	2
34	University of Würzburg	Germany	10/27/2005	4
35	Bauman Moscow State Technical University	Russia	7/26/2006	2
36	Cal Poly	USA	7/26/2006	14
37	Cornell University	USA	7/26/2006	5
38	Hankuk Aviation University	South Korea	7/26/2006	1
39	Montana State University	USA	7/26/2006	9
40	Nihon University	Japan	7/26/2006	4
41	Politecnico di Torino	Italy	7/26/2006	3
42	University of Arizona	USA	7/26/2006	2
43	University of Hawaii	USA	7/26/2006	3
44	University of Illinois	USA	7/26/2006	4
45	University of Kansas	USA	7/26/2006	1
46	Hokkaido Institute of Technology	Japan	9/22/2006	1
47	National University of Comahue	Argentina	1/10/2007	1
48	University of Louisiana	USA	4/17/2007	2
49	University of Sergio Arboleda	Colombia	4/17/2007	1
50	Fachhochschule Aachen	Germany	4/28/2008	2
51	Technical University of Delft	Netherlands	4/28/2008	2
52	Kagawa University	Japan	1/23/2009	3
53	Tohoku University	Japan	1/23/2009	4
54	Tokyo Metropolitan College of Industrial Technology	Japan	1/23/2009	1
55	Anna University	India	4/20/2009	1
56	Texas A&M University	USA	7/15/2009	2
57	University of Texas	USA	7/15/2009	5
58	Ufa State Aviation Technical University	Russia	9/17/2009	1
59	Ecole Polytechnique Fédérale de Lausanne	Switzerland	9/23/2009	1
60	Istanbul Technical University	Turkey	9/23/2009	5
61	Kagoshima University	Japan	5/20/2010	2
62	Soka University	Japan	5/20/2010	1

63	University Space Engineering Consortium	Japan	5/20/2010	1
64	Waseda University	Japan	5/20/2010	2
65	Indian university consortium	India	7/12/2010	1
66	Scuola universitaria della Svizzera italiana	Switzerland	7/12/2010	1
67	University of Michigan	USA	11/20/2010	7
68	University of Southern California	USA	12/8/2010	1
69	Colorado Space Grant Consortium	USA	3/4/2011	3
70	Kentucky Space	USA	3/4/2011	7
71	M.V. Lomonosov Moscow state university	Russia	4/20/2011	1
72	Nanyang Technological University	Singapore	4/20/2011	8
73	Indian Institute of Technology Kanpur	India	10/12/2011	1
74	Auburn University	USA	10/28/2011	1
75	Utah State University	USA	10/28/2011	2
76	Budapest University of Technology and Economics	Hungary	2/13/2012	1
77	University of Bologna	Italy	2/13/2012	1
78	University of Bucharest	Romania	2/13/2012	1
79	University of Montpellier II	France	2/13/2012	2
80	University of Vigo	Spain	2/13/2012	3
81	Warsaw University of Technology	Poland	2/13/2012	2
82	Kyushu Institute of Technology	Japan	5/17/2012	11
83	FPT Technology Research Institute	Vietnam	10/4/2012	1
84	Fukuoka Institute of Technology	Japan	10/4/2012	1
85	San Jose State University	USA	10/4/2012	6
86	Samara Aerospace University	Russia	4/19/2013	4
87	Technical University of Dresden	Germany	4/19/2013	2
88	University of Tartu	Estonia	5/7/2013	1
89	COSMIAC	USA	11/20/2013	1
90	Drexel University	USA	11/20/2013	1
91	Saint Louis University	USA	11/20/2013	2
92	Thomas Jefferson High School	USA	11/20/2013	1
93	University of Florida	USA	11/20/2013	2
94	US Military Academy	USA	11/20/2013	1
95	Vermont Technical College	USA	11/20/2013	1
96	Cape Peninsula University of Technology	South Africa	11/21/2013	2
97	Institute of Space Technology Islamabad	Turkey	11/21/2013	1
98	Narvik University College	Norway	11/21/2013	1
99	Pontifical Catholic University of Peru	Peru	11/21/2013	3
100	Technical University of Munich	Germany	11/21/2013	2
101	University of Maryland Baltimore County	USA	11/21/2013	1
102	Kyung Hee University	SKOR	11/21/2013	1
103	City University of New York	USA	12/6/2013	1
104	Kaunas University of Technology	Lithuania	1/9/2014	2
105	Osaka Prefecture University	Japan	2/27/2014	1
106	Shinsu University	Japan	2/27/2014	1
107	Tama Art University	Japan	2/27/2014	2
108	Teikyou University	Japan	2/27/2014	1
109	University of Tsukuba	Japan	2/27/2014	2
110	Taylor University	USA	4/18/2014	1
111	Wakayama University	Japan	5/24/2014	1
112	National Cheng Kung University	Taiwan	6/19/2014	2
113	Space Lab Herzliya Science Center	Israel	6/19/2014	1
114	University of the Republic (Uruguay)	Uruguay	6/19/2014	1
115	Igor Sikorsky Kiev Polytechnic Institute	UKR	6/19/2014	2

116	SPUTNIX	CIS	6/19/2014	2
117	MIT/SSL	USA	7/13/2014	1
118	National University of Engineering	Peru	8/19/2014	1
119	Kyushu University	Japan	11/6/2014	1
120	Nagoya University, Daido University	Japan	11/6/2014	3
121	SERPENS	Brazil	8/19/2015	1
122	Harbin Institute of Technology	China	9/19/2015	2
123	Zhejiang University	China	9/19/2015	2
124	Salish Kootenai College	USA	10/8/2015	1
125	University of Alaska Fairbanks	USA	10/8/2015	1
126	St. Thomas More Cathedral School	USA	12/6/2015	1
127	National University of Singapore	Singapore	12/16/2015	1
128	Tomsk Polytechnic University	Russia	3/31/2016	1
129	Université de Liège	Belgium	4/25/2016	1
130	College of Engineering, Pune	India	6/22/2016	1
131	Sathyabama University	India	6/22/2016	1
132	Shaanxi Engineering Laboratory	China	6/25/2016	1
133	Universidad Politécnica de Cataluña	Spain	8/15/2016	2
134	IIT Bombay	India	9/26/2016	1
135	Escola Municipal Presidente Tancredo de Almeida Neves	Brazil	12/9/2016	1
136	CAST	China	12/28/2016	1
137	Northwestern Polytechnical University	China	1/9/2017	2
138	Al-Farabi Kazakh National University	Kazakhstan	2/15/2017	2
139	Aalto University	Finland	4/18/2017	3
140	Cal State Northridge	USA	4/18/2017	1
141	Democritus University of Thrace	Greece	4/18/2017	1
142	École de Mines	France	4/18/2017	1
143	École Polytechnique	France	4/18/2017	1
144	Seoul National University	South Korea	4/18/2017	4
145	University of Adelaide	Australia	4/18/2017	1
146	University of Alberta	Canada	4/18/2017	1
147	University of Colorado	USA	4/18/2017	1
148	University of New South Wales	Australia	4/18/2017	3
149	University of Patras	Greece	4/18/2017	1
150	University of Sydney	Australia	4/18/2017	1
151	Nanjing University of Science and Technology	PRC	11/9/2011	4
152	Southwestern State University	Russia	6/14/2017	3
153	Fachhochschule Wiener Neustadt	Austria	6/23/2017	1
154	Noorul Islam University	India	6/23/2017	1
155	Slovak Organization for Space Activities	Slovakia	6/23/2017	1
156	Universidad de Chile	Chile	6/23/2017	1
157	University College London	UK	6/23/2017	1
158	Ventspils University	Latvia	6/23/2017	1
159	CosmoMayak	Russia	7/14/2017	1
160	Moscow Aviation Institute	Russia	7/14/2017	1
161	University of Stuttgart	Germany	7/14/2017	1
162	Penn State University	USA	8/14/2017	1
163	Embry-Riddle	USA	11/18/2017	1
164	Northwest Nazarene University	USA	11/18/2017	1
165	MIT/LL	US	11/18/2017	1
166	Korea Aviation University	SKOR	1/12/2018	1
167	Yonsei University	SKOR	1/12/2018	2
168	Chosun University	SKOR	1/12/2018	2
169	Chungnam University	SKOR	1/12/2018	1
170	Huai'an Youth Comprehensive Development Base	PRC	1/19/2018	1

171	University of Nairobi	KEN	4/2/2018	1
172	Brown University	US	5/21/2018	1
173	Rowan University	US	5/21/2018	1
174	UCLA	US	9/15/2018	2
175	Ryman Sat Project	JPN	9/22/2018	1
176	Shizuoka University	JPN	9/22/2018	3
177	Belarusian State University (BSU)	BEL	10/29/2018	1
178	Aichi University of Technology	JPN	10/29/2018	1
179	Irvine Public School Foundation	US	11/11/2018	2
180	Masdar Institute of Science and Technology	UAE	11/17/2018	1
181	Instituto Tecnológico de Aeronáutica (ITA)	BRAZ	12/3/2018	1
182	Crown Prince Foundation	JOR	12/3/2018	1
183	King Mongkut's University of Technology North Bangkok	THAI	12/3/2018	1
184	University of North Carolina	US	12/3/2018	1
185	Weiss School	US	12/3/2018	1
186	Georgia Tech	US	12/3/2018	2
187	Korea Aerospace University	SKOR	12/3/2018	1
188	Aarhus University	DEN	12/5/2018	1
189	University of Southern Indiana	US	12/5/2018	1
190	New Mexico Institute of Mining and Technology	US	12/16/2018	1
191	West Virginia University	US	12/16/2018	1
192	North Idaho STEM Charter Academy	US	12/16/2018	1
193	Space Kidz	INDI	1/24/2019	1