Definition and Requirements of Small Satellites Seeking Low-Cost and Fast-Delivery

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Edited by: Mengu Cho, Filippo Graziani

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International Academy of Astronautics
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Editors:

Mengu Cho
Filippo Graziani

IAA Study on Definition and Requirements of Small Satellites Seeking Low-Cost and Fast-Delivery

IAA Study Group 4.18 Members

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EXECUTIVE SUMMARY

This document is the final report of IAA study group 4.18, "Definition and Requirements of Small Satellites Seeking Low-Cost and Fast-Delivery". The study group started in fall 2014. Its objectives are to examine the definitions of small satellites, identify the requirements every satellite should follow regardless of its size or development philosophy and then reflect some of the findings to the draft of ISO-20991, "Space Systems - Requirements for Small Spacecraft". The standard aims at describing minimum requirements for small satellites to answer the concerns raised over due to the recent explosive growth of small satellite launches.

Over the course of the study, intensive discussion was made about how to describe small satellites best. The majority of the opinions was that neither "mass" nor "size" is suitable for defining small satellites. Rather, philosophy of design, manufacturing, mission, program management, etc., should be used for the definition. The study group came to the conclusion that using the term "**lean satellite**" to reflect satellite development philosophy is more suitable than saying "small satellite".

In the ISO-20991 standard, the word of "small spacecraft" is used as a result of minimum consensus among the ISO member countries. The word of "lean satellite" could not get the consensus. IAA study report is not bound to consensus. Therefore, throughout the present document, the word of "lean satellite" is used. **The reader should note that "small spacecraft" in the ISO-20991 standard and "lean satellite" are identical.** Moreover, it may be more appropriate to call the present subject "lean satellite program" or "lean satellite mission" rather than "lean satellite" since what we try to achieve is to bring value to customers or stakeholders through the satellite program or mission at low-cost and in a quick manner. The satellite itself is just a mean to do so and a part of deliverable, although the satellite is a symbol of the overall program or mission. In the rest of this document, the reader may replace the term "lean satellite" by "lean satellite program" or "lean satellite mission" according to the context of each phrase.

A lean satellite is a satellite that utilizes non-traditional, risk-taking development and management approaches with the aim to provide value of some kind to the customer at low-cost and without taking much time to realize the satellite mission. The satellite size is small merely as a result of seeking low-cost and fast-delivery. To achieve these two characteristics, the satellite design relies on the use of non-space-qualified (or non-space-graded) Commercial-Off-The-Shelf (COTS) units, and the satellite size inherently becomes smaller. The design accepts a certain level of risk associated with the use of COTS. The number of team members also becomes smaller with the lean approach. Approaches chosen for lean satellites are different from the ones used for traditional satellites where the priority of reliability often supersedes cost and schedule.

Historically, the word "lean" originated from Toyota Production System (TPS) introduced to the world by a best-seller book, "The Machine That Changed the World". According to the official website of Toyota Motors, the objective of TPS is: *"making the vehicles ordered by customers in the quickest and most efficient way, in order to deliver the vehicles as quickly as possible"*. Changing the word vehicles to satellites neatly fits the philosophy of designing and making small spacecraft. The idea of "lean" is now expanding to "lean manufacturing", "lean development", and "lean enterprise".

Lean satellites seek to deliver value to the customer (the end-user or the purchaser) at minimum cost and in the shortest possible schedule by minimizing waste. The important key words are value and waste. There may be some differences in terms of customers and the value they seek between traditional satellites and lean satellites, but the basic scheme that value is created by satellites orbiting in space and delivered from space to ground via radio signals is the same. The difference from traditional satellites is that lean satellites put more emphasis on low-cost and fast-delivery rather than other considerations.

The lean concept distinguishes three types of activities. The first one is a value added activity. The second one is a non-value added activity. The third one is pure waste. The principle of lean concept is to constantly improve the flow of products or information by eliminating pure waste through the conversion of value-less activities to value-adding activities.

Lean manufacturing originated in the world of automobiles production, but we cannot apply the lean concept used in automobiles directly to satellites. This is because the unit value of satellites varies by four orders of magnitude while it varies only by one order of magnitude for the case of automobiles. Moreover, satellite missions vary from entertainment functions to military functions; hence, generating different sets of requirements depending on the considered mission, whereas the prime mission of automobiles is transportation in all cases.

Due to the technological progress of small spacecraft, new types of customers are emerging and more value from satellites through lower unit price and faster system delivery is desired. Mega-constellations consisting of hundreds or thousands of satellites are also being proposed and traditional satellites development philosophy cannot be applied to mega-constellations because the total cost would be prohibitively high. Small spacecraft and mega-constellations can benefit from the application of the lean concept to satellites, although it must be modified to accommodate the differences between satellites and automobiles. Developing the lean satellite concept is an interesting subject for systems engineering.

In the study group, a list of 16 questions or criteria for defining a lean satellite was formulated. The 16 questions were divided into 9 categories with different weighting: (1) total cost, (2) delivery time, (3) simplicity, (4) risk taking, (5) risk mitigation, (6) reliability requirement, (7) mission duration, (8) launch, and (9) waste minimization. Some categories are further divided to multiple questions. To convey importance, each question has a weight and each answer has a score. By adding up the points of the answers based on the 16 questions, the total sum lies between 0 and 100. The questions can be considered at any time during the system life cycle and they may be used to set the target at the start of the program, to evaluate the ongoing program at the middle of it, or to reflect upon the program at the end of it.

The study group collected answers from 35 existing satellites and 8 hypothetical satellites. The distribution of the answers given by the 35 existing satellites was analyzed. The majority of satellites cost less than 3 million USD. On the other hand, it takes longer than 2 years for many satellites from the program start to satellite delivery. More than two-third of the satellites allow single-point-of-failure, evaluate and manage the risk based on experience and knowledge of the team, and allow the consecutive mission downtime longer than one day. More than two-third of the satellites also assume a mission duration shorter than 2 years and tries to minimize waste.

The study group collected experiences from 18 persons from 15 countries about requirements they had to comply with. The requirements were divided into several categories: debris mitigation, frequency regulation, satellite registration, safety, passivation, external relationship, export control, and others. It is found that many requirements are in common. In February 2016, a Committee Draft for Comments, ISO/CDC/20991 “Space systems — Requirements for small spacecraft” was issued. Based on the study group findings, the requirements, as described below, were reflected onto ISO/CDC/20991.

- **Safety**
  Every spacecraft, regardless of its size, mission, value, capability or any other nature, shall comply with general safety requirements. Specific safety requirements depending on the launcher are stated in the launcher Interface Control Document (ICD).
- **Debris mitigation**
  Every spacecraft, regardless of its size, mission, value, capability or any other nature, shall comply with debris mitigation requirement.
- **Use of radio frequency**
  Every spacecraft, regardless of its size, mission, value, capability or any other nature, shall comply with international and domestic regulations regarding the use of radio frequencies. Ground station operations shall also comply with international and domestic regulations. International frequency coordination shall be carried out through the International Telecommunication Union (ITU) before spacecraft is launched.
- **UN registration**
  Every spacecraft, regardless of its size, mission, value, capability or any other nature, shall be registered to the United Nations (UN) after launch. The registration is typically done through a government body of the country that owns the spacecraft.
- **Launch interface**
  Once a launcher ICD is agreed as a part of launch contract, the payload, i.e., spacecraft or satellite, shall comply with the ICD.
- **Testing**
  A unit based on COTS parts and technology shall be qualified against the test level and duration described in ISO-19683 before being sold as “a space unit” to provide the minimum assurance that it has a certain level of tolerance against the space environment.
- **CubeSat**
  If a spacecraft is to be launched as a CubeSat, it shall comply with the requirements described in ISO-17770.

In addition to these requirements, “main payload, adjacent payload(s), and launcher harmlessness” were added to ISO/CDC/20991 to address the issues related to piggy-back launch. “Verification” was also added to address how the requirements described above should be verified.

After receiving comments on ISO/CDC/20991 from ISO/TC20/SC14 P-member countries until April 2016, the revised version, the Committee Draft for Voting ISO/CDV/20991, was submitted to ISO. The draft was circulated for voting from July 6, 2016, to September 28, 2016. The draft obtained more than two-third majority of the P-member votes. Although the draft obtained enough votes to proceed to a Draft International Standard (DIS), a unanimous consensus of having the document as an International Standard was not obtained. During ISO/TC20/SC14 plenary meeting in June 2017, it was decided that the ISO project proceeds to make a Technical Specification instead of International Standard and the draft be balloted as a Draft Technical Specification. A Technical Specification addresses work where it is believed that there will be a future, but not immediate, possibility of agreement on an International Standard. It can contain normative descriptions. The Technical Specification was approved by ballots in fall 2017 and will be published early 2018. Three years after the publication of the ISO/TS, the document will be voted again to decide whether it will be modified to become an International Standard or not.

From IAA study group 4.18, the concept of lean satellite was born. This offers new research opportunities that may have an impact on systems engineering disciplines. To promote the lean satellite concept further, a forum to discuss and study it is necessary. Hence, it is preferable to have an annual meeting where people interested in the idea of lean satellite get together, make research presentations, exchange ideas and discuss collaborations.

1. INTRODUCTION

The explosive growth of small satellite launches as shown in Figure 1 raises concern over space debris, safety, radio spectrum use, and more. Small satellites range from a 1kg CubeSat to a satellite weighing well over 100kg, but have a common characteristic of low-cost and fast-delivery. In the past, small satellites, especially the lighter ones, were used mainly for educational or experimental purposes. Nowadays, however, even commercial CubeSats started to appear and the commercial exploitation of small satellites raises concern over reliability as they cannot provide the same level of reliability as traditional large/medium satellites.

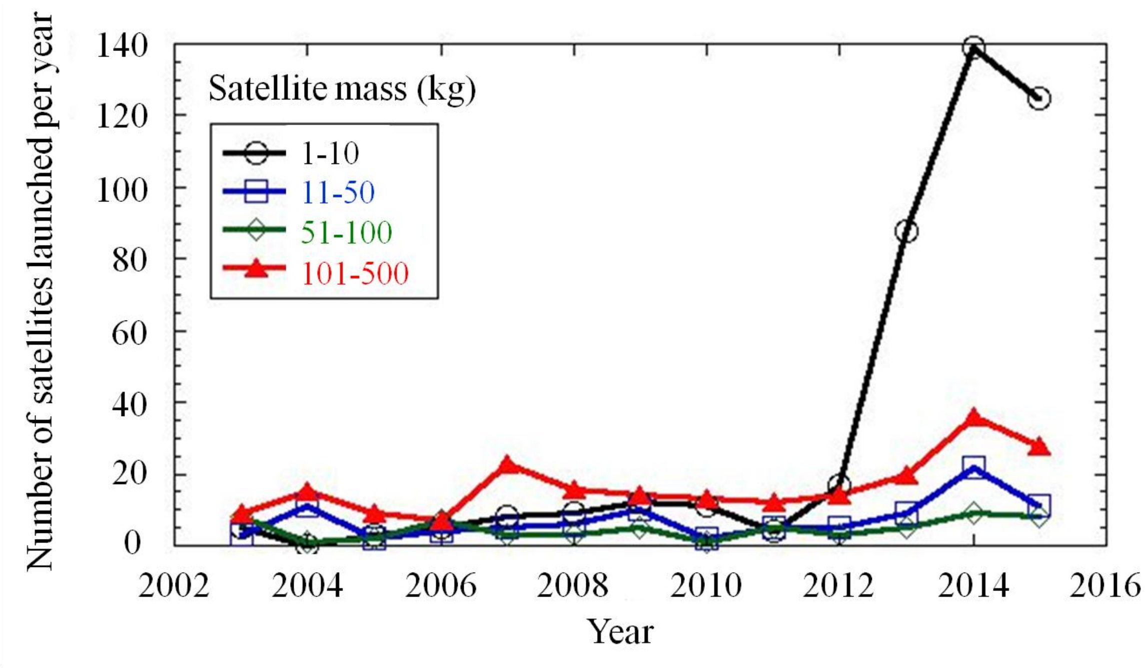

Figure 1 Recent trend of worldwide small satellites

In 2014, an activity started at ISO/TC20/SC14 to make an ISO standard that defines what is a small satellite, sets requirements for small satellites to answer the aforementioned concerns, and lays down the foundation for commercial activities utilizing small satellites. Although the ISO activity is primarily intended for commercial satellites, satellites with educational or academic purpose may be affected by this standard. Hence, inputs to the ISO activity from the communities related to small satellites, especially university and emerging-country satellites, are highly sought-after.

The study group 4.18, “Definition and Requirements of Small Satellites Seeking Low-Cost and Fast-Delivery”, was approved by IAA Commission 4 during IAC 2014 in Toronto. The objectives of the study group are to examine the definitions of small satellites, identify the requirements every satellite should follow regardless of its size or development philosophy and then reflect some of the findings to the ISO draft. As of October 2015, the study group consists of 25 members listed on the IAA Website, but also involves more than a hundred experts who subscribed to the Nano-satellite Environment Test Standardization (NETS) mailing list, which was originally formed in 2011 to discuss the international standard on small satellite testing (ISO/CD/19683), but whose role expanded to encompass discussions on standards for small satellites at large.

Since the kick-off meeting at IAC 2014, various meetings were held. One important milestone was the International Workshop on Small-Scale Satellite Standardization held in Kitakyushu, Japan, from November 17 to 19, 2014, in which 88 persons from 27 countries, including 44 persons from outside Japan, attended. During the workshop, a round-table discussion was held to discuss the terminology to describe small satellites. Prior to the workshop, a request was made through NETS mailing list to post several sentences to define small satellites. In total, 27 people responded. The majority of the opinions was that neither “mass” nor “size” is suitable for defining small satellites. Rather, philosophy of design, manufacturing, mission, program management, etc., should be used for the definition. The round-table discussion came to the conclusion that using the term “lean satellite” to reflect satellite development philosophy is more suitable than saying “small satellite”. The round-table participants also agreed on collecting through an e-mail list comments and information in each country regarding the suitable definition of scale and requirements for lean satellites.

In October, 2015, a new work item “Space Systems - Requirements for Small Spacecraft” was accepted by ISO/TC20/SC14. This is now designated as ISO/CDV/20991. During the SC14 plenary meeting in June 2015, it was decided to use the term “small spacecraft” for the standard title as the term “lean satellite” was judged premature. The term “lean satellite” is used throughout the rest of this report. **The reader should note that “small spacecraft” in the ISO/CDV/20991 and “lean satellite” are identical.** As the terminology of “lean satellite” becomes mature, it will be reflected into the standard revisions that are carried out every 5 years after the standard publication. As of now, lean satellites are rapidly evolving, not only in technology but also in other aspects, such as business environment. The ISO revision cycle of 5 years is indeed much longer than the time scale of lean satellite evolution. One advantage of having an IAA study on lean satellites is that we can revise the lean satellite concepts on a much shorter timeframe than ISO.

It may also be more appropriate to call the present subject “lean satellite program” or “lean satellite mission” rather than “lean satellite” since what we try to achieve is to bring value to customers or stakeholders through the satellite program or mission at low-cost and in a quick manner. The satellite itself is just a mean to do so and a part of deliverable, although the satellite is a symbol of the overall program or mission. In the rest of this document, the reader may replace the term “lean satellite” by “lean satellite program” or “lean satellite mission” according to the context of each phrase.

This report consists of six chapters. The second chapter introduces how the idea of “lean” is applied to satellites after briefly describing the concept of “lean” in general. The third chapter introduces the scale for lean satellites, which is based on ideas collected through the NETS mailing list. Lean satellite developers, operators, or users were given 16 questions. By answering the 16 questions, the respondent could evaluate how strongly their satellites possess characteristics of lean satellites on a scale from 0 to 100. The fourth chapter describes requirements for lean satellites. Even if lean satellites are built with a different philosophy from traditional satellites, they are still satellites as long as they fly in space and emit radio waves. The requirements in chapter 4 are the ones every satellites should comply with regardless of their nature. The requirements are based on the experience of lean satellite developers from 15 countries collected through the NETS mailing list. The fifth chapter describes applicability of this report to ISO/CDV/20991 draft. The sixth chapter concludes the report with a concise statement about the definition of lean satellites. The chapter also lists future issues regarding the promotion of the concept of lean satellites.

This report is a product of joint activities through the NETS mailing list and more than 8 international meetings from 2014 to 2016. The names of contributors are listed in Appendix A.

2. LEAN SATELLITE CONCEPT

Historically, the word "lean" originated from Toyota Production System (TPS) [1] introduced to the world by a best-seller book, "The Machine that Changed the World" [2]. According to the official website of Toyota Motors, the objective of TPS is: *"making the vehicles ordered by customers in the quickest and most efficient way, in order to deliver the vehicles as quickly as possible"* [3]. Changing the word "vehicles" to "satellites" neatly fits the philosophy of designing and making small spacecraft.

Molnau *et al.* [4] introduced lean satellite production, taking an example from the Iridium program that created a constellation of 66 satellites. From 1990s to 2000s, the Lean Aerospace Initiative (LAI) program was active at the Massachusetts Institute of Technology. The program later became the Lean Advancement Initiative, which was a consortium of entities from academia, industry, and government. In LAI, mainly the aircraft sector was involved, but several research efforts were also conducted in the space sectors [5]. The idea of "lean" is now expanding to "lean manufacturing", "lean development", and "lean enterprise" [6-9].

Lean satellites seek to deliver value to the customer (the end-user or the purchaser) at minimum cost and in the shortest possible schedule by minimizing waste. The important key words are value and waste. The value depends on customers. For an example, TV broadcasting satellites provide amusement and/or information to their end-users and provide sales revenue to the satellite service providers. Table 1 lists the customers (end-users and purchasers), and the value of traditional satellites, lean satellites, automobiles, and other products.

Table 1 Customers and value of various products

Product	Customer		Value to the customer
	End-user	Purchaser	
Traditional satellites	• National research institutes • Intelligence (spy) organizations • Military headquarters • Soldiers in the field • Satellite TV viewers • Car navigation users	• Governments • Military • Satellite service providers	• Information • Entertainment • Research data • National security
Lean satellites	In addition to traditional satellites: • Researchers at universities	In addition to traditional satellites:	In addition to traditional satellites:

	(research satellites) • Students (educational satellites) • Rich people (“my” satellite)	• Universities • Private persons	• Learning opportunity (educational) • Satisfaction (private satellites)
Civil aircraft	Travelers	Airline companies	Transport method
Fighter aircraft	Air force pilots	Military	National security
Automobiles	General consumers	Same as the user	• Transport method • Personal satisfaction
Mobile phones	General consumers	Same as the user	• Information • Personal satisfaction
Mechanical wristwatch	Rich persons	Same as the user	• Prestige • Personal satisfaction

There may be some differences between traditional satellites and lean satellites in terms of customers and their desired value, but the basic scheme that value is created by satellites orbiting in space and delivered from space to ground via radio signals is the same. The difference from traditional satellites is that lean satellites put more emphasis on low-cost and fast-delivery rather than other considerations. The value provided by automobiles is much simpler than the value provided by satellites. Automobiles, indeed, provide mainly a method of transportation and for the case of high-class automobiles, personal satisfaction.

The lean concept distinguishes three types of activities. The first one is a value added activity, such as transforming information or verification to reduce uncertainty. The second one is a non-value added activity, such as manufacturing motion to pick-up parts or safety inspections required by law. The third one is pure waste, called “muda” in Japanese. Taichi Ono [1], the founder of TPS, once listed six “mudas” in factories: (1) over-processing, (2) stock (inventory), (3) making too much, (4) waiting, (5) making defective products, and (6) transportation. The principle of the lean concept is to constantly improve the flow of products or information by eliminating pure waste through the conversion of value-less activities to value-adding activities.

Lean manufacturing originated from the world of automobiles production. One can argue that automobile companies such as Toyota can apply the lean concept to all the products they produce from low-end compact cars, such as the Corolla brand, to high-end luxury cars, such as the Lexus brand. For satellites development and manufacturing, however, we cannot apply the development philosophy of a CubeSat with a typical cost of 100 thousand USD to a traditional satellite costing more than 100 million USD. Moreover, we cannot apply the lean concept in automobiles directly to satellites because the unit value of satellites varies by four orders of magnitude while it varies only by one order of magnitude for the case of automobiles. Satellite missions also vary from entertainment functions to military functions; hence, generating different sets of requirements depending on the mission, whereas the prime mission of automobile is transportation in all cases. Mega-constellations consisting of hundreds or thousands of satellites are also being proposed and though the production of 1,000 satellites is an unprecedented level of mass production in the space sector, it is far less than the level of automobiles mass production. Therefore, the same economic law of mass production cannot apply to the lean satellite industry. Table 2 lists the differences between lean satellites and automobiles.

NOTE 1: the colored rows in Table 2 are common attributes between lean satellites and automobiles.

Table 2 Differences between lean satellites and automobiles

	Lean satellite	Automobile
End-user	• National research institutes • National intelligence organizations • Military headquarters • Soldiers in the field • Satellite TV viewers • Car navigation users • University researchers • Students • Rich persons	General consumers
Purchaser	• Governments • Military • Satellite service providers • Universities • Private persons	Same as end-user
Value to the user	• Information • Amusement • Research data • National security • Learning opportunity • Satisfaction	• Method of transportation • Satisfaction

Electronics parts	COTS (automobile grade or lower)	COTS (automobile grade)
Working environment	Extreme environment (ex.: vacuum, radiation)	• Outdoor • Rain • Snow • Dust • Vibration • Thermal cycle
Value that can be added to the product	• Processing • Distribution of information • Utilization of information	• Options inside car • Speed
Solution business	Yes	No
Product with the same design	1 to 1,000	10,000 to 1,000,000
Number of parts	10,000 to 100,000	~100,000
Design renewal time	1 to 3 years	1 to 3 years
Importance of brand	Not necessary	Important
Lead time from order to delivery	6 months to 2 years	1 month
Product life cycle	1 month to 3 years	~ 10 years
Components suppliers	Worldwide (limited)	Worldwide (unlimited)
Importance of integration	Important	Important
Supply chain	Vertical (impossible to make 100% in-house)	Vertical and horizontal
Dependability requirement (must work any time)	High (not as high as for traditional satellites)	Not so high
Reliability	Important	Frequent maintenance
Maintenance, repair	No	Yes
Safety requirement	Not so high	Very high
Annual production worldwide	100 to 500	65,000,000 (passenger car)
Unit price, USD	1M to 10M	10K to 100K
Unit mass, kg	1 to 100	500 to 3,000
Price/kg, USD/kg	40K	20
Total market size, USD	200M	1,300,000M

It is found from Table 2 that there are only a few requirements in common between lean satellites and automobiles and hence, it is very difficult to apply lean concepts, as they are, to satellites though some concepts of "lean" are necessary for satellites. Due to the technological progress of small spacecraft, new types of customers are emerging who want more value from satellites through lower unit price and faster system delivery. Traditional satellites development philosophy cannot be applied to mega-constellations because the total cost would be prohibitively high. Small spacecraft and mega-constellations can benefit from the application of the lean concepts to satellites, though they must be modified to accommodate the differences between satellites and automobiles. Oppenheim *et al.* [10] wrote: *"Systems engineering which* *grew out of the space industry to help deliver flawless complex systems is focused on technical performance and risk management. Lean which grew out of Toyota to help deliver quality products at minimum cost is focused on waste minimization, short schedules, low cost, flexibility, and quality. Both have the common goal to deliver system lifecycle value to the customer."*

Developing the lean satellite concept is an interesting subject for systems engineering. We can [10]: *"deliver the best lifecycle value for technically complex systems with minimum resources."*

3. SCALE FOR LEAN SATELLITES

At the end of the Kitakyushu workshop in November 2014, homework was distributed via the NETS mailing list. The homework consisted of three parts. The first part asked for a list of questions or criteria for defining a lean satellite. The second part asked for a list of requirements satellite developers had to comply with before their lean satellite was launched, such as regulatory, legal, and treaty requirements. The third part asked for a list of tasks needed to further promote the acceptance of lean satellites. By March 2015, 22 persons and groups responded. For the first part of the homework, 84 questions were collected. By July 2015, the questions were narrowed down to 16, which are listed in Table 3.

The sixteen questions are made of 9 categories with different weighting: (1) total cost, (2) delivery time, (3) simplicity, (4) risk taking, (5) risk mitigation, (6) reliability requirement, (7) mission duration, (8) launch, and (9) waste minimization. Some categories were further divided into multiple questions. To convey importance each question has a weight and each answer has a score. For example, if the answer to the first question was A = 7 million USD, then the score is 2. By multiplying the weight of the question, 5 in this case, the total number of points obtained by this question is 10. By adding up the points of the answers based on the 16 questions, the total sum lies between 0 and 100.

Q1 is divided into two cases depending on whether the satellite program intends to develop and operate a single satellite or multiple satellites including a constellation program. The numbers used in the scale, such as the upper limit of 15 million USD or 10 million USD needs to be examined further. For most university satellite projects, where student labor is used extensively, the total cost can be less than 3 million USD or even 1 million USD, unless high-end technology/science mission is involved. For commercial satellites, it is challenging to keep the cost lower than these values because of labor costs. A mega-constellation such as OneWeb is trying to achieve 0.5 million USD per satellite [11]. Innovations in manufacturing methods, components procurement, ground segment configuration, and launch strategy, are necessary to achieve cost-reduction goal.

One may disagree with including non-recurring costs (costs of ground stations, test facilities, etc.), in the calculation for total cost. Lean satellite programs purpose is to bring value to the customer, which includes the developers themselves if the mission purpose is non-commercial, such as education, technology demonstration, etc. In this case, all costs needed to deliver the value should be counted. Satellite developers need to be innovative to deliver value to the customer at low-cost and in a timely manner. Hence, not only recurring costs but also non-recurring costs should be kept low. It is true that the first satellite developed by an organization will cost more than follow-on satellites because there are initial costs involved, such as ground stations, testing facilities, and more. Yet, as long as it is necessary to deliver value to the customer, non-recurring costs should be counted. We should always debate whether the infrastructure investment helps to add value for the customer.

Q2 is somewhat ambiguous: how do we define the starting point of a program? If a satellite developer makes a commercial satellite based on a contract with a customer, we can set the contract date (or the date when initial investment is secured) as the starting point. For a government satellite, the satellite program may span over several phases, such as feasibility study, pathfinder development, and actual satellite fabrication. The largest part of the money is committed when a contract is made with the government to actually build a satellite. That time may be regarded as the starting point. For university satellites, a satellite program can be started with a very small amount of money committed. Therefore, the kick-off meeting may be regarded as the starting point.

Q3 to Q6 are related to simplicity. Minimizing the number of mission payloads (Q3) helps to reduce the delivery time by shortening the time required for design and verification. It also helps to make the satellite system robust. If software occupies a significant portion of mission payload, e.g. mobile phone applications for PhoneSats, it can also be counted as a payload. A small number of operational team members (Q4) helps to reduce operational costs. It can be achieved by making a satellite simple and easy to operate. A small number of satellite development team members (Q5) not only helps to reduce personnel costs, but also facilitates better communication within the team. This leads to significantly reducing indirect discussion time, such as email-based discussion, and communication errors. Hence, a small development team may effectively reduce the delivery time. There may be an optimum number of development personnel for a given complexity of a satellite. Having more team members enables parallel work, but requires more management overhead. Simple handling (Q6) helps to reduce the handling costs including special infrastructure necessary to handle hazardous or explosive material or components. It also helps to reduce the effort required for safety reviews, which sometimes become substantial work if thorough verification is required to assure the safety of material or components.

Q7 to Q10 are related to how much lean satellites accept risk. Screening and management at the parts level (Q7) increase the final cost and the delivery time. Instead, lean satellite developers often choose verification at higher levels, such as at the component level or system level thereby taking on risk of additional cost and delay if defective parts are found at higher-level verification. Use of non-space qualified (or more precisely non-space graded) COTS components (Q8) is one of the salient characteristics of lean satellites. As COTS parts/materials are not originally intended for use in space, their use certainly increases the risk of failure in space. However with a suitable verification strategy, the risk can be taken. Q9 is a choice between “Yes” and “No” for the use of new technologies that are not guaranteed to work in space. “Yes” to Q9 does not mean everything in a satellite is new and efforts to lower risk by proper verifications are necessary. “No” to Q9 means that the satellite design is conservative and there is more emphasis on reliability and mission assurance.

Q11 concerns how to mitigate risks. As lean satellites take many risks, risks must be properly evaluated and managed. It should be stressed that lean satellites do not leave risks untouched. Lean satellites take advantage of their own simplicity, wherein the relationship between risks and consequences are easily seen by experienced team members, rather than employing expensive and/or time-consuming testing and/or analysis with heavy documents as used in traditional satellite projects. Since the replacement cycle of each generation of lean satellites is short, one can accumulate experience more readily than traditional satellites by working on various satellite programs. The small team size also leads to multiple tasks given to each member; thus, accumulated experience and knowledge of personnel is an enormous asset for lean satellite programs.

Q12 is related to how lean satellites regard satellite failures. It is true that lean satellites fail more often than traditional satellites [12], but the ultimate goal of satellites is to bring “value” to customers, i.e. realize successful and productive missions. As long as the mission goal is achieved at low-cost and in a timely manner, the loss of a single satellite is tolerable. Even if it is a single satellite mission, as long as the total cost and schedule (including a back-up satellite) is acceptable to the customer, the loss can be acceptable. For a multiple satellites project, in the case some of the satellites are lost, as long as it is acceptable to the customers to have the mission fulfilled with the remaining satellites generating less value or in the case back-up satellites are available within an acceptable time frame, the loss of satellites can be acceptable in the final evaluation.

Q13 concerns the dependability of satellites. Due to the low reliability of a single satellite, lean satellites are not suitable for missions that require full-time dependability, such as military missions, unless a careful back-up scheme is in place, such as automatic switching to a redundant system, including a back-up satellite prepared in advance. The customer needs to accept the reality that lean satellites are not always available for service.

Q14 is related to the length of the total system life cycle: from mission concept to operation in space and finally to satellite disposal. The longer we intend to operate a satellite in orbit, the less demand there is to deliver the satellite quickly. There are many things to be verified to assure a long mission life in orbit. For example, the policy on parts selection would have to change to assure stronger radiation tolerance, which would increase the final cost.

Q15 is also related to the length of the total system life cycle. If a satellite is delivered in 6 months at breakneck speed, but subsequently waits on the ground for 2 years until launch, it unfortunately surrenders all advantages of being a lean satellite. Lean satellites should be planned in such a way that rapid access to space is assured. Current success of CubeSats results from the use of a particular container, i.e. the Payload Orbital Deployer (POD) container, which assures compatibility among different launchers. Presently there is no dedicated launcher for lean satellites. Therefore, choosing a mission that critically depends on a particular orbit, e.g. requiring Sun-synchronous orbit (SSO), is at grave risk if the launch is, for some reason, delayed. The mission should be chosen, or modified, to be less vulnerable or less sensitive to launch schedule changes.

Q16 is related to an important aspect of "lean": **waste minimization**. There are many types of waste in a satellite project. One of them is the significant time wasted for transportation and communication. For example, to conduct a test at a different location, the satellite must be carefully packed and shipped. Once it arrives at the testing site, the satellite has to be inspected for any damage during that shipping. Typically, one or two days are lost when a satellite is shipped to a different place. When we consider the return trip, two to four days are lost in total. Moreover, the travel and the transportation are not inexpensive, especially if we need to hire a truck with special carriage suspension. Innovative ideas to carry out tests as much as possible at the primary developing site and careful test planning to minimize logistics are necessary. Moreover, note that email communication between two parties is often a waste of time because no progress occurs until the reply comes. On the other hand, simply walking to a colleague's desk or making a call solves a given issue instantly. The time needed to assemble team members in one place for a meeting is also a waste that can be resolved by keeping team members in close proximity all of the time.

Table 3 Scale for lean satellites

No	Category	Weight	Question	Scale	Score	HORYU-II	Your satellite
1	Total cost	5	If your satellite program is a single satellite program, answer this question. Total cost including: a satellite, non-recurring cost (e.g. infrastructure investment, etc), launch, and operation, A	A ≥ 15MUSD	0		
				10MUSD ≤ A < 15MUSD	1		
				5MUSD ≤ A < 10MUSD	2		
				3MUSD ≤ A < 5MUSD	3		
				A< 3MUSD	4	20	

1’	Total cost	5	If your satellite program contains multiple satellites, answer this question. Total cost including: satellites, non-recurring cost (e.g. infrastructure investment, etc), launch, and operation divided by the number of satellites, A’	A’ ≥ 10MUSD	0		
				5MUSD ≤ A’ < 10MUSD	1		
				2MUSD ≤ A’ < 5MUSD	2		
				1MUSD ≤ A’ < 2MUSD	3		
				A’ < 1MUSD	4		
2	Satellite delivery time	5	Time from the program start to delivery, B	B ≥ 3 years	0		
				2 ≤ B < 3 years	1		
				1 ≤ B < 2 years	2	10	
				6 months ≤ B < 1 year	3		
				B < 6 months	4		
3	Simple satellite	1	Number of mission payloads, H	5 ≤ H	0		
				3 ≤ H < 5	1	1	
				H ≤ 2	2		
4	Simple operation	1	Number of persons needed to operate per satellite pass, AE	5 ≤ AE	0		
				3 ≤ AE < 5	1		
				AE ≤ 2	2	2	
5	Simple management	2	Number of people engaged in satellite development, C	C ≥ 30 persons	0		
				20 ≤ C < 30 persons	1		
				10 ≤ C < 20 persons	2	4	
				C < 10 persons	3		
6	Simple handling	1	No hazardous/explosive alternative is chosen to make satellite handling easier	NO	0		
				YES	1	1	
7	Risk taking	1	Screening and management of individual parts based on test results (e.g., radiation) is carried out	All parts	0		
				All non-space qualified COTS parts	1		
				Only mission critical parts or no screening and management	2	2	
8	Risk taking	2	Percentage of non-space qualified COTS parts/material usage, D	D ≤ 10%	0		
				10 < D ≤ 50%	1		
				50 < D ≤ 90%	2		
				90% < D	3	6	

9	Risk taking	2	Use of non-flight proven technology, non-space qualified manufacturing, procurement of components via Internet from unknown manufacturers are allowed and encouraged to achieve the required specifications at lesser cost and/or shorter schedule	NO	0		
				YES	1	2	
10	Risk taking	2	Single-point-of-failure is allowed in satellite design to make satellite simple or to comply with launch provider's requirements, etc	NO	0		
				YES	1	2	
11	Risk mitigation	5	Risk is evaluated and managed based on collective experience and knowledge of team members rather than expensive and/or time-consuming testing and/or analysis with heavy documents	NO	0		
				YES	1	5	
12	Reliability requirement	4	Failure of single satellite jeopardise the overall satellite program (replenishing satellite can be built and launched fairly easily)	YES	0	0	
				NO	1		
13	Reliability requirement	2	Consecutive mission down time until recovery is allowed up to F	$F \leq 90$ minutes	0		
				90 minutes $< F \leq 1$ day	1		
				1 day $< F \leq 1$ week	2		
				1 week $< F$	3	6	
14	Mission duration	1	Satellite mission duration, E	$E \geq 5$ years	0		
				$3 \leq E < 5$ years	1		
				$2 \leq E < 3$ years	2	2	
				$1 \leq E < 2$ years	3		
				$E < 1$ years	4		
15	Launch	5	Access to space is prioritized by designing launcher compatibility (i.e., POD) or having mission less dependent on orbit	NO	0		
				YES, either launch compatibility or non-strict orbit requirements	1	5	
				YES, both launch compatibility and non-strict orbit requirements	2		

16	Waste minimization	8	Waste associated with transportation time (satellite hardware, human) and communication delay (emails exchange) is minimized by conducting the satellite development/integration/testing at one place with all the team members located within close proximity as much as possible	NO	0		
				YES	1	8	
Total number of points						76	

In Table 3, the answers for the case of HORYU-II [13], a satellite developed by Kyushu Institute of Technology and launched in 2012, are shown as examples. The total number of points of HORYU-II is 76. The far right column in Table 3 is left intentionally blank. Using this blank column, readers are encouraged to answer these questions for their own satellites. The answers collected for various satellites are detailed in Appendix B.

The questions in Table 3 can be considered at any time during the system life cycle. We may use this table to set the target at the start of the program, to evaluate the ongoing program at the middle of it, or to reflect upon the program at the end of it. Appendix B gives answers given by various satellites. The answers were collected through emails (ZA-AeroSat (QB50 CubeSat) [14] and SNUSAT-1 (QB 50 CubeSat) [15]) or during exercise sessions at the workshop in Rome in December 2015. The summary and description of each satellite is given in Appendix C. In total, there are answers from 35 existing satellites and 8 hypothetical satellites. Some of the existing satellite ended their missions, some are not yet launched. Among the 35 existing satellite, the average score is 68 points. The highest score is 90 points for ZA-AeroSat (QB50). There are two satellites with a score smaller than 50 points, Tsinghua-Xinwei Telecom Smart Tel Satellite (Tsinghua University, China) and LARES (Sapienza University of Rome). Both satellites are expensive and took a long time to develop.

Table 4 gives the distribution of the answers given by the 35 existing satellites (up to No.35 in Appendix C). The 35 satellites were further divided into academic, i.e. built by universities for academic or training purpose, and non-academic. It is interesting to see that the majority of satellites cost less than 3 million USD. On the other hand, it takes longer than 2 years from program start to delivery for many satellites. This is especially true for academic satellites.

Then, almost two-third of the 35 satellites had more than 10 persons engaged in satellite development (Q5). It is also especially true for academic satellites.

It can be seen that academic satellites take more risk than non-academic satellites. Parts screening was done for some of non-academic satellites, but rarely for academic satellites (see Q7). Academic satellites rely heavily on the use of non-space qualified COTS parts (Q8) and the use of non-flight proven technologies is encouraged for most of academic satellites, but not encouraged for most of non-academic satellites (Q9).

Moreover, more than two-third of the satellites, academic and non-academic, allow single-point-of-failure (Q10), evaluate and manage risks based on experience and knowledge of the team (Q11), and allow consecutive mission downtime longer than one day (Q13). Finally, more than two-third of the satellites, academic and non-academic, assumes a mission duration shorter than 2 years (Q14) and tries to minimize waste (Q16).

From these results, we can see that there is still room for improvement in terms of cutting the delivery time and the number of people engaged in a satellite development. Academic satellites take more risk than non-academic satellites, which is not surprising. As many satellite programs still rely on the success of single satellite mission (Q12), non-academic satellites still hesitate to take more risk. As the satellite missions diversify and more constellation programs appear, we will see bolder approaches.

Table 4 Distribution of the answers given by 35 existing satellites

No	Category	Weight	Question	Scale	Mark	Number of satellites answered		
						Academic	Non-academic	Total
1	Total cost	5	If your satellite program is a single satellite program, answer this question. Total cost including: a satellite, non-recurring cost (e.g. infrastructure investment, etc), launch, and operation, A	A ≥ 15MUSD	0	0	0	0
				10MUSD ≤ A < 15MUSD	1	0	1	1
				5MUSD ≤ A < 10MUSD	2	2	3	5
				3MUSD ≤ A < 5MUSD	3	1	0	1
				A< 3MUSD	4	21	3	24
1’	Total cost	5	If your satellite program	A’ ≥ 10MUSD	0	0	0	0

			contains multiple satellites, answer this question. Total cost including: satellites, non-recurring cost (e.g. infrastructure investment, etc), launch, and operation divided by the number of satellites, A’	5MUSD ≤ A’ < 10MUSD	1	0	0	0
				2MUSD ≤ A’ < 5MUSD	2	0	1	1
				1MUSD ≤ A’ < 2MUSD	3	0	2	2
				A’ < 1MUSD	4	0	1	1
2	Satellite delivery time	5	Time from the program start to delivery, B	B ≥ 3 years	0	8	4	12
				2 ≤ B < 3 years	1	8	2	10
				1 ≤ B < 2 years	2	6	3	9
				6 months ≤ B < 1 year	3	2	2	4
				B < 6 months	4	0	0	0
3	Simple satellite	1	Number of mission payloads, H	5 ≤ H	0	3	5	8
				3 ≤ H < 5	1	5	1	6
				H ≤ 2	2	16	5	21
4	Simple operation	1	Number of persons needed to operate per satellite pass, AE	5 ≤ AE	0	0	1	1
				3 ≤ AE < 5	1	5	0	5
				AE ≤ 2	2	19	10	29
5	Simple management	2	Number of people engaged in satellite development, C	C ≥ 30 persons	0	3	0	3
				20 ≤ C < 30 persons	1	1	4	5
				10 ≤ C < 20 persons	2	12	2	14
				C < 10 persons	3	8	5	13
6	Simple handling	1	No hazardous/explosive alternative is chosen to make satellite handling easier	NO	0	0	4	4
				YES	1	24	7	31
7	Risk taking	1	Screening and management of individual parts based on test results (e.g., radiation) is carried out	All parts	0	1	1	2
				All non-space qualified COTS parts	1	4	5	9
				Only mission critical parts or no screening and management	2	19	5	24
8	Risk taking	2	Percentage of non-space qualified COTS parts/material usage, D	D ≤ 10%	0	0	2	2
				10 < D ≤ 50%	1	3	3	6
				50 < D ≤ 90%	2	3	3	6
				90% < D	3	18	3	21

9	Risk taking	2	Use of non-flight proven technology, non-space qualified manufacturing, procurement of components via Internet from unknown manufacturers are allowed and encouraged to achieve the required specifications at lesser cost and/or shorter schedule	NO	0	2	8	10
				YES	1	22	3	25
10	Risk taking	2	Single-point-of-failure is allowed in satellite design to make satellite simple or to comply with launch provider's requirements, etc	NO	0	2	2	4
				YES	1	21	9	30
11	Risk mitigation	5	Risk is evaluated and managed based on collective experience and knowledge of team members rather than expensive and/or time-consuming testing and/or analysis with heavy documents	NO	0	2	2	4
				YES	1	22	9	31
12	Reliability requirement	4	Failure of single satellite jeopardise the overall satellite program (replenishing satellite can be built and launched fairly easily)	YES	0	14	8	22
				NO	1	10	3	13
13	Reliability requirement	2	Consecutive mission down time until recovery is allowed up to F	$F \leq 90$ minutes	0	1	0	1
				90 minutes $< F \leq$ 1 day	1	1	1	2
				1 day $< F \leq$ 1 week	2	6	6	12
				1 week $< F$	3	16	4	20
14	Mission duration	1	Satellite mission duration, E	$E \geq 5$ years	0	0	1	1
				$3 \leq E < 5$ years	1	2	0	2
				$2 \leq E < 3$ years	2	4	1	5
				$1 \leq E < 2$ years	3	9	6	15
				$E < 1$ years	4	9	3	12
15	Launch	5	Access to space is prioritized by designing launcher compatibility (i.e., POD) or having mission less dependent on orbit	NO	0	1	1	2
				YES either launch compatibility or non-strict orbit requirements	1	14	5	19
				YES, both launch compatibility and non-strict orbit requirements	2	9	5	14

16	Waste minimization	8	Waste associated with transportation time (satellite hardware, human) and communication delay (emails exchange) is minimized by conducting the satellite development/integration/testing at one place with all the team members located within close proximity as much as possible	NO	0	5	2	7
				YES	1	19	9	28

Appendix D lists the characteristics of some lean satellites in terms of cost, development methodology, quality control, verification strategy, risk management, risk control, radiation measures, and others. They were collected from developers who had various experiences about complying with the requirements of their own satellites.

Based on the discussion during the Rome workshop in December 2015, the questions were revised as listed in Table 5. Some revisions are made to clarify the meaning of the questions, such as Q2, Q5, Q6, Q8, Q10, Q13, Q14 and Q15. The answers of Q9, Q11, Q16 were changed to scaling rather than simple “Yes/No” answer. The maximum score of each question remains the same, giving the maximum total score of 100.

<u>NOTE 2</u>: in Table 5, the changes made from Table 3 are marked in red.

Table 5 Revised scale for lean satellites

No	Category	Weight	Question	Scale	Score	Your satellite
1	Total cost	5	If your satellite program is a single satellite program, answer this question. Total cost including: a satellite, non-recurring cost (e.g. infrastructure investment, etc), launch, and operation, A	A ≥ 15MUSD	0	
				10MUSD ≤ A < 15MUSD	1	
				5MUSD ≤ A < 10MUSD	2	
				3MUSD ≤ A < 5MUSD	3	
				A < 3MUSD	4	
1’	Total cost	5	If your satellite program contains multiple satellites, answer this question. Total cost including: satellites, non-recurring cost (e.g. infrastructure investment, etc), launch, and operation divided	A’ ≥ 10MUSD	0	
				5MUSD ≤ A’ < 10MUSD	1	
				2MUSD ≤ A’ < 5MUSD	2	
				1MUSD ≤ A’ < 2MUSD	3	
				A’ < 1MUSD	4	

			by the number of satellites, A’			
2	Satellite delivery time	5	Time from the program start to delivery, B Time from the program start to delivery of the first satellite if the program contains multiple satellites, B	$B \geq 3$ years	0	
				$2 \leq B < 3$ years	1	
				$1 \leq B < 2$ years	2	
				6 months $\leq B <$ 1 year	3	
				$B <$ 6 months	4	
3	Simple satellite	1	Number of mission payloads, H	$5 \leq H$	0	
				$3 \leq H < 5$	1	
				$H \leq 2$	2	
4	Simple operation	1	Number of persons needed to operate per satellite pass, AE	$5 \leq AE$	0	
				$3 \leq AE < 5$	1	
				$AE \leq 2$	2	
5	Simple management	2	Number of persons (equivalent to full person) engaged in satellite development, C	$C \geq 30$ persons	0	
				$20 \leq C < 30$ persons	1	
				$10 \leq C < 20$ persons	2	
				$C < 10$ persons	3	
6	Simple handling	1	Hazardous/explosive alternative is avoided to make satellite handling easier	NO	0	
				YES	1	
7	Risk taking	1	Screening and management of individual parts based on test results (e.g., radiation) is carried out	All parts	0	
				All non-space graded parts	1	
				Only mission critical parts or no screening and management	2	
8	Risk taking	2	Percentage of non-space graded parts/material usage, D	$D \leq 10\%$	0	
				$10 < D \leq 50\%$	1	
				$50 < D \leq 90\%$	2	
				$90\% < D$	3	
9	Risk taking	1	Use of non-flight proven technology, non-space qualified manufacturing, procurement of components via Internet from unknown manufacturers are allowed and encouraged to achieve the required specifications at lesser cost and/or shorter schedule	Not allowed	0	
				Allowed if necessary	1	
				Allowed and encouraged	2	
10	Risk taking	2	Single-point-of-satellite-failure is allowed in satellite design to make satellite simple	NO	0	
				YES	1	
11	Risk mitigation	1	Risk is evaluated and managed based on collective experience and knowledge of team members rather than expensive and/or time-consuming verifications with heavy documents	Very strong NO	0	
				Strong NO	1	
				NO	2	
				YES	3	
				Strong YES	4	
				Very strong YES	5	

12	Reliability requirement	4	Failure of single satellite jeopardise the overall satellite program (replenishing satellite can be built and launched fairly easily)	YES	0	
				NO	1	
13	Reliability requirement	2	Consecutive mission down time of a single satellite until recovery is allowed up to F	F≤ 90 minutes	0	
				90 minutes < F ≤ 1 day	1	
				1 day < F ≤ 1week	2	
				1 week < F	3	
14	Mission duration	1	Mission required lifetime of each satellite, E	E ≥ 5 years	0	
				3 ≤ E < 5 years	1	
				2 ≤ E < 3 years	2	
				1 ≤ E < 2 years	3	
				E < 1 year	4	
15	Launch	5	Access to space is prioritized by designing launcher compatibility (i.e., POD) or having mission less dependent on orbit	NO	0	
				YES, either launch compatibility or non-specific orbit requirements	1	
				YES, both launch compatibility and non-specific orbit requirements	2	
16	Waste minimization	1	Waste associated with transportation time (satellite hardware, human) and communication delay (emails exchange) is minimized by conducting the satellite development/integration/testing activities at one place with all the team members located within close proximity as much as possible	Waste minimization is not recognized	0	
				Waste minimization is recognized, but not tried	2	
				Waste minimization is recognized and tried	4	
				Waste minimization is recognized, tried, and monitored constantly	6	
				Waste minimization is recognized, tried, and treated as priority items	8	
Total number of points						

Currently, Table 5 can be applied to any type of lean satellites regardless of its mission. Different scales can be established depending on the value a satellite intends to generate for education, for science, for interplanetary, for technology, for business, or else. This work is left as a future task.

Questions in Tables 3 and 5 may be applicable to a satellite program made of up to several satellites, but are difficult to be applied to a constellation program made of tens or hundreds of satellites. It is important to design an individual satellite in such a way that it is scalable to be a part of a constellation, but a question to address that point is missing. Making a series of satellite bus systems is also often used for traditional satellites. Examples of these are GEO telecommunication satellites where major manufacturers offer a line-up of satellite bus series, such as Boeing 702 or Lockheed Martin A2100. These satellite buses are not, however, intended for mass production on a scale of a hundred per year. Mega-constellations assuming over 500 satellites are being planned and to achieve those, a new approach to satellite systems engineering is going to be necessary. The satellite should be designed for mass production, but that is not all. In addition, the total cost of the satellite system architecture, including the ground system and the launch, should be sufficiently low so as to provide quality service to the customer. The operation of a constellation is very different from the operation of a single satellite and Q4 alone in Table 5 misses the point. The service should also be initiated swiftly enough so as to not miss a given business opportunity and Q2 in Table 5 is not enough to address that point. A question related to the time from the program start to the service start should be included. The launch compatibility (Q15) is important for constellations, but those programs require specific orbit to achieve the mission objectives. The number of persons engaged in satellite development (Q5) should be divided into the number of persons in satellite design and persons in satellite production.

Molnau *et al.* [4] wrote an article about a lean satellite concept taking as an example the production in 1990s of the first Iridium generation. At the peak of the launch campaign, an Iridium team assembled one satellite every 4.3 days [16]. Certainly it was a great achievement considering the typical assembly time needed for a satellite as complex as Iridium, which had an average power load of 620W provided by two rotating solar paddles and had three antennas pointing toward different directions. The total mass was nearly 700kg and the satellite size was 4m [17]. If we apply Table 3 or 5 to the Iridium project, however, the tallied score would be low as the project consumed more than 5 billion USD [16] for 66 satellites and it took 5 years from the official program announcement on July 29, 1993 [18], to the completion of the constellation deployment in November 1998.

4. REQUIREMENTS FOR LEAN SATELLITES

Experiences of 18 persons from 15 countries about requirements they had to comply with were collected through the NETS mailing list and are listed in Appendix E. Those who contributed are from Brazil, China, France, Germany, India, Israel, Italy, Japan, Korea, Singapore, South Africa, Spain, Turkey, UK, and USA. These were collected via the NETS mailing list.

Appendix E is divided into several categories: debris mitigation, frequency coordination, satellite registration, safety, passivation, external relationship, export control, and others. It is found that many requirements are in common. Major agreements among the different satellites are highlighted in color in Appendix E and Table 6 lists the main commonalities.

Table 6 Common requirements from Appendix E

Requirement	Number of mentions
Demonstrating the less-than 25 years orbital decay time by analysis	13
Frequency coordination through IARU for the case of amateur radio band	16
International frequency coordination through ITU	11
Domestic coordination with a national body	11
Compliance with domestic regulations regarding the use of ground station	5
Registration of space object with the UN	9
Compliance with safety regulations imposed by launch provider	8
Radio emission after a certain time from satellite separation	11
Vibration test	10
Submission of material list	3
Thermal bakeout	3
Passivation mechanism	5

None of the requirements in Table 6 is unanimous. For example, it is expected that all the satellites shall comply with the launch provider’s safety requirements and that vibration test is required. This can be explained by the fact that Appendix E data were compiled based on the memory of each contributor and some requirements did not stay strongly in the memory of some contributors or the answers were not specific enough to name a specific test.

Based on these findings, the following requirements may be reflected to the ISO/CDV/20991 on small spacecraft standard.

- **Safety**
  Every spacecraft, regardless of its size, mission, value, capability or any other nature, shall comply with general safety requirements. Specific safety requirements depending on the

launcher are stated in the launcher Interface Control Document (ICD).

- **Debris mitigation**
  Every spacecraft, regardless of its size, mission, value, capability or any other nature, shall comply with the debris mitigation requirement.
- **Use of radio frequency**
  Every spacecraft, regardless of its size, mission, value, capability or any other nature, shall comply with international and domestic regulations regarding the use of radio frequencies. Ground station operations shall also comply with international and domestic regulations. International frequency coordination shall be done through the International Telecommunication Union (ITU) before spacecraft is launched.
- **UN registration**
  Every spacecraft, regardless of its size, mission, value, capability or any other nature, shall be registered to the United Nations (UN) after launch. The registration is typically done through a government body of the country that owns the spacecraft.
- **Launch interface**
  Once a launcher ICD is agreed as a part of launch contract, the payload, i.e., spacecraft or satellite, shall comply with the ICD.
- **Testing**
  A unit based on COTS parts and technology shall be qualified against the test level and duration described in ISO-19683 before being sold as "a space unit" to provide the minimum assurance that it has a certain level of tolerance against the space environment.
- **CubeSat**
  If a spacecraft is to be launched as a CubeSat, it shall comply with the requirements described in ISO-17770.

5. Applicability to ISO-20991

In February 2016, a Committee Draft for Comments, ISO/CDC/20991 "Space systems — Requirements for small spacecraft" was issued. The CDC version is a result of discussion at the Rome workshop in December 2016 and coordination between Japanese/French SC14 delegations after the December workshop.

The scope of ISO/CDC/20991 is the following:

"This standard describes minimum requirements for small spacecraft.

Small spacecraft may employ untraditional spacecraft development and management philosophy. These spacecraft projects are usually budget-limited or mass-limited, which makes a single (exclusive) launch unaffordable.

The scope of this standard encompasses different categories of small spacecraft, so-called mini-, micro-, nano-, pico- and femto-, as well as CubeSat spacecraft. Therefore, for the sake of convenience, the term "small spacecraft" is used throughout this document as a generic term.

Regardless of the development philosophy, there are minimum requirements every spacecraft shall comply with. This standard explicitly states those requirements and also refers to existing applicable standards. In that sense, this standard serves as the top standard to cover the minimum requirements for various stages of small spacecraft system life-cycle with emphasis on design, launch, deployment, operation, and disposal phases. In this way, (1) safety, (2) harmlessness to co-passengers and launcher, and (3) debris mitigation, are all assured.

This standard is addressed to small spacecraft developers, as well as dispenser providers and/or the launch operators."

From the scope definition, 9 requirements are listed. Most of those are the same as those written in the fourth chapter of this report with some minor modifications and additions. The 9 requirements are listed as:

5.1 Launch interface

5.2 Safety

5.3 Main payload, adjacent payload(s), and launcher harmlessness

5.4 Debris mitigation

5.5 Use of radio frequencies

5.6 UN registration

5.7 Verification for design and manufacturing

5.8 CubeSat

6 Verification

“5.3 Main payload, adjacent payload(s), and launcher harmlessness” was added to the ISO draft to address the issues related to piggy-back launch. In ISO/CDC/20991, the requirements are written as:

*“**5.3 Main payload, adjacent payload(s), and launcher harmlessness***

5.3.1 Separation

Capability of separation and jettisoning from launcher, with respect to given parameters, such as speed, cone angle separation or others, in order to avoid any collision during separation, shall be demonstrated.

An aborted separation in case multiple point attachments are not fully released shall not create a situation which might induce damage to adjacent payload(s) or to the launcher.

5.3.2 Out-gassing

If a small spacecraft is launched as an auxiliary payload, i.e. piggy-back payload, or shares the launch vehicle with others, it shall satisfy maximum out-gassing criteria specified in the launcher ICD.

Note: If not specified in the launcher ICD, the numbers in ISO-17770 shall be used.

5.3.3 Dummy specimen

If a small spacecraft is launched as an auxiliary payload, i.e. piggy-back payload, or shares the launch vehicle with others, a dummy spacecraft representative for MCI shall be prepared according to the launch contract.

Note: in case the foreseen small spacecraft, as auxiliary spacecraft, would not be in time, or would finally not be accepted to be launched together with the main paying passenger, this dummy may be mounted on the launcher, but not separated from the launcher, to avoid some last minute dynamic coupled analysis.

5.3.4 Power state, radio transmission and deployable mechanism

If a small spacecraft is launched as an auxiliary payload, i.e. piggy-back payload, or shares the launch vehicle with others, it shall comply with requirements on the state of satellite power during launch phase, the start of radio emission and the activation of deployable mechanism specified in the launcher ICD.

Note: Typically, small spacecraft are required to turn off the power with multiple inhibits during its launch phase. As per the launcher ICD, it is also required to start the radio transmission and activate the deployable mechanism only after a certain time has elapsed from the launch vehicle separation or the release into space.

Note: "Turn off" means no current flows in the circuit.

5.3.5 Radio frequency compatibility

The radio frequency compatibility with launcher, the main payload(s) and/or other small spacecraft shall be assured as required in the ICD under launch operator management."

"5.7 Verification for design and manufacturing" corresponds to testing requirements as described in the fourth chapter with slight modifications:

"5.7 Verification for design and manufacturing

Testing is a part of verification. Small spacecraft try to minimize the testing cost while managing risks. ISO-19683 describes minimum test requirements to qualify the design and manufacturing methods of small spacecraft and units, and to accept the final products.

ISO-19683 puts emphasis on achieving reliability against infant mortality after launch to orbit while maintaining low-cost and fast-delivery.

A unit based on COTS parts and technology shall be qualified against the test level and duration described in ISO-19683 to provide the minimum assurance that it has a certain level of tolerance against the launch environment and the space environment after launch vehicle separation."

"6 Verification" was added to address the issue on how the requirements described above should be verified. In ISO/CDC/20991, it is written as:

"6 Verification

Verification of compliance with requirements listed below shall be documented with sufficient precision and quality to allow review and approval by the appropriate authority.

- *Safety (5.2)*
- *Main payload, adjacent payload(s), and launcher harmlessness (5.3)*
- *Debris mitigation (5.4)*
- *Use of radio frequencies (5.5)*
- *Testing related to safety, debris mitigation, and harmlessness to co-passengers and launcher (5.7)*
- *CubeSat (5.8)*

The documentation regarding these verifications may be required by the launch operator to guaranty harmlessness to the main passenger or the co-passengers of the flight."

After receiving comments on ISO/CDC/20991 from ISO/TC20/SC14 P-member countries until April 2016, the revised version, the Committee Draft for Voting ISO/CDV/20991, was submitted to ISO. The draft was circulated for voting from July 6 to September 28, 2016. The draft obtained more than two-third majority of the P-member votes. Although the draft obtained enough votes to proceed to a Draft International Standard (DIS), a unanimous consensus of having the document as an International Standard was not obtained. During ISO/TC20/SC14 plenary meeting in June 2017, it was decided that the ISO project proceeds to make a Technical Specification instead of International Standard and the draft be balloted as a Draft Technical Specification. A Technical Specification addresses work where it is believed that there will be a future, but not immediate, possibility of agreement on an International Standard. It can contain normative descriptions. The Technical Specification was approved by ballots in fall 2017 and will be published early 2018. Three years after the publication of the ISO/TS, the document will be voted again to decide whether it will be modified to become an International Standard or not. The lean satellite community will continue giving important inputs to the ISO document.

6. CONCLUSION

A lean satellite is a satellite that utilizes non-traditional, risk-taking development and management approaches with the aim to provide value of some kind to the customer at low-cost and without taking much time to realize the satellite mission. The satellite size is small merely as a result of seeking low-cost and fast-delivery. To achieve these two characteristics, the satellite design relies on the use of non-space-qualified (or non-space-graded) COTS units, and the satellite size inherently becomes smaller. The design accepts a certain level of risk associated with the use of COTS parts. The number of team members also becomes smaller with the lean approach. Approaches taken for lean satellites are different from the ones used for traditional satellites for which reliability often supersedes cost and schedule as shown in Figure 2.

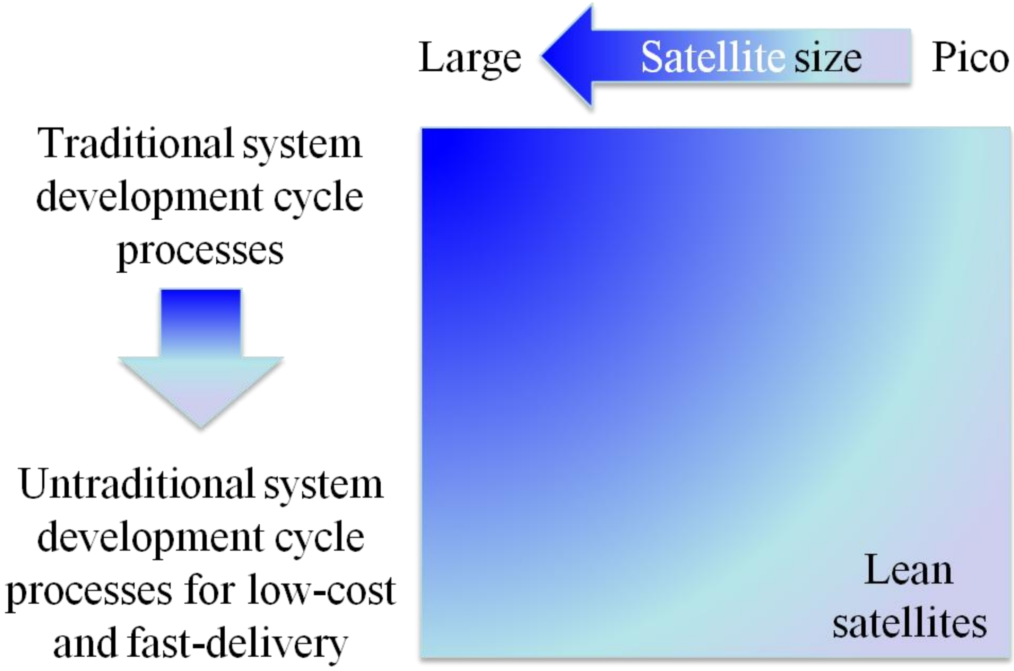

Figure 2 Applicability of lean satellite concepts

From the study group 4.18, the new concept of "lean satellite" is born. It started from a discussion on how to designate small satellites, but as the study progressed, new research opportunities emerged and they may have an impact on systems engineering disciplines. Traditionally, satellite stakeholders are mostly limited to governments in rich countries including military and satellite service providers. Proliferation of lean satellites is changing the landscape and universities, small businesses, and developing countries are emerging as new stakeholders. For the traditional satellite stakeholders, dependability on satellite service is a high priority to ensure high return on investment and systems engineering disciplines have evolved to provide a flawless system no matter how complex the system became. There may be lean satellite stakeholders who are favoring reliability and dependability and hence, apply traditional space systems engineering disciplines to their satellite program. For some of the lean satellite stakeholders, however, the priority is to utilize satellites in space, but not with 100% dependability. Systems engineering disciplines used for traditional satellites need to be reexamined from the perspective of delivering value to the new stakeholders.

An effort to reexamine in terms of verification, especially testing, already started in a project to develop ISO-19683 standard, but there are other issues. The questions described in lean satellite scale, and listed in Table 5, give a direction for other areas to be further investigated.

One issue is optimum simplicity, which involves design and management philosophy. If a satellite is simple and involves a small number of persons, there will be few problems associated with interface, communication, integration and others. At the same time, the satellite capability is limited due to limited knowledge and skills of the team members, limited functionalities of the system, and limited workforce. Hence, to find the optimum simplicity depends on whether the value generated by the satellite can satisfy the stakeholder's needs. It might also be possible to theorize the optimum simplicity.

Waste minimization is not yet fully implemented in lean satellites development and management, although many persons recognize its importance as seen in Table 4. The best practice of waste minimization should be collected and shared among the lean satellite community.

Risk management is an important area to be reexamined. Although lean satellites take more risks than traditional satellites, risks management is still necessary. However, efforts spent in risks management should be less than those by traditional satellites. Hence investigating the risks management processes may be an interesting subject area.

To promote the lean satellite concept further, a forum to discuss and study it is necessary. Although the study group 4.18 finishes its role with this final report in 2016, it is preferable to have an annual meeting where people interested in the concepts of lean satellite get together, make research presentations, exchange ideas and discuss collaborations. The community built around the study group 4.18 needs to work hard to realize and sustain such annual meetings.

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APPENDIX A - List of contributors

1. Co-Chair
    - Mengu Cho, Kyushu Institute of Technology
    - Filippo Graziani, GAUSS SRL
2. Secretary
    - John Polansky, Kyushu Institute of Technology
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    - Muhammad Alkali, Kyushu Institute of Technology
    - Hala Almubarak, Kyushu Institute of Technology
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    - Zulkifli Abdul Aziz, ATSB
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    - Merlin Barschke, TU Berlin
    - Igor Belokonov, Samara State Aerospace
    - Sidi Bendoukha, Kyushu Institute of Technology
    - Barbara Bermudez-Reyes, Autonomous University of Nuevo Leon
    - Cesar Bernal, ISIS
    - Christophe Bonnal, CNES
    - Benjamin Bonsu, Kyushu Institute of Technology
    - Eduardo E. Burger, LIT/INPE
    - Chantal Cappelletti, Universidad de Brasilia
    - Gustavo Carpignano, DIYSATELLITE
    - Joseph Casas, NASA MSFC
    - Adelaida Castillo Duran, Kyushu Institute of Technology
    - Aitor Conde, GAUSS SRL
    - Alessandro Cuttin, University of Trieste

- Erdenebaatar Dashdondog, Kyushu Institute of Technology
- Candido Osvaldo De Moura, INPE
- Julian Dines, Science and Technology Facilities Council
- Adrian Done, University Suceava Romania
- Walter Dos Santos, INPE
- Otavio Durao, INPE
- Laurent Dusseau, Montpellier University Space Center
- Matteo Emanuelli, University of Picardie Jules
- Essien Ewang, Kyushu Institute of Technology
- Dmytro Faizullin, Kyushu Institute of Technology
- Pauline Faure, Kyushu Institute of Technology
- Jorge Alfredo Ferrer Perez, U.N.A.M-Mexico
- David Finkleman, SkySentry
- Johnny Finnham, ICEYE Ltd
- Roger Franzen, Australian National University
- Carlos Romo Fuentes, U.N.A.M-Mexico
- Hiroshi Fukuda, Kyushu Institute of Technology
- Paolo Gasbarri, Sapienza University of Rome
- Steve Greenland, Clyde Space
- Akshay Gulati, IIT Madras
- Jian Guo, TU Delft
- Norizam Hamzah, ATSB
- Daniel Hernandez, Devil-Hop
- Higuchi, Fuji Limited
- Keiichi Hirako, IHI
- Junpei Horibe, Kyushu Institute of Technology
- Shigeru Imai, JAMSS
- Sana Iyban, ICEYE Ltd
- Alex Jablonski, Canadian Space Agency
- Jyh-Ching Juang, National Cheng Kung University
- Thomas Jurczynski, Kyushu Institute of Technology
- Rei Kawashima, UNISEC

- Hideaki Kikuchi, Astrex
- Otto Koudelka, TU Graz
- Eduardo Martin Lopez, ISAE-Supaero
- Kay Soon Low, Nanyang Technological University
- Ayman Mahmoud, NARSS
- Yoshihiro Mashima, Kyushu Institute of Technology
- Marta Massimiani, GAUSS SRL
- Hirokazu Masui, Kyushu Institute of Technology
- Naomi Mathers, Australian National University
- Nguyen Duc Minh, Kyushu Institute of Technology
- Kinya Miyagi, Kyushu Institute of Technology
- Yasuyuki Miyazaki, Nihon University
- Jorge Monteiro, University of Beira Interior
- Shinichi Nakasuka, University of Tokyo
- Eiko Okada, Astrex
- Yumiko Okada, Kyushu Institute of Technology
- Mikhail Ovchinnikov, KIAM RAS
- Alime Ozyildirim, ASELSAN
- Giovanni Palmerini, Sapienza University of Rome
- Claudio Paris, Sapienza University of Rome
- Ji Hyun Park, Seoul National University
- Jose Antonio Perez Gurmein, U.N.A.M-Mexico
- Franco Pérez Lissi, University of Vigo
- Ammarin Pimnoo, Kyushu Institute of Technology
- Eduardo Pinho, University of Beira Interior
- Mauro Pontani, Sapienza University of Rome
- Jordi Puig-Suari, Cal Poly
- Rahmi Rahmatillah, Kyushu Institute of Technology
- Jose Alberto Ramirez A., U.N.A.M-Mexico
- Martin Richter, SSC
- Bagus Adiwiluhung Riwanto, Aalto University
- Daniel Rockberger, IAI

- Rafael Rodriguez, Kyushu Institute of Technology
- Stephan Roemer, Astro-und Feinwerktechnik Adlershof GmbH
- Dmitry Roldugin, KIAM
- Manola Romeros, ONERA
- Mathias Rousselet, Montpellier University
- Rainer Sandau, IAA
- Klaus Schilling, University Würzburg
- Bungo Shiotani, University of Florida
- Ito Sho, Kyushu Institute of Technology
- E. Simons, University of Surrey
- Frederick Slane, SIF
- Vladislav Solovey, GAUSS SRL
- Fernando Stancato, EMBRAER
- Herman Steyn, Stellenbosch University
- Stephan Stolz, Astro-und Feinwerktechnik Adlershof GmbH
- Nguyen Tien Su, Kyushu Institute of Technology
- Bianca Szasz, Kyushu Institute of Technology
- Sakurako Takahashi, JAMSS
- Taiwo Tejumola, Kyushu Institute of Technology
- Auro Tikani, INPE
- Tuomas Tikka, Aalto University
- Sheral Tissera, NTU
- Marco Truglio, GAUSS SRL
- Akira Tsuchida, JAMSS
- Sibel Turkoglu, Istanbul Technical University
- Craig Underwood, University of Surrey
- Hayakawa Yoshiaki, Canon Electronics
- Gangtie Zheng, Tsinghua University

APPENDIX B - **Results of applying the scale as described in Table 3 to various satellites (1/5)**

No	Category	Weight	Question	Scale	Contributor	Mengu Cho	Mengu Cho	Herman Steyn	Ji Hyun Park	Eduardo Martin Lopez	Fernando Aguado Agelet	Filippo Graziani
					Affiliation	Kyushu Institute of Technology	Kyushu Institute of Technology	Stellenbosch University	Seoul National University	ISAE-Supaero	University of Vigo	GAUSS SRL
					Score	HORYU-II	HORYU-IV	ZA-AeroSat (QB50)	SNUSAT-1 (QB50)	Jump Sat	HUMSAT-D	UNISAT-7
1	Total cost	5	If your satellite program is a single satellite program, answer this question. Total cost including: a satellite, non-recurring cost (e.g. infrastructure investment, etc), launch, and operation, A	A ≥ 15MUSD	0							
				10MUSD ≤ A < 15MUSD	1							
				5MUSD ≤ A < 10MUSD	2							
				3MUSD ≤ A < 5MUSD	3				15			
				A< 3MUSD	4	20	20	20		20	20	20
1’	Total cost	5	If your satellite program contains multiple satellites, answer this question. Total cost including: satellites, non-recurring cost (e.g. infrastructure investment, etc), launch, and operation divided by the number of satellites, A’	A’ ≥ 10MUSD	0							
				5MUSD ≤ A’ < 10MUSD	1							
				2MUSD ≤ A’ < 5MUSD	2							
				1MUSD ≤ A’ < 2MUSD	3							
				A’ < 1MUSD	4							
2	Satellite delivery time	5	Time from the program start to delivery, B	B ≥ 3 years	0					0		
				2 ≤ B < 3 years	1		5		5			
				1 ≤ B < 2 years	2	10		10			10	10
				6 months ≤ B < 1 year	3							
				B < 6 months	4							
3	Simple satellite	1	Number of mission payloads, H	5 ≤ H	0		0					0
				3 ≤ H < 5	1	1						
				H ≤ 2	2			2	2	2	2	
4	Simple operation	1	Number of persons needed to operate per satellite pass, AE	5 ≤ AE	0							
				3 ≤ AE < 5	1		1					
				AE ≤ 2	2	2		2	2	2	2	2
5	Simple	2	Number of people engaged in	C ≥ 30 persons	0		0					

	manageme nt		satellite development, C	20 ≤ C < 30 persons	1							
				10 ≤ C < 20 persons	2	4				4	4	
				C < 10 persons	3			6	6			6
6	Simple handling	1	No hazardous/explosive alternative is chosen to make satellite handling easier	NO	0							
				YES	1	1	1	1	1	1	1	1
7	Risk taking	1	Screening and management of individual parts based on test results (e.g., radiation) is carried out	All parts	0							
				All non-space qualified COTS parts	1					1		1
				Only mission critical parts or no screening and management	2	2	2	2	2		2	
8	Risk taking	2	Percentage of non-space qualified COTS parts/material usage, D	D ≤ 10%	0							
				10 < D ≤ 50%	1					2		
				50 < D ≤ 90%	2						4	
				90% < D	3	6	6	6	6			6
9	Risk taking	2	Use of non-flight proven technology, non-space qualified manufacturing, procurement of components via Internet from unknown manufacturers are allowed and encouraged to achieve the required specifications at lesser cost and/or shorter schedule	NO	0						0	
				YES	1	2	2	2	2	2		2
10	Risk taking	2	Single-point-of-failure is allowed in satellite design to make satellite simple or to comply with launch provider's requirements, etc	NO	0							
				YES	1	2	2	2	2	2	2	2
11	Risk mitigation	5	Risk is evaluated and managed based on collective experience and knowledge of team members rather than expensive and/or time-consuming testing and/or analysis with heavy documents	NO	0						0	
				YES	1	5	5	5	5	5		5
12	Reliability requiremen t	4	Failure of single satellite jeopardise the overall satellite program (replenishing satellite can be built and launched fairly easily)	YES	0	0	0			0		0
				NO	1			4	4		4	

13	Reliability requirement	2	Consecutive mission down time until recovery is allowed up to F	F ≤ 90 minutes	0							
				90 minutes < F ≤ 1 day	1							
				1 day < F ≤ 1 week	2				4	2	4	4
				1 week < F	3	6	6	6				
14	Mission duration	1	Satellite mission duration, E	E ≥ 5 years	0							
				3 ≤ E < 5 years	1							
				2 ≤ E < 3 years	2	2	2					
				1 ≤ E < 2 years	3						3	3
				E < 1 years	4			4	4	4		
15	Launch	5	Access to space is prioritized by designing launcher compatibility (i.e., POD) or having mission less dependent on orbit	NO	0							
				YES, either launch compatibility or non-strict orbit requirements	1	5	5			5	5	5
				YES, both launch compatibility and non-strict orbit requirements	2			10	10			
16	Waste minimization	8	Waste associated with transportation time (satellite hardware, human) and communication delay (emails exchange) is minimized by conducting the satellite development/integration/testing at one place with all the team members located within close proximity as much as possible	NO	0				0	0	0	
				YES	1	8	8	8				8
Total number of points					-	76	65	90	70	52	63	75

APPENDIX B - Results of applying the scale as described in Table 3 to various satellites (2/5)

No	Category	Weight	Question	Scale	Contributor	Aitor Conde, Marco Truglio	Jose Alberto Ramirez A.	Carlos Romo Fuentes, Jose Antonio Perez Gurmein, Jorge Alfredo Ferrer Perez			Akshay Gulati	Bagus Adiwiluhung Riwanto	Tuomas Tikka	Fernando Stancato
					Affiliation	GAUSS SRL	U.N.A.M Mexico	U.N.A.M Mexico			IIT Madras	Aalto University	Aalto University	EMBRAER
					Score	UNISAT-6	ULISES 2.0	Satellite Quetzal			IITM SAT	AALTO-2	AALTO-1	UNOSAT
1	Total cost	5	If your satellite program is a single satellite program, answer this question. Total cost including: a satellite, non-recurring cost (e.g. infrastructure investment, etc), launch, and operation, A	A ≥ 15MUSD	0									
				10MUSD ≤ A < 15MUSD	1									
				5MUSD ≤ A < 10MUSD	2			10		10				
				3MUSD ≤ A < 5MUSD	3									
				A< 3MUSD	4	20	20		20		20	20	20	20
1’	Total cost	5	If your satellite program contains multiple satellites, answer this question. Total cost including: satellites, non-recurring cost (e.g. infrastructure investment, etc), launch, and operation divided by the number of satellites, A’	A’ ≥ 10MUSD	0									
				5MUSD ≤ A’ < 10MUSD	1									
				2MUSD ≤ A’ < 5MUSD	2									
				1MUSD ≤ A’ < 2MUSD	3									
				A’ < 1MUSD	4									
2	Satellite delivery time	5	Time from the program start to delivery, B	B ≥ 3 years	0		0				0	0	0	
				2 ≤ B < 3 years	1			5	5	5				5
				1 ≤ B < 2 years	2									
				6 months ≤ B < 1 year	3	15								
				B < 6 months	4									
3	Simple satellite	1	Number of mission payloads, H	5 ≤ H	0	0								
				3 ≤ H < 5	1				1				1	
				H ≤ 2	2		2	2		2	2	2		2
4	Simple operation	1	Number of persons needed to operate per satellite pass, AE	5 ≤ AE	0									
				3 ≤ AE < 5	1				1	1				

				AE ≤ 2	2	2	2	2			2	2	2	2
5	Simple management	2	Number of people engaged in satellite development, C	C ≥ 30 persons	0						0			
				20 ≤ C < 30 persons	1									
				10 ≤ C < 20 persons	2			4	4	4			4	4
				C < 10 persons	3	6	3					6		
6	Simple handling	1	No hazardous/explosive alternative is chosen to make satellite handling easier	NO	0									
				YES	1	1	1	1	1	1	1	1	1	1
7	Risk taking	1	Screening and management of individual parts based on test results (e.g., radiation) is carried out	All parts	0									
				All non-space qualified COTS parts	1	1				1				1
				Only mission critical parts or no screening and management	2		2	2	2		2	2	2	
8	Risk taking	2	Percentage of non-space qualified COTS parts/material usage, D	D ≤ 10%	0									
				10 < D ≤ 50%	1									
				50 < D ≤ 90%	2		4							
				90% < D	3	6		6	6	6	6	6	6	6
9	Risk taking	2	Use of non-flight proven technology, non-space qualified manufacturing, procurement of components via Internet from unknown manufacturers are allowed and encouraged to achieve the required specifications at lesser cost and/or shorter schedule	NO	0							0		
				YES	1	2	2	2	2	2	2		2	2
10	Risk taking	2	Single-point-of-failure is allowed in satellite design to make satellite simple or to comply with launch provider's requirements, etc	NO	0									
				YES	1	2	2	2	2	2	2	2	2	
11	Risk mitigation	5	Risk is evaluated and managed based on collective experience and knowledge of team members rather than expensive and/or time-consuming testing and/or analysis with heavy documents	NO	0									
				YES	1	5	5	5	5	5	5	5	5	5
12	Reliability requirement	4	Failure of single satellite jeopardise the overall satellite program (replenishing satellite can be built and launched fairly easily)	YES	0	0	0	0	0	0	0		0	
				NO	1							4		4

13	Reliability requirement	2	Consecutive mission down time until recovery is allowed up to F	F ≤ 90 minutes	0									
				90 minutes < F ≤ 1 day	1									
				1 day < F ≤ 1 week	2	4						4		
				1 week < F	3		6	6	6	6	6		6	6
14	Mission duration	1	Satellite mission duration, E	E ≥ 5 years	0									
				3 ≤ E < 5 years	1				1					
				2 ≤ E < 3 years	2					2				
				1 ≤ E < 2 years	3	3		3			3		3	3
				E < 1 years	4		4					4		
15	Launch	5	Access to space is prioritized by designing launcher compatibility (i.e., POD) or having mission less dependent on orbit	NO	0									
				YES, either launch compatibility or non-strict orbit requirements	1		5	5	5	5	5		5	5
				YES, both launch compatibility and non-strict orbit requirements	2	10						10		
16	Waste minimization	8	Waste associated with transportation time (satellite hardware, human) and communication delay (emails exchange) is minimized by conducting the satellite development/integration/testing at one place with all the team members located within close proximity as much as possible	NO	0									
				YES	1	8	8	8	8	8	8	8	8	8
Total number of points					-	85	66	63	69	60	64	76	67	74

APPENDIX B - Results of applying the scale as described in Table 3 to various satellites (3/5)

No	Category	Weight	Question	Scale	Contributor	Jordi Puig-Suari	Martin Richter	E. Simons	Claudio Paris	Jyh-Ching Juang	Sibel Turkoglu	Steve Greenland			
					Affiliation	Cal Poly	SSC	University of Surrey	Sapienza University of Rome	National Cheng Kung Univ.	Istanbul Technical University	Clydespace			
					Score	Exocube	Alsat-1N	STRAND-1	LARES	PACE	BeEagleSat	P	S	O	UKube-1
1	Total cost	5	If your satellite program is a single satellite program, answer this question. Total cost including: a satellite, non-recurring cost (e.g. infrastructure investment, etc), launch, and operation, A	A ≥ 15MUSD	0										
				10MUSD ≤ A < 15MUSD	1										
				5MUSD ≤ A < 10MUSD	2				10						
				3MUSD ≤ A < 5MUSD	3										
				A< 3MUSD	4	20	20	20		20	20				
1’	Total cost	5	If your satellite program contains multiple satellites, answer this question. Total cost including: satellites, non-recurring cost (e.g. infrastructure investment, etc), launch, and operation divided by the number of satellites, A’	A’ ≥ 10MUSD	0										
				5MUSD ≤ A’ < 10MUSD	1										
				2MUSD ≤ A’ < 5MUSD	2							10			
				1MUSD ≤ A’ < 2MUSD	3								15		15
				A’ < 1MUSD	4									20	
2	Satellite delivery time	5	Time from the program start to delivery, B	B ≥ 3 years	0				0	0		0			0
				2 ≤ B < 3 years	1	5					5		5		
				1 ≤ B < 2 years	2		10							10	
				6 months ≤ B < 1 year	3			15							
				B < 6 months	4										
3	Simple satellite	1	Number of mission payloads, H	5 ≤ H	0			0							0
				3 ≤ H < 5	1		1								
				H ≤ 2	2	2			2	1	2	2	2	2	
4	Simple operation	1	Number of persons needed to operate per satellite pass, AE	5 ≤ AE	0				0						
				3 ≤ AE < 5	1		1				1				
				AE ≤ 2	2	2		2		2		2	2	2	2
5	Simple management	2	Number of people engaged in satellite development, C	C ≥ 30 persons	0										
				20 ≤ C < 30 persons	1				2	2		2			
				10 ≤ C < 20 persons	2	4		4					4		

				C < 10 persons	3		6				6			6	6
6	Simple handling	1	No hazardous/explosive alternative is chosen to make satellite handling easier	NO	0							0	0	0	0
				YES	1	1	1	1	1	1	1				
7	Risk taking	1	Screening and management of individual parts based on test results (e.g., radiation) is carried out	All parts	0		0		0						
				All non-space qualified COTS parts	1							1			
				Only mission critical parts or no screening and management	2	2		2		2	2		2	2	2
8	Risk taking	2	Percentage of non-space qualified COTS parts/material usage, D	D ≤ 10%	0				0					0	
				10 < D ≤ 50%	1		2				2	2	2		
				50 < D ≤ 90%	2			4							4
				90% < D	3	6				6					
9	Risk taking	2	Use of non-flight proven technology, non-space qualified manufacturing, procurement of components via Internet from unknown manufacturers are allowed and encouraged to achieve the required specifications at lesser cost and/or shorter schedule	NO	0				0			0	0	0	0
				YES	1	2	2	2		4	2				
10	Risk taking	2	Single-point-of-failure is allowed in satellite design to make satellite simple or to comply with launch provider's requirements, etc	NO	0										
				YES	1	2	2	2	2	2	2	2	2	2	2
11	Risk mitigation	5	Risk is evaluated and managed based on collective experience and knowledge of team members rather than expensive and/or time-consuming testing and/or analysis with heavy documents	NO	0		0		0						
				YES	1	5		5		5	5	5	5	5	5
12	Reliability requirement	4	Failure of single satellite jeopardise the overall satellite program (replenishing satellite can be built and launched fairly easily)	YES	0	0	0		0	0		0			0
				NO	1			4			4		4	4	
13	Reliability requirement	2	Consecutive mission down time until recovery is allowed up to F	F ≤ 90 minutes	0										
				90 minutes < F ≤ 1 day	1			2							
				1 day < F ≤ 1 week	2		4		4						

				1 week < F	3	6				6	6	6	6	6	6
14	Mission duration	1	Satellite mission duration, E	$E \geq 5$ years	0				0						
				$3 \leq E < 5$ years	1										
				$2 \leq E < 3$ years	2			2							
				$1 \leq E < 2$ years	3	3	3					3	3		3
				$E < 1$ years	4					4	4			3	
15	Launch	5	Access to space is prioritized by designing launcher compatibility (i.e., POD) or having mission less dependent on orbit	NO	0						0				
				YES, either launch compatibility or non-strict orbit requirements	1		5		5						
				YES, both launch compatibility and non-strict orbit requirements	2	10		10		10		10	10	10	10
16	Waste minimization	8	Waste associated with transportation time (satellite hardware, human) and communication delay (emails exchange) is minimized by conducting the satellite development/integration/testing at one place with all the team members located within close proximity as much as possible	NO	0		0		0						
				YES	1	8		8		8	8	8	8	8	8
Total number of points					-	78	57	83	26	73	70	53	70	80	63

APPENDIX B - Results of applying the scale as described in Table 3 to various satellites (4/5)

No	Category	Weight	Question	Scale	Contributor	Klaus Schilling	Philip Bangest	Daniel Rockberger	Gangtie Zheng	Roemer Stephan		Alessandro Cuttin	Yasuyuki Miyazaki	
					Affiliation	Univ. Würzburg	Univ. Würzburg	IAI	Tsinghua university	Astro-und Feinwerktechik		University of Trieste	Nihon University	
					Score	UWE1, 2, 3	UWE-3		Tsinghua - Xinwei Telecom Smart Tel Sat.	TET-X	LAPAN-TUBSAT	Atmocube	SEEDS-II	SPROUT
1	Total cost	5	If your satellite program is a single satellite program, answer this question. Total cost including: a satellite, non-recurring cost (e.g. infrastructure investment, etc), launch, and operation, A	A ≥ 15MUSD	0									
				10MUSD ≤ A < 15MUSD	1				5					
				5MUSD ≤ A < 10MUSD	2			10		10				
				3MUSD ≤ A < 5MUSD	3									
				A< 3MUSD	4	20	20				20	20	20	20
1’	Total cost	5	If your satellite program contains multiple satellites, answer this question. Total cost including: satellites, non-recurring cost (e.g. infrastructure investment, etc), launch, and operation divided by the number of satellites, A’	A’ ≥ 10MUSD	0									
				5MUSD ≤ A’ < 10MUSD	1									
				2MUSD ≤ A’ < 5MUSD	2									
				1MUSD ≤ A’ < 2MUSD	3									
				A’ < 1MUSD	4									
2	Satellite delivery time	5	Time from the program start to delivery, B	B ≥ 3 years	0		0	0						0
				2 ≤ B < 3 years	1				5					
				1 ≤ B < 2 years	2	10				10			10	
				6 months ≤ B < 1 year	3						15	15		
				B < 6 months	4									
3	Simple satellite	1	Number of mission payloads, H	5 ≤ H	0			2		0		0		
				3 ≤ H < 5	1						1			1
				H ≤ 2	2	2	2		2				2	
4	Simple operation	1	Number of persons needed to operate per satellite pass, AE	5 ≤ AE	0									
				3 ≤ AE < 5	1									
				AE ≤ 2	2	2	2	2	2	2	2	2	2	2
5	Simple management	2	Number of people engaged in satellite development, C	C ≥ 30 persons	0							0		
				20 ≤ C < 30 persons	1			2	2					
				10 ≤ C < 20 persons	2	4				4				4

				C < 10 persons	3		6				6		6	
6	Simple handling	1	No hazardous/explosive alternative is chosen to make satellite handling easier	NO	0									
				YES	1	1	1	1	1	1	1	1	1	1
7	Risk taking	1	Screening and management of individual parts based on test results (e.g., radiation) is carried out	All parts	0									
				All non-space qualified COTS parts	1	1			1	1				
				Only mission critical parts or no screening and management	2		2	2			2	2	2	2
8	Risk taking	2	Percentage of non-space qualified COTS parts/material usage, D	D ≤ 10%	0									
				10 < D ≤ 50%	1					2				
				50 < D ≤ 90%	2			4	4					
				90% < D	3	6	6				6	6	6	6
9	Risk taking	2	Use of non-flight proven technology, non-space qualified manufacturing, procurement of components via Internet from unknown manufacturers are allowed and encouraged to achieve the required specifications at lesser cost and/or shorter schedule	NO	0				0	0	0			
				YES	1	2	2	2				2	2	2
10	Risk taking	2	Single-point-of-failure is allowed in satellite design to make satellite simple or to comply with launch provider's requirements, etc	NO	0	0	0		0	0				
				YES	1			2			2	2	2	2
11	Risk mitigation	5	Risk is evaluated and managed based on collective experience and knowledge of team members rather than expensive and/or time-consuming testing and/or analysis with heavy documents	NO	0					0				
				YES	1	5	5	5	5		5	5	5	5
12	Reliability requirement	4	Failure of single satellite jeopardise the overall satellite program (replenishing satellite can be built and launched fairly easily)	YES	0			0		0	0	0	0	
				NO	1	4	4		4					4
13	Reliability requiremen	2	Consecutive mission down time until recovery is allowed up to F	F ≤ 90 minutes	0	0								
				90 minutes < F ≤ 1 day	1			2						

	t			1 day < F ≤ 1 week	2				4	4	4	4		
				1 week < F	3		6						6	6
14	Mission duration	1	Satellite mission duration, E	E ≥ 5 years	0									
				3 ≤ E < 5 years	1									1
				2 ≤ E < 3 years	2				2					
				1 ≤ E < 2 years	3			3				3	3	
				E < 1 years	4	4	4			4	4			
15	Launch	5	Access to space is prioritized by designing launcher compatibility (i.e., POD) or having mission less dependent on orbit	NO	0				0					
				YES, either launch compatibility or non-strict orbit requirements	1			5		5	5	5		5
				YES, both launch compatibility and non-strict orbit requirements	2	10	10						10	
16	Waste minimization	8	Waste associated with transportation time (satellite hardware, human) and communication delay (emails exchange) is minimized by conducting the satellite development/integration/testing at one place with all the team members located within close proximity as much as possible	NO	0	0			0					
				YES	1		8	8		8	8	8	8	8
Total number of points					-	71	78	50	37	51	81	75	85	69

APPENDIX B - Results of applying the scale as described in Table 3 to various satellites (5/5)

No	Category	Weight	Question	Scale	Contributor	Jorge Monteiro, Eduardo Pinho, Ana Azevedo	Mikhail Ovchinnikov	Julian Dines		Dmitry Roldugin	Slane	Johnny Finnham, Sana Iyban	Adrian Done
					Affiliation	University of Beira Interior	KIAM RAS	Science and Technology Facilities Council		KIAM	SIF	ICEYE Ltd	University Suceava Romania
					Score	N/A	Mission design of various satellites	A: High-res CubeSat image concept	B: Multi-spectral nanosat constellation concept	ADCS algorithms, MD, no specific satellites	ISO compliant s/c		
1	Total cost	5	If your satellite program is a single satellite program, answer this question. Total cost including: a satellite, non-recurring cost (e.g. infrastructure investment, etc), launch, and operation, A	A ≥ 15MUSD	0								
				10MUSD ≤ A < 15MUSD	1								
				5MUSD ≤ A < 10MUSD	2						10		
				3MUSD ≤ A < 5MUSD	3			15			15		
				A< 3MUSD	4	20	20			20			20
1’	Total cost	5	If your satellite program contains multiple satellites, answer this question. Total cost including: satellites, non-recurring cost (e.g. infrastructure investment, etc), launch, and operation divided by the number of satellites, A’	A’ ≥ 10MUSD	0								
				5MUSD ≤ A’ < 10MUSD	1				5				
				2MUSD ≤ A’ < 5MUSD	2						10		
				1MUSD ≤ A’ < 2MUSD	3						15		
				A’ < 1MUSD	4								
2	Satellite delivery time	5	Time from the program start to delivery, B	B ≥ 3 years	0				0		0		
				2 ≤ B < 3 years	1			5			1		
				1 ≤ B < 2 years	2		10			10	10		10
				6 months ≤ B < 1 year	3								
				B < 6 months	4	20							
3	Simple satellite	1	Number of mission payloads, H	5 ≤ H	0								
				3 ≤ H < 5	1								
				H ≤ 2	2	2	2	2	2※	2	2		2
4	Simple operation	1	Number of persons needed to operate per satellite pass, AE	5 ≤ AE	0								
				3 ≤ AE < 5	1	1	1						
				AE ≤ 2	2			2	2	2	2		2

5	Simple manageme nt	2	Number of people engaged in satellite development, C	$C \geq 30$ persons	0								
				$20 \leq C < 30$ persons	1		2		2				
				$10 \leq C < 20$ persons	2	4		4		4※※	4		
				$C < 10$ persons	3						6		6
6	Simple handling	1	No hazardous/explosive alternative is chosen to make satellite handling easier	NO	0								
				YES	1		1	1	1	1	1		1
7	Risk taking	1	Screening and management of individual parts based on test results (e.g., radiation) is carried out	All parts	0								
				All non-space qualified COTS parts	1		1		1	1			
				Only mission critical parts or no screening and management	2			2			2		2
8	Risk taking	2	Percentage of non-space qualified COTS parts/material usage, D	$D \leq 10\%$	0								
				$10 < D \leq 50\%$	1			2	2		2		
				$50 < D \leq 90\%$	2		4				4		
				$90\% < D$	3					6			6
9	Risk taking	2	Use of non-flight proven technology, non-space qualified manufacturing, procurement of components via Internet from unknown manufacturers are allowed and encouraged to achieve the required specifications at lesser cost and/or shorter schedule	NO	0						0		
				YES	1		2	2	2	2			2
10	Risk taking	2	Single-point-of-failure is allowed in satellite design to make satellite simple or to comply with launch provider's requirements, etc	NO	0						0		
				YES	1	2	2	2	2	2	2		2
11	Risk mitigation	5	Risk is evaluated and managed based on collective experience and knowledge of team members rather than expensive and/or time-consuming testing and/or analysis with heavy documents	NO	0	0							
				YES	1		5	5	5	5	5		5

12	Reliability requirement	4	Failure of single satellite jeopardise the overall satellite program (replenishing satellite can be built and launched fairly easily)	YES	0	0	0	0					
				NO	1				4	4	4		1
13	Reliability requirement	2	Consecutive mission down time until recovery is allowed up to F	F ≤ 90 minutes	0								
				90 minutes < F ≤ 1 day	1		2			2			
				1 day < F ≤ 1 week	2						4		
				1 week < F	3			6	6				6
14	Mission duration	1	Satellite mission duration, E	E ≥ 5 years	0								
				3 ≤ E < 5 years	1								
				2 ≤ E < 3 years	2				2				
				1 ≤ E < 2 years	3			3		3	3		3
				E < 1 years	4	4	4						
15	Launch	5	Access to space is prioritized by designing launcher compatibility (i.e., POD) or having mission less dependent on orbit	NO	0								
				YES, either launch compatibility or non-strict orbit requirements	1	5	5		5	5	5		
				YES, both launch compatibility and non-strict orbit requirements	2			10					10
16	Waste minimization	8	Waste associated with transportation time (satellite hardware, human) and communication delay (emails exchange) is minimized by conducting the satellite development/integration/testing at one place with all the team members located within close proximity as much as possible	NO	0	0			0		0		
				YES	1		8	8		8			8
Total number of points					-	58	69	41	58	77	57-59	68	86

APPENDIX C - Summary of scales and description of each satellite introduced in Appendix B

No	Contributor	Affiliation	Satellite Name	Total score	Comments and satellite description
1	Mengu Cho	Kyushu Institute of Technology	HORYU-II	76	HORYU-II is a 30cm cubic satellite weighing 7kg. Its mission is high voltage technology demonstration. It was built by students.
2	Mengu Cho	Kyushu Institute of Technology	HORYU-IV	65	HORYU-IV is a 30cm cubic satellite weighing 10kg. Its mission is high voltage arcing experiment. It was built by students and paid personnel.
3	Herman Steyn	Stellenbosch University	ZA-AeroSat (QB50)	90	http://www.cubespace.co.za/#!projectsaerosat/c213e
4	Ji Hyun Park	Seoul National University	SNUSAT-1 (QB50)	70	https://snusat.wordpress.com/snusat-1/
5	Eduardo Martin Lopez	ISAE-Supaero	Jump Sat	52	I have given the marks related to the JumpSat mission, the 3U CubeSat developed by ISAE-Supaero. It will have 2 payloads: a low cost star-tracker and a radiation sensor. Objectives: (1) in-orbit demonstration technology of low cost star tracker and AOCS system developed by students; (2) mapping Earth's radiation through the radiation belts.
6	Fernando Aguado Agelet	University of Vigo	HUMSAT-D	63	http://www.humsat.org
7	Filippo Graziani	GAUSS SRL	UNISAT-7	75	UNISAT-7: octopart shape, diameter 450mm, height 370mm, weight 36kg, COTS made, 3U CubeSat and POD
8	Aitor Conde, Marco Truglio	GAUSS SRL	UNISAT-6	85	UNISAT-6 is a small satellite with fixed payloads on-board and it also acts as a launch platform for CubeSats.
9	Jose Alberto Ramirez A.	U.N.A.M-Mexico	ULISES 2.0	66	Experimental schedule, artistic project, 1st space experience.
10	Carlos Romo Fuentes	U.N.A.M-Mexico	Satellite Quetzal	63	Weight < 75kg, size 50×50×50cm, mission: air pollution particles detection and remote sensing photograph over national territory.
11	Jose Antonio Perez Gurmein	U.N.A.M-Mexico	Satellite Quetzal	69	Small satellite with the mission of air pollution particle detection and remote sensing photograph
12	Jorge Alfredo Ferrer Perez	U.N.A.M-Mexico	Satellite Quetzal	60	Quetzal is a MIT-UNAM initiative to measure pollution from different sources. Its volume is 50×50×60cm with a weight of 100kg. Quetzal carries a spectrometer and a camera for remote sensing purposes.
13	Akshay Gulati	IIT Madras	IITM SAT	64	IITM SAT is a 10kg satellite (30×30×30cm). The payload is 5kg, high energy (electric and proton) detector. The purpose is to measure the sudden increase of these particles that are precipitated from Van Allen belts in LEO. This will help in

					studying earthquake prediction strategies.
14	Bagus Adiwiluhung Riwanto	Aalto University	AALTO-2	76	Part of QB50 project, 2U CubeSat, university student project.
15	Tuomas Tikka	Aalto University	AALTO-1	67	Multi-payload technology demonstration mission, 3U CubeSat, student project.
16	Fernando Stancato	EMBRAER	UNOSAT	74	The main mission is to test a new design of energy management system and download the data.
17	Jordi Puig-Suari	Cal Poly	Exocube	78	http://polysat.calpoly.edu/launched-missions/cp10-exocube/
18	Martin Richter	SSC	Alsat-1N	57	https://www.gov.uk/government/news/uk-space-agencys-second-cubesat-mission-is-taking-shape
19	E. Simons	University of Surrey	STRAND-1	83	http://amsat-uk.org/satellites/telemetry/strand-1/
20	Claudio Paris	Sapienza University of Rome	LARES	26	LARES (Laser Relativity Satellite) launched 2012. Passive spacecraft, spherical shape of 36cm diameter, mass 396kg. Payload: Laser retro-reflectors.
21	Jyh-Ching Juang	National Cheng Kung University	PACE	73	PACE is a 2U CubeSat with the mission to perform in-orbit attitude determination and control experiments.
22	Sibel Turkoglu	Istanbul Technical University	BeEagleSat	70	http://www.nanosat.jp/images/report/pdf/NSS-05-0403.pdf
23	Steve Greenland	Clyde Space	P	53	There is a distinction here between parts we know to perform in space and parts which have been through a formal development process ⇒ answering as 'new' parts not flown. P: science mission for major space agency @ CDR. S: EO mission working with major space agency @ PDR. O: commercial telecoms. constellation @ CDR. UKube-1: UK government mission, launched @ EOL.
24			S	70	
25			O	80	
26			U Kube-1	63	
27	Klaus Schilling	University Würzburg	UWE1, 2, 3	71	UWE1, 2, 3 was 1U CubeSat, with specific technology test objectives related to internet in space, attitude determination, attitude control with the overall objective of formation flying technology basics provision.
28	Philip Bangest	University Würzburg	UWE-3	78	http://www7.informatik.uni-wuerzburg.de/forschung/space_exploration/projects/uwe_3/
29	Daniel Rockberger	IAI		50	This is a 3U CubeSat with an IR camera. The camera is the payload and has been developed by a non space company. The project is about 2 years overdue and therefore consuming many hours of engineers putting cost up.
30	Gangtie Zheng	Tsinghua	Tsinghua -	37	130kg. After 1 year, still working.

		University	Xinwei Telecom Smart Tel Sat.		
31	Roemer Stephan	Astro-und Feinwerktechik	TET-X	51	TET-X on orbit verification satellite, succeeded. A former TET-1 for low cost 10 million USD.
32			LAPAN-TUBSAT	81	LAPAN-TUBSAT satellite built 2004-2005 for LAPAN for EO (successful for more than 5 years).
33	Alessandro Cuttin	University of Trieste	Atmocube	75	Atnocube is a 1U CubeSat with educational purposes and as a small but innovative payload
34	Yasuyuki Miyazaki	Nihon University	SEEDS-II	85	SSEEDS-II (Space Engineering Education Satellite II) is a 1U CubeSat, 1kg in weight developed by university students. The mission of SEEDS-II is the demonstration of original bus system.
35	Yasuyuki Miyazaki	Nihon University	SPROUT	69	
36	Jorge Monteiro, Eduardo Pinho, Ana Azevedo	University of Beira Interior	N/A	58	The concept associated to our satellite is to analyze the conditions to form plasma and prove a theory related to the blackout in telecommunications during the reentrance in atmosphere. This theory is based on the idea that manipulating a magnetic field would allow to open a communication window during the blackout. The satellite is on a beginning phase and it is just theoretical idea yet.
37	Mikhail Ovchinnikov	KIAM RAS	Mission design of various satellites	69	From simple university satellites up to professional micro-satellites for science applications (Samsat, tablesat, formosat-T, Cnibis-M, CBN-2, etc.).
38	Julian Dines	Science and Technology Facilities Council	A: High-res CubeSat image concept	69	A = single-satellite mission, high-resolution visible imaging, science mission.
39			B: Multi-spectral nanosat constellation concept	41	B = constellation of nano-satellites, multi-spectral visible, science mission.
40	Dmitry Roldugin	KIAM	ADCS algorithms, MD, no specific satellites	77	※ Why small number of payloads is better? If I can accommodate 15 payloads in small sat with < 3 million USD, isn't it good? ※※ For university satellite, the more the better. ※※※ Why not operate satellite for > 5 years with < 2 persons? ～15kg satellite from small company. Technology demonstration (testing of home-built components) failed probably due to battery (COTS).

41	Frederick Slane	SIF	ISO compliant S/C	57-59	All spacecraft produced compliant with ISO TC20/SC14 standards.
42	Johnny Finnham, Sana Iyban	ICEYE Ltd		68	http://iceye.fi/#intro
43	Adrian Done	University Suceava Romania		86	It is only an idea of satellite. It is necessary distinction at my home university. Idea of a technology demonstration satellite for power supply and radio stability. maybe 1U CubeSat or pocket satellite.

APPENDIX D - Characteristics of lean satellites summarized from experience of past satellite projects

Contributor	Mengu Cho (Kyutech, Japan)	Daniel Rockberger (IAI, Israel)	Steve Greenland (UOS/CSL, U.K.)	Laurent Dusseau Montpellier University Space Center (France)	Fernando Aguado (Vigo, Spain)
Satellite	Case of HORYU-II • Developed by a Japanese university, Kyushu Institute of Technology • Launched on May 16, 2012 • A piggy-back launch by H-IIA (Japan) to 680km SSO	-	Ukube-1 and other CSL nano-satellites	ROBUSTA-1A • 1U CubeSat • Launched in 2012 on the VEGA Maiden Flight • 350 × 1450km elliptical orbit	Case of HUMSAT-D • Developed by Vigo University (Spain) • 1U CubeSat launched on November 21, 2013, inside UNISAT-5 in a Dnepr rocket • SSO 625km
Cost	Satellite program costs including the non-recurrence cost is 200KUSD	• One of the leading requirements is cost and therefore no increase of budget can be allowed • Measures must be made to keep cost down such as little complex mechanisms for example	• 1.8 MGBP (UKSA recognized public cost) • Significantly lower actually monies seen by CSL	-	Financed by the Spanish Space National Programme and Vigo University
Development methodology	• Student built satellite • Education was one of the purpose	• To save time and costs the effective system of Concurrent Engineering is used • Small team, people do many different tasks • Outsource to sub-contractors as much as possible for competitive prices and quality • Off the shelf components used	• Use of interface emulator to facilitate concurrent development • NANOBED (current research) developing new tools to facilitate lean satellite-like development	ESA ECSS	• Tailoring of ECSS standards for the management and engineering processes. A lot of effort in system engineering activities • Small team (3-5 people), each person has multiple responsibility areas • Heritage from previous works • COTS parts
Quality control	-	Time and resources must be saved when it comes to quality	Agree upfront quality assurance approach with review body / oversight committee	ECSS tailored by ESA education office on the launch phase	Very detailed AIV procedures (step by step) to avoid human errors

Contributor	Bungo Shiotani (University of Florida, USA)	Gangtie Zheng (Tsinghua University, China)	Herman Steyn (University of Stellenbosch, South Africa)	Kay Soon Low (Singapore)	Kay Soon Low (Singapore)
Satellite	SwampSat • 1st CubeSat developed at the University of Florida • Launched on November 19, 2013 • Part of NASA's Educational Launch of Nanosatellites IV Program • 500km circular orbit	Case of Tsinghua-XinVei TelCom Smart Tel. Sat	Case of SumbandilaSat • Developed within 18 months by SunSpace, a spin-off company from the University of Stellenbosch • Launched by Soyuz-2B in September 2009 in 500km SSO	Case of VELOX-I nano-satellite • 4.281kg • Launched on June 30, 2014, by PSLV C23 • 650km SSO	Case of VELOX-PII • 1.33kg CubeSat • Launched on November 21, 2013, by Dnepr • 650km SSO
Cost	-	5.6 million USD	Total cost for spacecraft and launch less than 5 million USD	-	-
Development methodology	Methodology • Requirements verification matrix (inspection, analysis, test, demonstration) • Systematic approach for verification at each phase of the project life-cycle • Each member works on multiple subsystems • Reviews (internal and external) • Communication and consistency (especially documentation) throughout the team • Cap stone design	Most components and parts were developed by us for reducing costs	Small team of less than 40 engineers, specialists in specific subsystems	• Most of the bus followed the VELOX-PII • To save cost and time, two FM were built after EM. One use for qualification and the other acceptance	Follow the whole cycle, EM, QM and FM as this is the first CubeSat built and is different design from the micro-sat (i.e. X-SAT) built in the centre
Quality control	Quality • Hardware and software verification and validation in a systematic way • Two identical units developed (one is EDU and one is flight unit)	• Numerical analyses and simulations during the design stage for ensuring the design quality • Carefully test all components and parts before assembly	Quality assurance office was closely involved in all aspects of the project	• All components in general have space heritage • Manufacturing must meet IPC class 3 standards	• All components in general have space heritage • Manufacturing must meet IPC class 3 standards

Contributor	Alim Rustem Aslan (Turkey)	Alim Rustem Aslan (Turkey)	Marta Massimiani (Italy)
Satellite	Case of ITUpSAT1 • Developed by a Turkish university, Istanbul Technical University • Launched on September 23, 2009 • A piggy-back launch by PSLV C 14 (INDIA-ISRO) • 720km SSO	Case of TURKSAT 3U • Developed by a Turkish university, Istanbul Technical University with financial support of TURKSAT INC. • Launched on April 26, 2013 • A piggy-back launch by LM2D (CHINA-JSLC) • 650km SSO	UniSat-6 • Designed and manufactured by GAUSS SRL • Civil scientific satellite • Mass of 26kg • Launched on June 19, 2014, in a Dnepr cluster launch (700 to 610km, SSO)
Cost	• Small team • COTS and development using COTS	• Multidisciplinary team • COTS and development using COTS	Costs are limited and set at the beginning of the project
Development methodology	Table top, EQM and FM with associated testing	Table top, EQM and FM with associated testing	To save time and money thanks to the possibility to re-use technology and software already tested in-orbit during previous missions (heritage process)
Quality control	-	-	The heritage of previous missions increases the quality mission

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Satellite	Case of HORYU-II • Developed by a Japanese university, Kyushu Institute of Technology • Launched on May 16, 2012 • A piggy-back launch by H-IIA (Japan) to 680km SSO	-	Ukube-1 and other CSL nano-satellites	ROBUSTA-1A • 1U CubeSat • Launched in 2012 on the VEGA Maiden Flight • 350 × 1450km elliptical orbit	Case of HUMSAT-D • Developed by Vigo University (Spain) • 1U CubeSat launched on November 21, 2013 inside UNISAT-5 in a Dnepr rocket • SSO 625km
Verification strategy	Basically, verification by testing was chosen	• Lean satellites rely on heritage of components and expertise of team members • Less proof via analysis • Less proof via testing and qualification.	-	-	• Internal revisions of all the design documents (at system and subsystem levels) • Testing at each level, from individual subsystems to complete system • "Test Like You Fly" methodology for system validation
Risk mitigation (redundancy)	No redundancy	Less or no redundancy	-	-	No redundancy or only in key elements
Risk management	• Risks are taken • Single-point-of-failure was allowed	Some risks are taken	Assign percentage of budget to mitigate risks identified by review board	-	• Risk control during the whole project • Review of risks table at each project meeting
Radiation measures	No radiation test was performed	Short lifetime can be an advantage as to radiation measures	-	Radiation effects was taken into account from the early stages of design	-
Others	-	• If it is a low cost project, then best to make two satellites (the price should be about 1.6 times for two) • The good price launch may not be an ideal orbit	-	• Low cost project with very little external support. However, qualifying and launching the satellite triggered the development of CubeSats in the French community • Very first experience of space engineering	• Non-conformances and anomalies control during the whole project • Delivery of mass dummy

Contributor	Bungo Shiotani (University of Florida, USA)	Gangtie Zheng (Tsinghua University, China)	Herman Steyn (University of Stellenbosch, South Africa)	Kay Soon Low (Singapore)	Kay Soon Low (Singapore)
Satellite	SwampSat • 1st CubeSat developed at the University of Florida • Launched on November 19, 2013 • Part of NASA's Educational Launch of Nanosatellites IV Program • 500km circular orbit	Case of Tsinghua-XinVei TelCom Smart Tel. Sat	Case of SumbandilaSat • Developed within 18 months by SunSpace, a spin-off company from the University of Stellenbosch • Launched by Soyuz-2B in September 2009 • 500km SSO	Case of VELOX-I• nano-satellite • 4.281kg • Launched on June 30, 2014 by PSLV C23 • 650km SSO	Case of VELOX-PII • 1.33kg CubeSat • Launched on November 21, 2013 by Dnepr • 650km SSO
Verification strategy	-	-	-	-	-
Risk mitigation (redundancy)	-	-	• Single string spacecraft due to mass limit of 80 kg • Risk was handled by having many review meetings and structured project management • Software revision control system used	Some forms of redundancy are made but not full redundancy	Some forms of redundancy are made but not full redundancy
Risk management	Risks • Failure modes, effects and criticality analysis (FMECA) and fault tree analysis (FTA) performed to identify possible failures • Mitigation strategies developed and implemented (redundancy & robustness)	-	-	-	-
Radiation measures	-	-	-	-	-
Others	-	-	-	-	-

Contributor	Alim Rustem Aslan (Turkey)	Alim Rustem Aslan (Turkey)	Marta Massimiani (Italy)
Verification strategy	Case of ITUpSAT1 • Developed by a Turkish university, Istanbul Technical University • Launched on September 23, 2009 • A piggy-back launch by PSLV C 14 (INDIA-ISRO) • 720km SSO	Case of TURKSAT 3U •Developed by a Turkish university, Istanbul Technical University with financial support of TURKSAT INC. • Launched on April 26, 2013 • A piggy-back launch by LM2D (CHINA-JSLC) • 650km SSO	UniSat-6 • Designed and manufactured by GAUSS SRL • Civil scientific satellite • Mass of 26kg • Launched on June 19, 2014, in a Dnepr cluster launch (700 to 610km, SSO)
Risk mitigation (redundancy)	-	Development time was short	-
Risk management	No redundancy: same frequency for uplink and downlink as well as beacon	Redundancy: different frequencies for modem and beacon and transponder	They are reduced thanks to a redundancy design where the back-up system allows only the satellite basic functions
Radiation measures	-	-	-
Others	-	-	-

APPENDIX E - Requirements with which lean satellites had to comply

Contributor	Mengu Cho (Kyutech, Japan)	Daniel Rockberger (IAI, Israel)	Steve Greenland (UOS/CSL, U.K.)	Laurent Dusseau (Montpellier University Space Center, France)	Fernando Aguado (Vigo, Spain)
Satellite	Case of HORYU-II • Developed by a Japanese university, Kyushu Institute of Technology • A piggy-back launch by H-IIA (Japan) to 680km SSO on May 18, 2012	-	Ukube-1 and other CSL nano-satellites	ROBUSTA-1A • 1U CubeSat • Launched in 2012 on the VEGA Maiden Flight • 350 × 1450km elliptical orbit	Case of HUMSAT-D • Developed by Vigo University (Spain) • 1U CubeSat • Launched on November 21, 2013 inside UNISAT-5 in a Dnepr rocket • SSO 625km
Debris mitigation rule					
25 years rule	Demonstrate by analysis that the orbital decay within 25 years using a software provided by JAXA	If no propulsion then some analysis showing the 25 years decay of the satellite	Ukube-1 required to follow 25 years to high assuredness to acquire launch license	• 25 years rule • French space act (LOS) demonstrated with STELA (CNES software)	Demonstrate by analysis that the orbital decay is within 25 years
Others	-	If propulsion is onboard, then analysis that sufficient fuel and DV is possible to de-orbit at end of life.	Believe we should aim to achieve much better than 25 years (< 10 years?) to demonstrate responsible use of space given more disposal nature of our missions	-	-
Frequency regulation					
In case of amateur radio frequency	Use of amateur radio frequency coordinated through IARU	• Use of amateur radio frequency coordinated through IARU and local ministries of communications • Providing the radio amateur services of relay communications (this is a transceiver requirement) in order to comply as amateur	Use of amateur radio frequency coordinated through IARU for Ukube-1. Recognize this cannot be the solution for nano-satellites in general as this is not the purpose of these frequencies	Use of amateur radio frequencies, ITU declaration and IARU coordination	Use of amateur radio frequency coordinated through IARU
Frequency coordination with ITU	International frequency coordination through ITU	International frequency coordination through ITU when not amateur	International frequency coordination through ITU	-	International frequency register through ITU (no coordination required)
Domestic coordination	Radio license application to Japanese government (Ministry of Internal Affairs and Communications)	-	Work with OFCOM (U.K.) regulator on other frequencies for customers	-	Radio license application to local administration
Use of radio hardware	Only the licensed personnel can operate the ground station radio	-	-	-	Only radio amateurs can do operations

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Satellite	SwampSat • 1st CubeSat developed at the University of Florida • Launched on November 19, 2013 • Part of NASA's Educational Launch of Nanosatellites IV Program • 500km circular orbit	Case of Tsinghua-XinVei TelCom Smart Tel. Sat	Case of SumbandilaSat • Developed within 18 months by SunSpace, a spin-off company from the University of Stellenbosch • Launched by Soyuz-2B in September 2009 • 500km SSO	Case of VELOX-I nano-satellite • 4.281kg • Launched on June 30, 2014 by PSLV C23 • 650km SSO	Case of VELOX-PII • 1.33kg CubeSat • Launched on November 21, 2013 by Dnepr • 650km SSO
Debris mitigation rule					
25 years rule	• Simulations performed through NASA's DAS software (internal) • Orbital Debris Assessment Report (ODAR) conducted by NASA (external)	Follow the rule of Chinese Space Agency for debris mitigation, but with no devices on board for ensuring the 25years rule	Although it had a Butane propulsion system to maintain its altitude at 500km for 2-3 years; after that, the orbit will decay and the satellite will de-orbit within 5 years	Expecting to decay within 25 years similar to other nano-satellites	Expecting to decay within 25 years similar to other CubeSats
Others	-	-	-	-	-
Frequency regulation					
In case of amateur radio frequency	Amateur radio frequency coordination through IARU	-	• IARU frequency coordination for amateur UHF/VHF frequencies • ITU for UHF /VHF commercial and S-band frequencies • Application through government ICASA frequency regulator	Use of amateur radio frequency filing through Singapore Infocomm Development Authority to ITU	Use of amateur radio frequency filing through Singapore Infocomm Development Authority to ITU
Frequency coordination with ITU	International frequency coordination through ITU	-	International frequency coordination through ITU	International frequency coordination through ITU	International frequency coordination through ITU
Domestic coordination	Experimental Radio Station Construction Permit and License through U.S. Federal Communications Commission (FCC)	Borrowed frequency from Space Agency for the design life	Radio license application to national government's ICASA office	Radio license for both the satellite and ground station obtained formally from Singapore Infocomm Development Authority	Radio license for both the satellite and ground station obtained formally from Singapore Infocomm Development Authority
Use of radio hardware	Team members hold amateur radio license to operate ground stations	-	-	Licensed personnel was trained and in turns supervise operators	Licensed personnel was trained and in turns supervise operators

Contributor	Alim Rustem Aslan (Turkey)	Alim Rustem Aslan (Turkey)	Marta Massimiani (Italy)	Fernando Stancato (Brazil)	Merlin Barschke (TU Berlin, Germany)
Satellite	Case of ITUpSAT1 • Developed by a Turkish university, Istanbul Technical University • Launched on September 23, 2009 • A piggy-back launch by PSLV C 14 (INDIA-ISRO) • 720km SSO	Case of TURKSAT 3U • Developed by a Turkish university, Istanbul Technical University with financial support of TURKSAT INC. • Launched on April 26, 2013 • A piggy-back launch by LM2D (CHINA-JSLC) • 650km SSO	UniSat-6 • Designed and manufactured by GAUSS SRL • Civil scientific satellite • Mass of 26kg • Launched on June 19, 2014, in a Dnepr cluster launch (700 to 610km, SSO)	-	Case of BEESAT-3 (1kg), TechnoSat (20kg) and TUBIN (20kg))
Debris mitigation rule					
25 years rule	None	• De-orbiting system was not ready for the launch • Analysis for reentry	Demonstrate by analysis that the orbital decay will be within 25 years according to the IADC 25 years rule (requested by Italian Space Agency)	Guarantee 25 years between first orbit to reentry	25 years rule calculated with DAS
Others	-	-	-	-	-
Frequency regulation					
In case of amateur radio frequency	Use of amateur radio frequency coordinated through IARU	Use of amateur radio frequency coordinated through IARU	Use of amateur radio frequency coordinated through IARU, ITU and Italian Ministry of Communications (because UniSat-6 is a radio-amateur satellite)	Use of amateur radio frequency coordinated through IARU	Use of amateur radio frequency coordinated through IARU
Frequency coordination with ITU	International frequency coordination through ITU	International frequency coordination through ITU	-	-	International frequency coordination through ITU
Domestic coordination	Radio license application to Turkish government (Ministry of Transportation Maritimes and Communications)	Radio license application to Turkish government (Ministry of Transportation Maritimes and Communications)	-	-	-
Use of radio hardware	• There are licensed radio amateurs, such as myself. However LAB personnel in good command of equipment can use the ground station • The satellite is downlink only	• There are licensed radio amateurs, such as myself. However LAB personnel in good command of equipment can use the ground station • The satellite is downlink only	-	-	Only radio amateurs can do operations, or a person with educational radio amateur license must be present

Contributor	Eduardo E. Bürger (Brazil)	Akshay Gulati (Indian Institute of Technology Madras, India)	Ji Hyun Park (Seoul National University, Korea)	Shigeru Imai (JAMSS, Japan)	Otavio Durão (INPE, Brazil)
Satellite	Case of Brazilian CubeSat platform AESP14 http://www.aer.ita.br/~aesp14/	Case of IITMSAT Being developed by an Indian University, Indian Institute of Technology Madras	-	Case of J-SSOD satellites • Launched by H-IIB/HTV (Japan) or Space-X/Dragon (US), deployed from ISS • Altitude: 400km • Inclination: 51.6deg	-
Debris mitigation rule					
25 years rule	Demonstrate by analysis that the orbital decay is within 25 years using software provided by NASA, Debris Assessment Software, V2.0.	-	• Should follow UN recommendation of < 25 years lifetime • Either re-entry to Earth or escape of Earth Orbit. Satellites above 500 km shall consider this • Orbit altitude is low such that the orbit will decay in less than 25 years	If has propulsion system, satellite developer needs to show compliance with the orbital decay requirement	25 years rule
Others	-	-	-	Since satellite ballistic number is limited up to 100kg/m^2 by JAXA requirement, it automatically meets the orbital decay requirement of 25 years	-
Frequency regulation					
In case of amateur radio frequency	Use of amateur radio frequency coordinated through IARU	Use of amateur radio frequency coordinated through IARU	Frequency uses the amateur band satisfying the following reasons • the CubeSat is not used as commercial use • Amateur radio operators can practice their skills with CubeSats	Frequency authorization is needed through ITU, government ministry, IARU for use of amateur radio frequency, and NASA	IARU and ITU frequency coordination
Frequency coordination with ITU	International frequency coordination through ITU	International frequency coordination through ITU	-	-	-
Domestic coordination	Radio license application to Brazilian government (ANATEL – National Telecommunication Agency)	Radio license application to national government	-	-	-
Use of radio hardware	-	-	-	-	-

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Registration					
Satellite registration to UN	Registration of space object to UN after launch through Japanese government (Ministry of Foreign Affair)	• Not performed for very small (CubeSat) payloads • Should be performed for larger (over 100kg?) satellites	Registered with NORAD, UN, and UKSA	• Registration of space object to UN • Launch Through ESA Education Office	Registration of space object to UN
Satellite registration to others	-	-	• Launch license from U.K. government, had to answer Outer Space Act questions (space, operations, launch) to their satisfaction • Had to get 3rd party liability (covered by UKSA given their mission)	Registration to CNES	-
Safety					
Safety review/ Launcher requirement	-	Usually only as part of the launch requirements	• Letter of flight readiness from UKSA to launch provider • Short safety assurance brief prepared	Compliance with French Space ACT (LOS)	CubeSat Design Specification (CDS) compliance
Hazard analysis	Hazard analysis at the beginning of satellite design	-	Subsystem FMEA (not detailed FMECA and no reliability analysis)	-	-
Cold launch	Secure cold launch and no deployment by three inhibits	On/off battery inhibits as launcher requires (1-3 switches)	-		At least one deployment switch to leave all circuits open during launch
Hazardous material, pressurized container, propulsion	-	-	-	-	No pressurization, radioactive materials, explosive materials or propulsion systems allowed
Mechanical test	• Many mechanical tests (vibration and shock) to demonstrate no accidental switch-on or deployment • It was very challenging and time consuming to demonstrate: >> The three separation (activation) switches work >> No chattering of the separation switches during vibration	• Vibration tests mandatory to prove no parts will detach during launch and deployment will occur • Deployment test is mandatory if a deployer is involved • A release test is mandatory if a clamp band or similar system is used	• Testing performed to GEVS or launch provider specification where known • No detailed analysis by the launch provider (Roscosmos)	• Compliance with French Space ACT (LOS) • Mechanical, sine QSL, random • Analysis only for shock	Vibration tests: sinusoidal and random at levels specified in Dnepr user guide

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Registration					
Satellite registration to UN	-	-	Launch license from SA government, had to answer Outer Space Act questions (space, operations, launch) to their satisfaction	-	-
Satellite registration to others	FCC experimental license	Launch license from Chinese Space Agency	-	Registered through NORAD	Registered through NORAD
Safety					
Safety review/ Launcher requirement	• Internal reviews throughout the project life-cycle • Mission Concept Review (Internal) • System Definition Review (NASA) • Preliminary Design Review (NASA) • Critical Design Review (NASA, Lockheed) • Mission Readiness Review (NASA, ORS) • Post-Launch Assessment Review (Internal) • CubeSat Specification Document and ORS ICD that includes requirements, their verifications, and full suite of qualification tests (vibrations, thermal bakeout, etc.) • Deliverables (i.e., test reports to other report documents) to NASA and ORS	Apply to all security compliance of the launcher provider and Chinese Space Agency	• Had to satisfy all launcher requirements • Structural model was shock and vibration tested at launch agency	• Satellites subjected to all environmental tests including vibration, shock, TVC meeting launch service provider requirements for both QM and FM • In-house tests typically followed ESA standards	• Satellites subjected to all environmental tests including vibration, shock, TVC meeting launch service provider requirements for both QM and FM • Bakeout tests conducted • List of components submitted
Hazard analysis	-	Design reviews were conducted at every stage	• Hazard analysis was completed to satisfaction of launch agency • Internal FMEA analysis was done on some subsystems	-	-
Cold launch	-	-	-	-	-
Hazardous material, pressurized container, propulsion	-	-	-	-	-
Mechanical test	-	• During the design stage, finite element analyses were conducted for virtual vibration experiments • Vibration test requirement can be modified according to the natural frequencies of the satellite with a staff of launcher provider on site	• Qualification: vibration, shock, TVac, TID (only on some critical components) • Acceptance: Vibration and TVac	-	-

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Registration					
Satellite registration to UN	-	Registration of space object to UN after launch through TURKSAT and TURKISH government (Ministry of Foreign Affair)	Registration of space object to UN through ASI (Italian Space Agency)	Registration of space object to UN	Registration with the UN through DLR
Satellite registration to others	-	-	-	-	-
Safety					
Safety review/ Launcher requirement	-	-	Apply to security compliance of the launch provider (they are not very tight if no propulsion or hazard system is on board)	Apply to all security compliance of the launcher provider	-
Hazard analysis	-	-	-	-	-
Cold launch	-	-	-	-	-
Hazardous material, pressurized container, propulsion	-	-	-	-	-
Mechanical test	All necessary tests were carried out on site	All necessary tests were carried out on site	• Environmental tests (vibration is mandatory, thermal and EMI are suggested) • Design and fit-check validation according to the launch provider requests	-	• Qualification: vibration, shock, TV, TID • Acceptance: vibration and TV

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Registration					
Satellite registration to UN	-	-	-	-	-
Satellite registration to others	-	-	-	-	-
Safety					
Safety review/ Launcher requirement	-	Using ISRO's launch adapter to satisfy satellite envelope specification (dimensions and center of gravity)	-	-	-
Hazard analysis	Due to late launch definition, hazard analysis after satellite design. Had to change some small issues	-	-	Hazard analysis and verification are to be reviewed and approved by JAXA and NASA	-
Cold launch	Secure cold launch and no deployment by 4 inhibits, 2 Kill switches and 2 RBFs	-	-	Appropriate number of electrical inhibits is required for hazardous RF radiation, deployment of appendage such as antennas and solar panels, sub-satellite deployment and activation of propulsion system	-
Hazardous material, pressurized container, propulsion	-	-	-	-	Carry no fuel and others (done in conjunction with the launching agent)
Mechanical test	Vibration and review-of-design to demonstrate no accidental switch-on or deployment	Vibration and shock test plans and test reports to be submitted to ISRO	-	-	• Vibration testing (random and sine vibration and resonance survey) signed report • Submission of acceleration (quasi static) analysis

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Safety					
Documents	Many documents including tests and analysis	-	-	-	Deployment of antennas or other systems at least after 20 minutes from separation
Deployment	-	-	-	-	Failure modes analysis for antenna deployment.
Sharp-edge	-	-	-	-	-
Radio emission after separation	Radio emission only after 200 seconds or later from the satellite separation	In most cases nor radio emissions and or deployables can occur for the first 30min	-	Radio emission only after 30min or later from the satellite separation	No radio emissions during launch and after 30min from launch
Accidental radio emission	Demonstrate by analysis no hazard of accidental radio emission to the ground personnel	-	-	-	Remove before flight pin is mandatory for integration with the launcher
Battery	• Battery charging is not allowed at the launch site • Many documents related to battery safety, e.g. over-current and voltage protection design and verification, etc	-	• 5-10 days last contact before launch • CSL battery protection allows up to 120 days in launch ready configuration without drain	Battery recharging was possible on launch site and performed by ESA team	• Fit-check with the launcher interface • Lithium batteries documentation for transportation of the satellite
Electrical bonding	Electrical bonding of satellite to the rocket	-	• Continuity mechanical and electrical checks in advance of launch with ISIPOD • Live deployment test (mass model)	-	-
Material list /outgas/bakeout	Submission of material list to the launch provider	Declared material and process lists are a requirement	-	-	• Compliance with TML and CVCM levels in NASA-STD-6016 • TV bakeout

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Safety					
Documents	-	• Vibration tests were conducted with structural satellite • Vibration tests and TV tests with prototype and fly satellite • For fly satellite, vibration test level is much lower, and the TV test is only 24 hours	-	All test reports are generated	All test reports are generated
Deployment	-	Separation test with clamp-band is required	-	Functional test of deployment-POD mechanism	-
Sharp-edge	-	-	-	-	-
Radio emission after separation	-	Radio emission only after separation from the launch vehicle	-	No radio transmission for 10 minutes after separation	No radio transmission for 10min after separation
accidental radio emission	-	-	-	-	-
Battery	-	• Battery system with protections for short circuit, overcharge, over-discharge, tested separately before assembly (vibration and thermal cycle) • Fully charged at launch pad	The spacecraft Li-ion battery is finally charged during 12 hours after spacecraft/launcher mating before head fairing installation. After this operation the battery does not need to be recharged for a period of 14 days	• Final battery charging is conducted at launch site check out before transporting to the vertical integration tower • No charging at the vertical integration tower	-
Electrical bonding	-	No electrical bonding to the launch vehicle as the second payload	-	-	-
Material list /outgas/bakeout	-	Material should not be in the list of materials that cannot be used in space provided by the Chinese Space Industry	-		Bakeout test conducted

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Safety					
Documents	Many documents including tests and analysis	Many documents including tests and analysis	-	-	-
Deployment	-	-	-	-	-
Sharp-edge	-	-	-	-	-
Radio emission after separation	Radio emission only after 15min or later from the satellite separation	Radio emission only after 30min or later from the satellite separation	According to the launch provider request	-	No radio transmission for 15min after separation
accidental radio emission	-	-	-	-	-
Battery	-	-	-	-	-
Electrical bonding	-	-	-	-	-
Material list /outgas/bakeout	-	-	-	-	-

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Safety					
Documents	Around 10 documents including tests and analysis	Detailed description of pyro and propulsion subsystems (if any) to be provided	-	Many verification documents including test, inspection and analysis are required	Documentation to the launch service provider stating it is not a military satellite
Deployment	-	-	-	Sub-satellite deployment and propulsion system are permitted securing safe distance from ISS	-
Sharp-edge	TV, vibration (no shock), sharp edge inspection and fit-check tests required	-	-	Sharp-edge inspection on flight hardware by JAXA or their representative is required	-
Radio emission after separation	Radio emission only after 30min from the satellite separation	Radio emission only after 30min or later from the satellite separation	-	RF radiation only after 30min or later from satellite deployment from ISS	-
accidental radio emission	-	-	-	-	-
Battery	Battery requirements: discharge, overcharge, short-circuit protection (individual cell and battery pack)	Battery charging to be completed 12 days before launch	-	• Safety requirement for battery system consists of protection for short circuit, overcharge, over-discharge and flight cells screening test such as vacuum and random vibration • The requirements are strictly applied especially to Li-ion battery system • Since implementation of the requirements much depends on design and mission concept of each satellite, consulting JAXA in the design phase is highly recommended.	-
Electrical bonding	-	Ensuring electrical continuity between satellite and launch adapter by using surface coating specified by ISRO	-	-	-
Material list /outgas/bakeout	-	Thermal baking to be done on the satellite and test report to be submitted	-	Offgass testing is performed by JAXA at Tsukuba Space Center to evaluate toxicity to ISS cabin environment	Material list

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Passivation					
Passivation	Passivation mechanism (satellite kill-switch) incorporated	Satellite shutdown or reset ability	-	-	-
External relationship and export control					
External relationship (NDA)	Non-disclosure agreement with external organization	-	U.K.-Russia Bilateral	ESA education office	-
External relationship (others)	Careful handling of information provided by launch provider	-	-	• MoU with ESA • Product assurance handled by ESA on the launch phase	HUMSAT is a project of UN-OOSA BSTI programme
Export control	• Password lock of sensitive launcher information • Submission of participants list with each person's nationality	-	Only on US COTS items for launch in Russia	None	-
Others					
Other requirements	-	• One of the leading requirements is cost and therefore no increase of budget can be allowed • Measures must be made to keep cost down such as little complex mechanisms for example	-	Quality control follows ECSS tailored by ESA Education office on the launch phase	Tailoring of ECSS standards for the management and engineering processes

Contributor	Bungo Shiotani (University of Florida, USA)	Gangtie Zheng (Tsinghua University, China)	Herman Steyn (University of Stellenbosch, South Africa)	Kay Soon Low (Singapore)	Kay Soon Low (Singapore)
Passivation					
Passivation	• Reset and no transmission capability • US Government Orbital Debris Mitigation Standard Practices through NASA • Materials list to show spacecraft will not survive reentry	-	-	-	-
External relationship and export control					
External relationship (NDA)	• Cooperative Research And Development Agreement with NASA • Non-disclosure agreement (foreign national students) • Department of State license (foreign national students)	-	SA-Russia Bilateral	Non-disclosure agreement with external organization	Non-disclosure agreement with external organization
External relationship (others)	-	-	ICD document with launch provider, including a document confirming the spacecraft safety at all phases of prelaunch preparation, launching, and flight	-	-
Export control	US specific regulations (ITAR, EAR)	Should get permission from Chinese Space Agency	-	End user statement	End user statement
Others					
Other requirements	-	-	-	-	-

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Passivation					
Passivation	Passivation mechanism (satellite kill-switch) incorporated	Passivation mechanism (satellite kill-switch) incorporated	Satellite shutdown or reset ability according to ITU requirements	-	-
External relationship and export control					
External relationship (NDA)	-	-	NDA between customer (GAUSS SRL) and launch provider (ISC Kosmotras)	-	-
External relationship (others)	Careful handling of information provided by launch provider	Careful handling of information provided by launch provider	-	-	-
Export control	-	-	Italian Chamber of Commerce permission to export (depending on the launch site country)	-	-
Others					
Other requirements	-	-	-	-	-

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Passivation					
Passivation	-	-	-	-	-
External relationship & export control					
External relationship (NDA)	-	-	-	-	-
External relationship (others)	-	-	Agreement regarding collaborative projects have to contain: • Responsibilities and obligations of each parties • Property rights and ownership rights • Liability (Nation space laws, export laws, employment laws, etc.) • Choice of law and jurisdiction, etc.	-	-
Export control	-	-	• Restrictions probably will be present and legal paperwork will be required for GPS, Sun sensors, etc. • Export/Import regarding environmental tests abroad	-	-
Others					
Other requirements	-	-	-	-	-

International Academy of Astronautics (IAA)

A Brief Description

Founded:
16 August 1960, Stockholm, Sweden, by Theodore Von Karman. Independent non-governmental organization recognized by the United Nations in 1996.

Aims:
Foster the development of astronautics for peaceful purposes; Recognize individuals who have distinguished themselves in space science or technology; Provide a program through which members may contribute to international endeavors; Promote international cooperation in the advancement of aerospace science.

Structure:
Regular Meeting; Board of Trustees consisting of: President; four Vice-Presidents and twenty-eight Trustees, seven from each Section: Basic Sciences, Engineering Sciences, Life Sciences and Social Sciences. Current President: Dr. Peter Jankowitsch, Past-President: Dr Madhavan G. Nair, USA, Vice-Presidents: Dr. Francisco Mendieta-Jimenez, Mexico; Prof Liu Jiyuan, China; Dr. Hiroki Matsuo, Japan; Prof. Anatoly Perminov, Russia, Secretary General Dr. Jean-Michel Contant, France.

Activities:
Encourage international scientific cooperation through symposia and meetings in the area of: space sciences, space life sciences, space technology & system development, space systems operations & utilization, space policy, law & economy, space & society, culture & education; Publish cosmic studies dealing with a wide variety of topics including space exploration, space debris, small satellites, space traffic management, natural disaster, climate change, etc.

Cooperation with other Academies:
Establish cooperation with Royal Swedish Academy of Sciences (1985), Academy of Finland (1988), Royal Spanish Academy of Sciences (1989), German Academy of Sciences (1990), Kingdom of Netherlands (1990), Academies of Arts, Humanities & Sciences of Canada (1991), Austrian Academy of Sciences (1986, 1993), Israel Academy of Sciences and Humanities (1994), Norwegian Academy of Science and Letters (1995), Academy of Sciences of Turin (1997), Australian Academy of Sciences (1998), Royal Netherlands Academy of Arts and Sciences (1999), Brazilian Academy of Sciences (2000), Academy of Sciences of France (1988, 2001), U.S. Academy of Sciences (1992, 2002), U.S. Academy of Engineering (1992, 2002), U.S. Institute of Medicine (2002), Indian Academy of Sciences (1990, 2007), Academy of Sciences of South Africa (2011), Royal Society of South Africa (2011), Pontifical Academy of Sciences (2012), Academy of Sciences of Ukraine (2010, 2012), Chinese Academy of Sciences (1996, 2013).

Publications:
Publish the journal of the International Academy of Astronautics ACTA ASTRONAUTICA ranked 5th in the world; Yearbook, Dictionaries and CD-ROM in 24 languages (last languages Afrikaner and Swahili); Book Series on small satellite, conference proceedings, remote sensing and history. All publications available at https://shop.iaaweb.org.

Membership:
Active members 1200 in 87 countries in four Trustee Sections; Honorary members (2)
- *Africa:* Algeria, Burkina Faso, Cameroon, Egypt, Ethiopia, Ivory Coast, Kenya, Libya, Morocco, Nigeria, Senegal, South Africa, Tunisia.
- *Americas:* Argentina, Bolivia, Brazil, Canada, Chile, Columbia, Cuba, Ecuador, Guatemala, Mexico, Peru, Uruguay, USA, Venezuela.
- *Asia:* Bahrain, Burma, China, India, Indonesia, Irak, Iran, Israel, Japan, Kazakhstan, Korea, Kuwait, Kyrgyz Republic, Malaysia, Mongolia, Oman, Pakistan, Saudi Arabia, Singapore, Sri Lanka, Syria, Thailand, Turkey, Vietnam.
- *Europe:* Armenia, Austria, Belarus, Belgium, Bulgaria, Croatia, Cyprus, Czech Rep., Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Macedonia, Netherlands, Norway, Poland, Portugal, Romania, Russia, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom, Ukraine.
- *Oceania:* Australia, New Zealand.

IAA Office:
Office 6 rue Galilée, Po Box 1268-16, 75766 Paris Cedex 16, France; IAA Office Branches in Bangalore (India) and in Beijing (China) for its Study Center; Regional offices in Abuja (Nigeria), Tunis (Tunisia), Buea (Cameroon) and Nairobi (Kenya).

Mailing Address: IAA, PO Box 1268-16, F-75766 Paris Cedex 16, France
Telephone: 33 1 47 23 82 15, **Fax:** 33 1 47 23 82 16, email sgeneral@iaamail.org

Web Site: http://www.iaaweb.org
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