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Science Missions Using CubeSats

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Abstract As the role of missions and experiments carried out in outer space becomes more and more essential in our understanding of many earthly problems, such as resource management, environmental problems, and disaster management, as well as space science questions, thanks to their lower cost and faster development process CubeSats can benefit humanity and therefore, young scientists and engineers have been motivated to research and develop new CubeSat missions. Not very long after their inception, CubeSats have evolved to become accepted platforms for scientific and commercial applications. The last couple of years showed that they are a feasible tool for conducting scientific experiments, not only in the Earth orbit but also in the interplanetary space. For many countries, a CubeSat mission could prompt the community and young teams around the world to build the national capacity to launch and operate national space missions. This paper presents an overview of the key scientific and engineering gateways opened up to the younger scientific community by the advent and adaptation of new technology into CubeSat missions. The role of cooperation and the opportunities for capacity-building and education are also explored. Thus, the present article also aims to provide useful recommendations to scientists, early-career researchers, engineers, students, and anyone who intends to explore the potential and opportunities offered by CubeSats and CubeSats-based missions.

Key words CubeSat, Space science, Small satellites for space science, Education, Earth observation
Classified index Classified index P 35

0 Introduction

Since their inception, CubeSats have enjoyed widespread acceptance in the space science community, currently featuring a growing developer list. In fact, CubeSats can help reduce the costs of technical developments and scientific investigations, therefore lowering the entry-barriers to organizing space missions. As a result, CubeSats' popularity in countries with fewer resources to be devoted to space science has grown exponentially in the past few years, thus adding enormous value to education, researchers' experience, and collaborative relationships.

As of January 2020, over 1200 CubeSats have been launched worldwide, and for some countries, this constituted a considerable milestone, as it sometimes even represented the very first national satellites sent into space. Producing one's own satellites is evidently considered a national achievement and a source of national pride by each country, and coupled with realistic and focused goals, such satellites can efficiently help overcome the difficulties implied by a small research budget and little or no experience in the field of space technology. Small satellites thus represent an ideal opportunity for students, engineers, and scientists in different disciplines, including software development for on-board and ground computers, engineering, and management of sophisticated technical programs, to work together on the agile development and operation of space missions. In fact, as the "build-to-operations" cycle for CubeSats is less than three years, this allows university students to be involved in its development from its inception to the actual operating mission.

In this paper, we will focus on identifying suitable key sciences that can be developed for CubeSats science missions, what are the CubeSats' feasibilities for space development countries, on developing CubeSats space education systems to establish cooperative programs not only for the purpose of training, but also in view of the prospective collaboration in scientific or application missions, and on exploring the reports from the training section.

The synergy between communities is the key to advertise and improve CubeSats' capabilities, expanding the nowadays relatively limited but steadily increasing application of these technologies for scientific goals. In particular, we are especially interested in CubeSats that could potentially lead to breakthrough discoveries.

The answers to the questions on how to design a CubeSat, why CubeSats are needed, and what is most important for a space mission can be all summarized in the fact that, according to the specificities of a mission, a personalized manpower capability, mission-related financial resources, as well as a targeted organization management strategy is required.

When it comes to the rationale behind the launch of a CubeSat, a good and stable team represents an essential factor, together with a sound knowledge of CubeSats' development engineering, the subsystems of CubeSats, as well as of the experiments targeted. Last but not least, it is critical to be familiar with some other important elements of the mission, such as the launcher, frequency allocation, law, import/export regulations.

In this paper, we summarize in four sections the primary takeaways concerning CubeSats, the recommendations of researchers, engineers, and scientists to newcomers in the field, and the relevance of international collaboration for the development of CubeSats-based missions as well as for an enhanced international equilibrium. Therefore, the present article aims to provide the opportunity to learn more about CubeSats' architecture, their development, structure and characteristics, their launching and deployment techniques, design criteria, space engineering, as well as the current status of several countries' advanced studies and missions relying on CubeSats' technology.

1 An Overview

A close, synergistic, and interdisciplinary collaboration between space scientists, engineers, and the space industry lays the groundwork for CubeSats' studies and missions, tied up by the cross-fertilization and encouragement based on the realization of experiments and the achievement of cost-containment and cycle time-reduction. This way forward will be achieved by exploiting at most the Commercial Off-the-Shelf (COTS) components, currently underperforming in the space environment, but with the potential to provide high-impact and radical transformations in space application.

Ambitious CubeSats projects must be based on international collaboration between institutes, national space agencies, as well as private companies. Sharing the scientific concepts of the mission with the world is the key to creating the perfect environment to achieve great scientific discoveries.

Modularity as well as relatively low costs make CubeSats a great opportunity for institutions interested both in the scientific and engineering goals achievable with these small satellites' technology, an aspect which is already leading to the increase of small satellites developers. Compared to large satellites, small satellites entail low development costs and offer the opportunity to carry out scientific and technological tests over a short period of time (circa three years).

Last but not least, in recent years small satellites have also become a tool used to train students and give them a general understanding of satellite systems.

For all these reasons and thanks to CubeSats' interdisciplinary potential and varied approaches, we will now explore some CubeSats-based projects from four different points of views: physics, science, engineering, and education.

1.1 Physics-oriented Analysis

"CubeSats for Science Missions" from a physics point of view: what can we do and when? The answer to the usage of CubeSats for Science Missions from a different perspective, *i.e.*, the one of physics and from the work on mass reduction rates for spacecrafts is discussed, see "Small satellites for space science – A COSPAR scientific roadmap"[1] and "Will CubeSats introduce a Moore's law to space science missions?"[2].

As spacecraft subsystems become smaller, advanced studies may be performed with ever-lighter spacecrafts. This opens up new possibilities in space science missions. With a fixed-mass budget mission designer, it may be possible to aim at a variety of mission approaches. The available mass may be split up into many small identical units and these units may act as a swarm and cover a larger area or volume than a monolithic spacecraft of equivalent mass. Alternatively, a fraction of the mass budget could be reserved for small advanced probes that could extend the baseline or reach of a larger spacecraft. The probes may even be expendable allowing for more daunting missions. In Figure 1 the different mission scenarios using CubeSats are illustrated.

A typical argument against small spacecrafts is

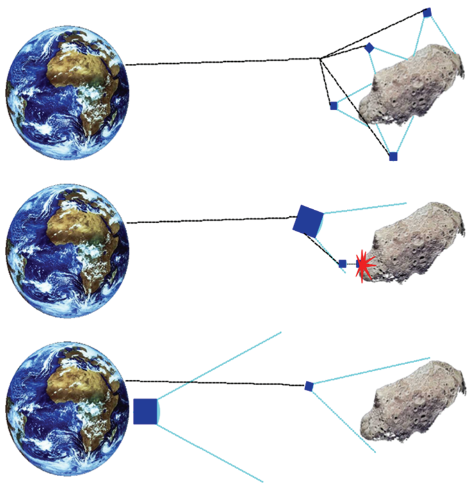

Fig. 1 Illustrations of mission scenarios using CubeSats

that the aperture size dictates the resolution of detectors. From the Fraunhofer diffraction theory in the equation below, it is evident that a way around this issue is to go closer $\alpha \approx \dfrac{2\lambda}{D}$, where α is the angular resolution of a telescope with aperture size D, whereas λ represents the wavelength of the observed light. As an example, the resolution of the Hubble space telescope and a 3U Dove satellite from the Planet Labs Inc is compared. Figure 2 shows the resolution *vs* distance for both spacecrafts, with Didymos as a target example. Didymos closest approach to the Earth (and Hubble space telescope) is roughly 10^{-2} AU or 1.5 million km. As seen, the Dove satellite will surpass the best-case resolution of Hubble space telescope when the Dove spacecraft is closer than about 2×10^{-4} AU or 30 000 km.

The study "Will CubeSats Introduce a Moore's Law to Space Missions?"[2] looks at the mass evolution of spacecrafts over time and it refers to the analysis of the capability and mass of similar class missions, used as a figure of merit. In other words, the mass required to obtain a certain performance is calculated for historic missions, but not all mission classes that were studied revealed a mass evolution similar to Moore's law. However, the Earth observation missions operating in the optical band did show a mass reduction tendency similar to Moore's law. The equation below shows the relation.

$$P_t = \frac{P_0}{2^{t/n}}.$$

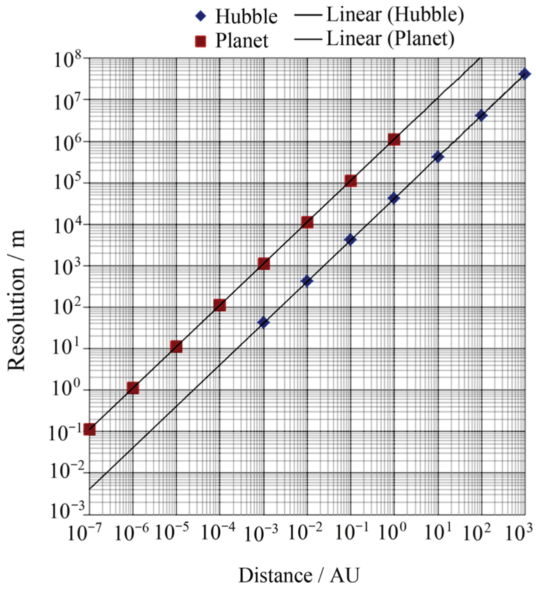

Fig. 2 Optical resolution at 550 nm as function of distance for the Hubble space telescope and a Dove satellite from Planet Labs Inc

Here P_0 is the mass required for a certain performance at time 0, P_t is the mass required for the same performance at time t, n is the reduction rate. The study showed mass reduction rates of approximately 127 months (10.5 years) prior to the introduction of CubeSats and a rate of 36 months for Earth observation satellites after the CubeSats have appeared. A much smaller study conducted on beepsats, *i.e.* satellites that only emits a beacon, showed a mass reduction rate of 55 months.

1.2 Science-driven Projects

One of the approaches adopted to gain access to space science is to answer science questions by means of already available technologies, and some examples of such kind of projects are presented below.

The SNIPE (Small scale magNetospheric and Ionospheric Plasma Experiment) mission for space weather research developed by the Solar and Space Weather Group, KASI, Korea, is going to be launched in 2021 into a polar orbit at an altitude of 500 km with an orbital high-inclination of 97.7°. The scientific goal of SNIPE is to identify temporal and spatial variations of small-scale plasma structures in ionosphere and magnetosphere. SNIPE consists of four 6U-nanosatellite, *i.e.*, each one made of 10 cm×10 cm ×60 cm cubic units (about 10 kg for each spacecraft), and this constellation is a formation flying and slowly separated from tens to several hundreds of kilometers for six months, while the spacecraft design lifetime is at least greater than one year (with a scientific operation time of six months). The SNIPE mission is equipped with scientific payloads, which can measure the following geophysical parameters: density/temperature of cold ionospheric electrons, energetic (about 100 keV) electron flux, and magnetic field vectors. All the payloads will have a high temporal resolution (better sampling rates than 10 Hz).

The science targets are as follows.

(1) Spatial scale and energy dispersion of electron microbursts.

(2) Temporal and spatial variations of plasma trough during magnetic storms.

(3) Temporal and spatial variations of electron density and temperature in polar cap patches.

(4) Measuring the length of coherence for bubbles/blobs.

(5) EMIC waves at the top of ionosphere.

Last but not least, this mission constitutes a beautiful example to have a synergy with other already existing space weather missions, such as THEMIS, MMS, ERG, and GOES, as well as ground observations like EISCAT and CARISMA networks.

An initiative for a science-driven swarm CubeSat mission was put forward by the Department of Physics at University of Cagliari, Italy. With the first detected Gravitational Waves event (in August 2017, GW170817) from merging neutron stars or merging of a neutron stars with a black hole, related to a short Gamma Ray Burst (GRBs), a new astrophysics era has started, the so-called Multi-Messenger Astrophysics. The operation of an efficient X-ray all-sky monitor with good localization capability will have a pivotal role on multi-messenger astrophysics in the next decade. The mission idea, called High Energy Rapid Modular Ensemble of Satellites (HERMES), aims to detect and accurately localize GRBs and other high-energy transients, such as the counterparts of GW events (merging of compact objects, supernovae), that can be deployed in a few years, thus bridging the gap between the aging, past generation of X-ray monitors (Swift, INTEGRAL, Agile, and Fermi) and the next ones.

Arcmin localization of most GRB with the flux of a few photons ($\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$) is therefore the final goal of the HERMES project. The HERMES concept is based on relatively small but innovative X-ray detectors (collecting area in the band between a few keV to a few hundred keV of $50\sim100\,\mathrm{cm}^2$), hosted by 3U CubeSats (10 cm×10 cm×30 cm, weight around 5~6 kg), launched in equatorial Low Earth Orbit (LEO). The transient position is obtained by studying the delay during the arrival times of the signal upon different detectors, placed hundreds/thousands of kilometers away (see Figure 3). This large increase of the discovery space on the physics/astrophysics of high-energy transients can lead to breakthrough discoveries in at least other four broad areas: (i) GRB inner engines; (ii) GRB jet composition; (iii) GRB radiative processes; (iv) the granular structure of space-time.

The Swiss Federal Institute of Technology, Lausanne, Switzerland (EPFL), together with the Paul Scherrer Institute in Switzerland (PSI), is working on a joint mission concept called CHESS (Constellation of High Energy Swiss Satellites), a student mission whose goal is to launch a constellation of four CubeSats for high-energy astrophysics studies in late 2021 (see Figure 4). It intends to bring together Swiss universities into a collaborative national project for

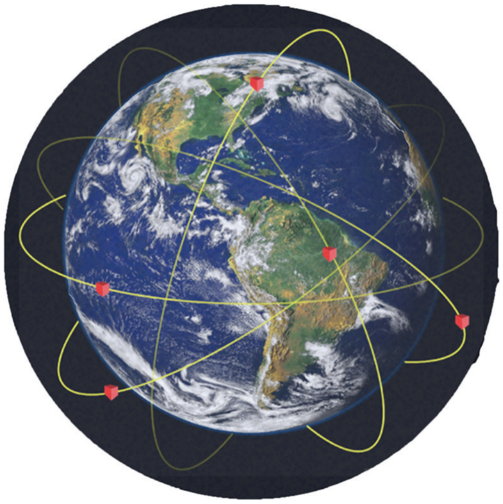

Fig. 3 HERMES mission. Credits: hermes.dsf.unica.it

scientific research. The four identical nanosatellites will embed a Hard X-Ray polarimeter developed at PSI, which is a novel, miniaturized detection system developed for precise observations of the solar system, the Sun, and even fundamental astrophysical processes occurring in distant galaxies. It will enable the simultaneous study of gamma-ray bursts and solar flares, including space weather phenomena.

With a carefully-synchronized timing between the CHESS CubeSats, it will be able to determine the direction of the detected Gamma-Ray Bursts and correlate the event with potential Gravitational Waves measurements. It is worth noting that, since the project is work in progress, some aspects of it, valid at the time of this writing and presented here, may have changed.

1.3 Engineering-driven Projects

Some of the recent activities involving deep-space exploration with CubeSats and/or small satellite platforms at ISAS/JAXA, Japan, are here investigated. Specifically, the mission requirements and trajectory design of two 6U Japanese CubeSat missions that will fly as a piggyback project of NASA's space launch system during its maiden mission Artemis-1 were reviewed. The two CubeSats are named EQUULEUS and OMOTENASHI and they differ greatly in terms of mission life span and objectives. OMOTENASHI is equipped with a solid rocket motor to decelerate its relative velocity with respect to the Moon and carry out the first lunar semi-hard landing (by the project requirement, the touchdown speed shall be less than 100 $\mathrm{m\cdot s^{-1}}$). Key technologies are being developed and will be proven to enable cheap and fast access to the surface of the Moon.

Fig. 4 CHESS 3U CubeSat constellation is a constellation of 3U CubeSats developed by the Swiss Federal Institute of Technology Lausanne. Its goal is to study high energy astrophysics with a hard X-ray Compton polarimeter as main payload. Credits: CHESS mission

EQUULEUS is another technology demonstrator that will fly by with the natural satellite to reduce its orbital energy and eventually insert into synodic resonant libration point orbits near the second Lagrangian point of the Earth-Moon system. From this privileged outpost, the spacecraft will study the lunar flash impacts that occur on the far side of the Moon and help characterize the size and distribution of Near-Earth Asteroids with data and statistics impossible to make with ground-based telescopes (see Figure 5). EQUULEUS will also study the cislunar dust environment and test key technology for future deep-space CubeSat missions, like a water resistojet propulsion system capable of delivering up to 80 $\mathrm{m\cdot s^{-1}}$ of Delta V (change in velocity).

The Mahidol University of Thailand recently introduced a space exploration payload for a CubeSat. The payload aims to detect the high-energy particles in space, cosmic ray, which will enable us to understand the behavior and origin of the particles. However, the key challenges include the development of a payload to observe the particles, their direction, and their energy. The main mission consists of 3U CubeSat at an altitude of 600 km in a polar orbit with an energy detector optimized between 2 MeV

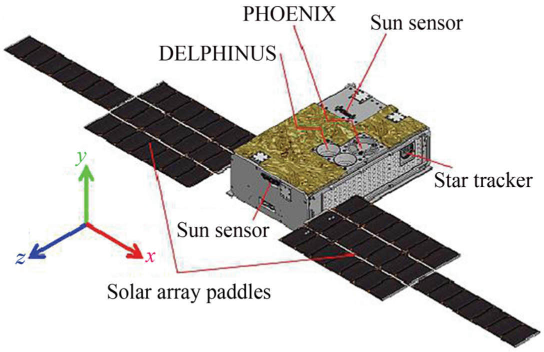

Fig. 5 External view of the deployed EQUULEUS nanosatellite. Picture credits: ISSL, JAXA

and 200 MeV energy range. Hence, the space exploration mission is the technological demonstration of Cosmic-ray electron/positron detection in space.

Also, more engineering work was put forward by the National Commission for Aerospace Research and Development (CONIDA), Peru, *i.e.* the microstrip antenna showing two models with circular polarization in the S and C band to be applied to the 3U CubeSat, including the technology of the UHF and VHF transceiver board an S band down-converter kit for ground satellite stations as well as the installation and maintenance of satellite receiving stations L, X band for weather forecast satellites AQUA, TERRA, METOP, and NOAA.

The Department of Electrical Engineering at the Faculty of Engineering, Prince of Songkla University, Thailand, is contributing to the first 1U CubeSat developed by King Mongkut's University of Technology North Bangkok (KMUTNB) within the scope of the KMUTNB Academic Challenge of Knowledge Satellite activities in Thailand. The first entirely built in Thailand 1U CubeSat is called KNACKSAT, developed in the context of the educational space technology program of Thailand (see Figure 6). The university team of five staff members and 25 students launched the 1U CubeSat *via* the Spaceflight's SSO-A (Sun Synch Express) mission in September 2018. The students' activities and learning process included satellite design review, space environment testing, satellite integration, ground station, and the signal elaboration received from the satellite, among others. Two other peculiar goals of this CubeSat were the amateur radio linear transponder as well as space pictures.

Fig. 6 KNACKSAT satellite, an acronym for KMUTNB Academic Challenge of Knowledge Satellite, is a 1U-CubeSat satellite (roughly 1.3 kg) developed by King Mongkut's University of Technology North Bangkok (KMUTNB), Thailand

Another example of a CubeSats' based project is to be found in the Institute of Space Technology, Islamabad, Pakistan, as it presents the CubeSats engineers' work related to the design of the magnetometer unit for a university microsatellite and the design of power subsystem for 3U CubeSat.

For what concerns the participation of Mongolia in the advancement of CubeSat studies and missions, two main projects can be mentioned, *i.e.* the BIRDS (Joint Global Multi-Nation Birds Satellite project) interdisciplinary satellite project and Mazaalai, the first Mongolian satellite. The BIRDS project is a multinational joint satellite plan for nonspacefaring countries supported by Japan and joined by four countries, *i.e.* Ghana, Mongolia, Nigeria, and Bangladesh, and that has already entered its fourth phase. In the context of this project, three Mongolian students have participated in the design, development, and operation of the country's first-ever satellite. Figure 7 shows the Mazaalai satellite. This satellite was sent to ISS through the SpaceX CRS-11 mission and launched in a Dragon spacecraft on the Falcon 9 rocket from NASA Kennedy Space Center. The satellite was in orbit around the Earth at an altitude of approximately 400 km and at an inclination of around 51°, completing an orbit every 92 minutes. Mazaalai is a 1U CubeSat launched on 3 June 2017,

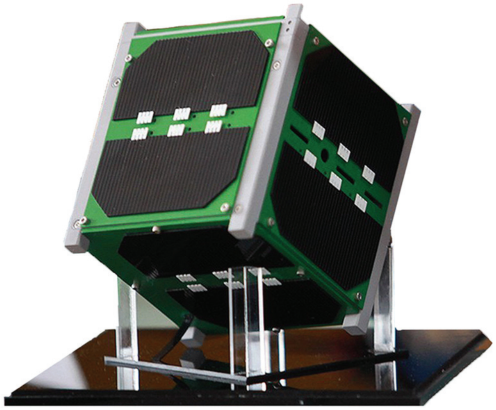

Fig. 7 Mazaalai satellite, named after the endangered (and native to Mongolia) Gobi bear, is the first Mongolian satellite launched into outer space on a Low Earth Orbit (LEO) as part of the SpaceX CRS-11 mission in June 2017

as part of the SpaceX CRS-11 mission. It was in orbit around the Earth at an altitude of approximately 400 km and at an inclination of around 51°, completing an orbit every 92 minutes. Unfortunately, Mazaalai was deorbited on 11 May 2019.

The Department of Astronautical Engineering of the University of Turkish Aeronautical Association, Turkey, put forward the five in-orbit CubeSats of Turkey. Two of these CubeSats are included in the QB50 project* and involve science payloads of multineedle Langmuir probe in addition to an X-ray detector in one of the satellites. Furthermore, the science mission plans of the University of Turkish Aeronautical Association (UTAA) using CubeSats were discussed. The main science focus at UTAA is placed on gravitational physics and in accord with this target, the mission ideas concern general relativity, especially gravitomagnetism.

Following a formal analogy between electromagnetism and linearized Einstein's gravity, gravitomagnetism represents the kinetic effect of gravity just like the magnetic effects for a moving electric charge. The tests of gravitomagnetism were carried out with some past satellite missions such as LAGEOS and Gravity Probe B. Nevertheless, there is always a definite need for tests of gravitomagnetism with improved accuracy. With the advancement of chip scale atomic clocks, which are suitable for CubeSat applications, it is easy to envision a CubeSat mission devoted to the study of gravitomagnetic effects, such as the frame-dragging effect due to Earth's rotation. This effect creates a difference in the signal rotating in the direction of Earth's rotation and in the opposite one. A mission concept proposal can be the one described in Ruggiero and Tartaglia, 2009, where three satellites in GEO orbits create electromagnetic signals rotating around Earth in opposite directions and time the rotation of these signals[3].

1.4 Education-driven Projects

Miniaturization of modern electronics and sensor technology has induced large-scale democratization of space access, as satellites can be built and launched with only a fraction of the former multimillion costs. This disruption has brought new opportunities to smaller and developing countries around the world to build national capacities to advance and run their own space assets. Affordable satellites bring also viability to large scale commercial constellation projects and bring new opportunities for education and science.

The Foresail satellites for space science by the Finnish Centre of Excellence in Sustainable Science represent a positive example of the development path from the first student-built spacecraft to the booming new space economy and national science satellite programs in Finland. The development took less than ten years and thus, the finnish example exemplifies the most important benefits of current space technology disruption and gives valuable insights to the countries and teams who find themselves on a similar path. The presentation showed the efficacy of well-channeled education to create economic activity and boost science outcomes.

The Foresail-1 CubeSat designed in Aalto University, Finland, carries interesting science payloads and technology demonstrators to deorbit the spacecraft[4,5]. The mission objective is to measure radiation belt losses using particle telescope, demonstrate Coulomb Drag Propulsion (CDP) for deorbiting, test an ultra-sensitive magnetometer, and prepare for high radiation missions. The Particle Telescope payload has the requirement to orient its detector with shorter collimator towards the Sun, while the detector with longer collimator serves to scan the environment. The CDP requires spin control for deploying and maintaining the tension of the tether to demonstrate the deorbiting (see Figure 8).

Another analysis of the educational advantages of CubeSats was explored by the Technical University of Munich, Germany (TUM), as three main points were put forward.

(1) Architectural and engineering – overview of university-built CubeSats.

(2) CubeSat deep space exploration – targets and missions.

(3) CubeSat deep space exploration – design con-

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[*] www.qb50.eu

siderations.

While the second and third presentations focused on deep space exploration with CubeSats, a goal pursued by more experienced teams and/or national space organizations, the first talk described the main lessons learned during 13 years of CubeSat development at the Technical University of Munich (TUM). CubeSats, once invented for educational purposes in 1999 by Bob Twiggs of Stanford University and Jordi Puig-Suari of California Polytechnic University[6], have evolved to become accepted platforms for scientific and commercial applications. This trend has recently accelerated and a 2016 report from the space studies board of the US National Academies of Sciences (NAS) found that over 80% of all science focused CubeSats were launched between 2010 and 2016 and more than 80% of peer-reviewed papers reporting science on CubeSats were produced from 2010 (see Ref. [7]). This acceleration is fueled by the miniaturization and increased utilization of Commercial Off-the-Shelf (COTS) parts and led to a more or less Moore's law equivalent growth of Ground Sampling Distance (GSD), data rate, and data volume of small satellites between 1990 and 2010[7].

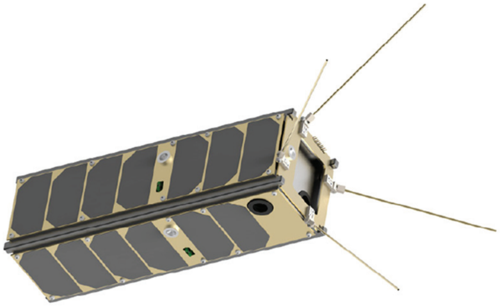

Fig. 8 Foresail-1 structure – It is a satellite mission of the Finnish Centre of Excellence for Sustainable Space, and its main payload is the Particle Telescope (PATE), developed by the University of Turku. Picture credits: Aalto University, Finland

Over the past 13 years, three CubeSats were successfully developed and launched at TUM. The endeavor started in 2006 with the development of First-MOVE (see Figure 9 on the left). The main goal of First-MOVE, as in many CubeSat programs of that time, was the hands-on education of undergraduate and graduate students and the ambitious design and build of a 1U CubeSat verification platform[8,9]. The First-MOVE was operated successfully during one month after its launch in late 2013. Until then, more than 70 students of different faculties had participated successfully in the project, with numerous educational and programmatic lessons learned[10]. Starting in April 2015, the second CubeSat of TUM, called MOVE-II (see Figure 9 on the right) was developed and launched into space in late 2018[11].

Besides hands-on education, a scientific experiment dedicated to novel solar cells is flown on this satellite mission[12]. CubeSats, in discrepancy with their bigger counterparts, can be built, tested, and launched very fast. A clone of MOVE-II, called MOVE-IIb was built and tested within six months,

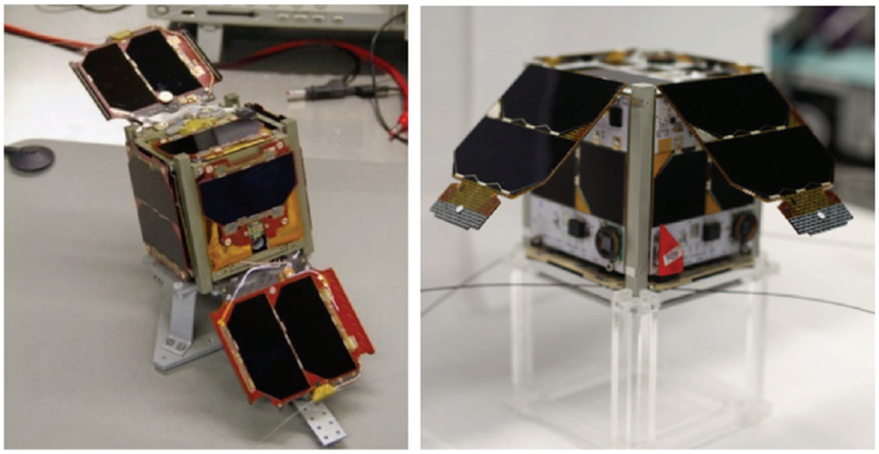

Fig. 9 First-MOVE (left) and MOVE-II (right), both are 1U-CubeSats from Institute of Astronautics (LRT) at the Technical University of Munich (TUM)

and launched into space in July 2019, within a year from the start of the project.

The most important lesson learned regarding university-built CubeSats (and also commercial missions) is the relation between complexity and cost/schedule. As stated by McCurdy[13], the aggregation of failures can be by explained by the Bearden rule: complexity in missions increases cost and development time, with a linear relationship for schedule and exponential for costs. If too much complexity is demanded out of a limited budget and schedule, it will lead to failures. This is especially worthwhile to be considered for interplanetary missions, as the launch opportunities are rare and thus the demand for more experiments on one specific mission is usually high. Looking at the results found by the aerospace company for SmallSat missions[14], a zone with impaired and failed missions, *i.e.* an area in which complexity is too high with respect to schedule and cost, can be seen in Figure 10.

The last couple of years showed that CubeSats are a feasible tool for conducting scientific experiments, both in the Earth orbit but also in the interplanetary space. The upcoming launch of Artemis-1 will deploy 13 CubeSats[15] with a broad variety of planned experiments into interplanetary trajectories and many future deep space launches will have reserved volume for scientific CubeSats. Independently from the mission, CubeSat developers should also keep the Bearden rule in mind when planning their scientific missions.

As an example of CubeSats-based endeavors that also function as a students' educating tool, the DUT-1 (Small Bright Eye) (see Figure 11) mission is the result of the joint efforts of Dalian University of Technology, Changguang Satellite Technology Co. Ltd., Tsinghua University, Wuhan University, and Xinjiang Institute of Physics and Chemistry with the participation of more than 100 students in the development. DUT-1 is the first 20 kg sub-meter high-resolution remote sensing 12U CubeSat and it includes three main payloads, *i.e.* a high-resolution camera (PAN/Multispectral low-cost and high-resolution camera), electric propulsion (μCAT micro-electric propulsion system), and a space radiometer to monitor the real-time dose rate in space. By means of state-of-the-art, innovative technology, concluding 3D printing structure, 3D printing launch pod, integrated ADCS, and reflect-array antenna,

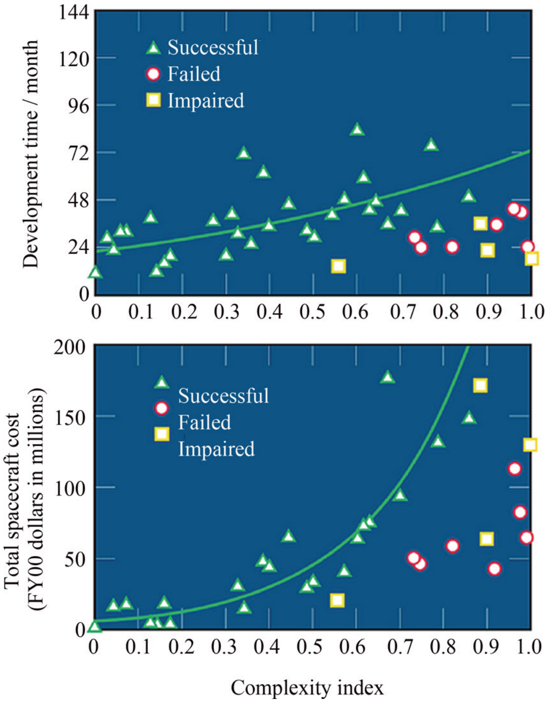

Fig. 10 Successful, failed and impaired SmallSat missions analyzed by the Aerospace Company[14]

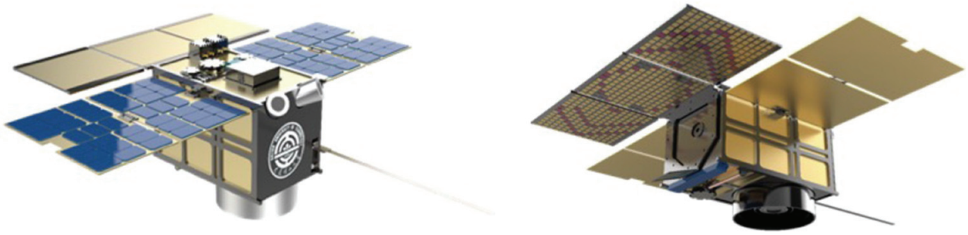

Fig. 11 DUT-1 Satellite developed by Dalian University of Technology, Changguang Satellite Technology Co. Ltd., Tsinghua University, Wuhan University, and Xinjiang Institute of Physics and Chemistry. Credits: DUT

and quality features, such as a pointing accuracy of $< 0.05^\circ$ and a transmission rate of $400\,\mathrm{Mbit{\cdot}s^{-1}}$, DUT-1 will be launched around June 2021.

Finally, the lessons learned during ten years of teaching experience and development of CubeSats to students at Polytechnic of Turin can be summarized in the following points (which are often overlooked by students): (i) the importance of good and exhaustive documentation, which is often a quite difficult task for students; (ii) the relevance of interdisciplinarity as students are typically focused on their specific field and often neglect other less known effects during the design of CubeSats; (iii) the significance of environmental conditions in the selection of parts; (iv) the lack of appropriate redundancy or, even worse, the use of redundancy in an appropriate way; (v) the unavailability of parameters of several components (*e.g.* rechargeable batteries); (vi) the lack of fault propagation effects in a complex design; (vii) the simpler, the better, as often simple procedures or circuits are more effective than complex ones; (viii) the huge impact of the harness.

In practice, from the education point of view, much was learned rather during the design phase than during the launch and operation. Some of the lessons include: (i) interdisciplinary team set-up; (ii) ability to build a complex system; (iii) great amount of knowledge and capabilities taught to students; (iv) students faced with the complexities of practical tasks.

Since design, manufacturing, test, and documentation account for 90% of the efforts and benefits with only 10% of the costs, while launch and operations account for 10% of the efforts and benefits with 90% of the costs (mostly for the sat-launch), some question the necessity of launching for teaching. Moreover, students should face a degree of complexity which is compatible with their knowledge. Therefore, they should be assigned with sub-subsystems only. It is utterly important for students to understand well the mission and its requirements in order to develop the subsystem handed to them, while system-level tasks should belong to permanent staff duties (teachers or Ph.D.).

Further details concerning the Polytechnic of Turin include: (i) the current activities on the development of smart structures promoted by the university; (ii) improvement of the primary structure of CubeSats by using the empty volume on lateral surfaces between lateral rods, increasing structural robustness, getting rid of useless items, and improving heat transfer; (iii) taking advantage of modern model-based design in the development of subsystems to decrease the complexity of students' tasks to make them accessible to master students and to improve the quality of the documentation as well as testing and qualifications; (iv) the embedding of most spacecraft functions inside the lateral surfaces of a CubeSat and make them also structural and thermal elements; (v) the improvement of the heat transfer of mechanical interconnections between removable structural elements; (vi) the embedding of electromechanical subsystems (*e.g.* magnetorquers or magnetic torquers, reaction wheels, batteries) inside the lateral skins of the spacecraft, making them thin enough; (vii) the description of the operation and optimization of on-board telescopes (tutorial); (viii) the concepts of attitude and optics required to understand the principles of operation of a telescope, both reflective and refractive; (ix) the performance parameters of a telescope (*e.g.* field of view, resolution); (x) the formulas to compute the focal length of telescopes and the relationships with telescope parameters; (xi) the physical phenomena leading to image aberrations; (xii) the optimization of geometrical parameters to improve telescope parameters given some mission-dependent constraints; (xiii) the introduction of a panel on the technological capabilities of modern and future CubeSats with a short introduction of state-of-the-art technologies.

2 Main Takeaways on CubeSat Technology and CubeSat Missions

The great efficiency resulting from high productivity at lower costs and lower energy-usage ensured by CubeSats (or small satellites) technology is deemed to outperform traditional satellites in these primary aspects. As a matter of fact, even though CubeSats were first developed at the university level for educational purposes, they do now represent an advantageous solution also for commercial missions led by space agencies as well as for joint projects across countries. Furthermore, researchers and engineers were also given the chance to inquire about potential collaboration opportunities at the international level based on CubeSats constellation missions. Specifically, scientists were able to acquire more knowledge on the aspects investigated in the following subchapters.

2.1 CubeSats Highlights: Efficiency, Constellation Missions, Deep-space Exploration

CubeSats are a convenient, light-weight, sustainable solution for space science missions as their production and launching costs are significantly lower than in traditional satellites. Their reduced dimensions come with several benefits not only in terms of reduced costs, but also in terms of risks and reachability. In fact, while large satellites can only cover a relatively limited portion of space, a constellation of CubeSats can work on a larger area at the same time, thus expanding the potential of space missions. While Earth-bound satellites remain vital for educational and scientific activities, CubeSats and small satellites in general still represent an invaluable asset for deep-space exploration (even though some questions remain on their feasibility for interplanetary missions).

In the last couple of years, it was proven that CubeSats are a feasible tool for conducting scientific experiments, both in Earth orbit but also in interplanetary space. The upcoming launch of Artemis-1 will deploy 13 CubeSats[15] with a broad variety of planned experiments into interplanetary trajectories and many future deep space launches will have reserved volume for scientific CubeSats. Even with a small 1U to 3U CubeSat, it is possible to carry out important missions involving inter-sat communication, remote sensing, and bioscience missions. Solar sail used in CubeSat to deorbit it also represented an interesting mission application.

2.2 CubeSats beyond Universities

CubeSats are still used for what they were first created for, *i.e.* education at universities. They are indeed a great teaching tool, but for some countries, they also often represent the very first national satellite launched at national level (*e.g.* Switzerland's first CubeSats launched in 2009).

Nevertheless, this rapidly developing field of CubeSat offers new opportunities for numerous space research areas. Using miniaturized, low-power instrumentation developed for cube satellites, it is possible to reduce the time from the mission concept to real measurements in space. CubeSat is also a cost-effective tool to get a payload into space to carry out research and develop new technologies.

2.3 Technical Knowledge

In terms of technical knowledge and takeaways, they can be summarized in the following points: (i) hardware and software reliability: design and testing; (ii) modular approach and its benefits; (iii) compact design subsystem; (iv) COTS, Rad hardening and reliability relation; (v) state-of-the-art sensors used on CubeSat; (vi) statistical trends of CubeSat; (vii) know-how development.

Fostering know-how development and sharing is a key strategy to improve skills and capabilities and in this regard, the following aspects where considered: (i) MOVE I Mission: overall design considerations; (ii) choice of Communications Bands (IARU/UIT); (iii) Italy's experience on teaching university students how to use CubeSats shows that it's worth it even if not launched[16,17]; (iv) engineering overview of foresail CubeSats; (v) aoxiang series CubeSats, development and trends; (vi) Aalto University and its vision of a “Finnish Centre of Excellence in Sustainable Space”; (vii) general application of the sequence: CubeSat Development by the integration of tested modules – Development by the integration of tested modules and design/implementation of a subsystem – Development by full custom design; (viii) management of Development Team and the challenge of knowledge management when working with students; (ix) Korean SNIPE, use of IRIDIUM as backup Communication and formation flight strategy (see Figure 12).

2.4 Importance of Interdisciplinary Research on CubeSats

The combination of physics, relativity, and astronomy together with engineering knowledge constitutes a win-win interdisciplinary approach. Physics-based presentations were particularly useful to understand the challenges associated with operating more than one satellite at a time as well as with finding optimal trajectories that would fulfill the mission objectives. Nevertheless, it was clear that without access to small satellite technologies, high-energy or general relativity-based missions would be overly costly and unfeasible. Scientists, especially those who deal with abstract topics such as relativity and astronomy, are more deeply involved in CubeSat missions than expected. Furthermore, also theoretical physicists have expressed deep interest in the CubeSat business and in a similar token, increased attention is dedicated to missions which do not prioritize technology but rather science questions, such as the Korean SNIPE mission. In fact, even though this mission does not adopt revolutionary and state-of-the-art technologies, it puts emphasis on ionospheric and magnetospheric science questions, as it was also the case of some other missions driven by science questions.

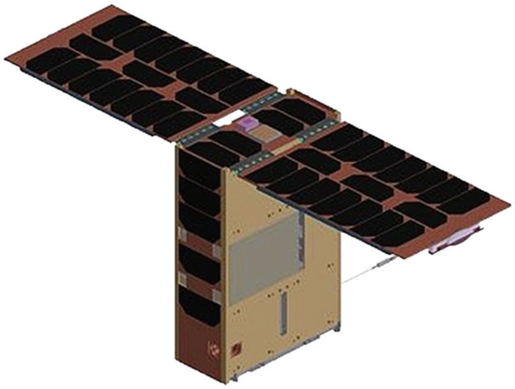

Fig. 12 South Korean SNIPE (Small scale magNetospheric and Ionospheric Plasma Experiment) Satellite is a south Korean mission for identifying temporal and spatial variation of small scale plasma structures in the ionosphere and magnetosphere. Credits: KASI

2.5 Costs and Complexity Relationship

One of the most important lessons learned from university-built CubeSats (and also commercial missions) is the relationship between complexity and cost/ schedule. As stated in the previous section, missions' complexity increases both costs and development time, with a directly proportional relationship in terms of schedule, while it is exponential for costs. Such relationship is a particularly significant for interplanetary missions, as the launch opportunities are rare and thus the demand for more experiments on one specific mission is usually high.

2.6 CubeSats' Main Challenges

Among the main challenges faced by developers, researchers, and engineers of CubeSats several factors can be enumerated, such as the lack of standardization in terms of interface, which may complicate the collaboration among different actors, and the need for improvement of CubeSats' structure. Furthermore, the space debris problem should not be neglected, a nowadays small but still rapidly growing problem. However, CubeSats are currently not the main concern in this regard, as only over 1200 CubeSats have been launched into space so far. A solution still needs to be found, and EPFL is working on it through CleanSpace One (see Figure 13). Finally, even though the interface standardization is a change required to simplify CubeSats-based collaboration, the standardization of the CubeSat deployer reduced the flexibility left to developers to adjust the shape and volume of a CubeSat.

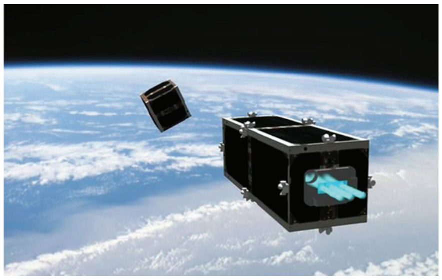

Fig. 13 CleanSpace One satellite is a technology demonstration satellite first developed by the Swiss Federal Institute of Technology in Lausanne (Ecole Polytechnique Fédérale de Lausanne, EPFL). Credits: EPFL

HERMES and CHESS missions can provide insights on an inspiring science application of CubeSat platforms. Both missions aim to study the electromagnetic counterparts of the gravitational waves, paving the way to multi-messenger astronomy. Furthermore, the discussions on the COSPAR Roadmap on Small Satellites for Space Science (4S) and on how to use CubeSats for science missions from a physics point of view can give a general perspective on the future science missions with CubeSats. In particular, the swarm explorations of a solar system body and the vision for a visit to Alpha Centauri with very tiny chip-size satellites are promising perspectives on solar system explorations and interstellar visits.

In addition to these visionary discussions, three currently operating missions can offer interesting insights, *i.e.* the Japanese Moon exploration project based on CubeSat technology, EQUULEUS and O-MOTENASHI, the Korean CubeSat constellation mission for small scale magnetospheric and ionospheric plasma studies, *i.e.* SNIPE, and the FORESAIL missions of Finland for studying space environment at LEO and GTO.

2.7 Cross-country Collaboration

As outlined in the last section of this article (International collaboration), despite the evident financial benefits guaranteed by CubeSats, the development and implementation of space science missions can still represent a tedious challenge in terms of financial, technical, and technological resources for many countries. Less developed countries nowadays have the capability to launch their own scientific CubeSats, but they may face some difficulties in terms of funding and governments' willingness to support the projects. Moreover, the cooperation between teams in the form of exchange of students and staff would help differentiate the experience among teams and improve future missions.

2.8 Overall Knowledge on Numerous Different Topics Acquired through CubeSats Education

Applied plasma physics, electric propulsion, experimentation, design, and development process. Experimental study of effects of electric and magnetic field on plasma, propulsion aystem about satellite, cold gas, liquid, resistors, RF ion, electrospray, pulse plasma, and vacuum arc thrusters, rain fade prediction software, some models affiliated with Mega-cells such as Loo model, Statistical model, Corazza model, Lutz Two state channel model, Physical-statistical models, Time share of shadowing models, Time series model, Wideband model, Two satellite model, Mobile-satellite channel model, Radiometry missions, Atmospheric radiometry, Deep space missions, Design optimization of CubeSat telescopes and imagers for Earth and space observation, Classification of satellites, future trends of CubeSat technology, High gain microstrip antenna design for CubeSats, COSPAR roadmap on Small Satellites for Space Science (4S) engineering overview of Foresail satellites, PharmaSat, GraviSat, SporeSat, EcASat and BioSental, Small scale Magnetospheric and Ionospheric Plasma Experiment (SNIPE) solid state telescope, magnetometer, several ground stations.

3 Recommendations for Newcomers in CubeSats' Missions

3.1 CubeSats for Interdisciplinary, Multi-layered Collaboration

CubeSats provide the largest single standard launch market available at the moment, creating a rapidly developing ecosystem around it. They ensure easy access to a wide range of innovative ideas to any country that enters the field, as CubeSats do not simply represent a standard spacecraft but rather a collaboration, innovation, and education platform. A single CubeSat launch is not necessarily a big breakthrough in space technology, but it prompts the community and young teams around it to build the national capacity to launch and operate national space missions.

CubeSats also constitute a very affordable platform for hands-on learning of space technology and it has so far shown a strong capability to incubate new business ideas. It is also an affordable instrument for developing space science and scientific missions and raise overall awareness about topics related to global technology.

First of all, they can be developed fast and cheap. As such, CubeSats make space research accessible for universities all around the world and put space research in high gear, leading to amazing possibilities. Perhaps, future planetary missions could also include one or two student-led CubeSats that would operate independently of the main spacecraft, limiting the cost-related impacts to the primary mission. It is undeniable that the possibility to build one's own spacecraft to make measurements on Mars or a comet or anywhere else in the solar system could energize the next generation of planetary scientists and engineers. These scientists and engineers can get involved in the entire life cycle of the satellite, thereby facilitating and maximizing technology transfer.

Secondly, countries afoot the CubeSat industry should consider the community aspect and enable their young CubeSat teams to visit conferences and workshops to develop connections. In order to be successful, the CubeSat developments should always involve a novel element in order to start partnerships with other industry players. A CubeSat is legislatively equal to a large spacecraft and therefore, a single national CubeSat can lead to significant developments in the national legislation as well as in the organization of space activities at a higher level.

Last but not least, CubeSats represent a very good option for engineers to work in collaboration with other engineering departments. A CubeSat-based project can involve electronics, communication, mechanics, aerospace, and system engineers, who can all commit to the mission to polish their skills and gear up for big satellites and bigger projects.

3.2 Key Lessons for Newcomers in the CubeSats' Industry

Newcomers in the CubeSat missions have the opportunity to work on a wide range of missions. Nowadays, researchers are running numerous important projects by means of CubeSat technology, including remote sensing, communication, Earth-imaging, space exploration, inter-sat communication, air traffic management, ship tracking, and there are many other missions which could be carried out by means of CubeSat technology.

Therefore, newcomers in CubeSat missions are encouraged as follows.

(1) To focus on and be creative with the scientific motivations beyond their projects. While building and operating a satellite in space remains a key activity for educational and social purposes, it is true that some interesting scientific experiments could be made "along the way" while developing the necessary protocols and know-how to design and operate a CubeSat. A clear scientific purpose would widen the impact of their corresponding spacecraft project as well as attract the interest of the international community.

(2) To focus on intersystem tests, *i.e.* a test program that should evolve around sub-system interactions. A rudimentary standard function test of each sub-system is naturally mandatory before system integration, but letting the sub-systems perform with each other will assure full functionality and at the same time give sub-system developers a deeper understanding of their own system. Although the space environment is different from a lab setting and it is hostile to satellites, the major reasons for CubeSat failures built by new-comers are inter-system failures.

(3) To keep the Bearden rule in mind when planning a mission. This does not necessarily imply the reduction or resizing of the scientific outputs and goals of the mission, it rather means to reduce the complexity of experiments and of the satellite itself. This can be deeply enhanced by the already available subsystems or products on the market, also coming from terrestrial applications, which can be reused in CubeSat missions. At the end of the day, CubeSats have to be fast-to-build and relatively cheap, but both characteristics can be aligned with the scientific objectives of the mission, as proven by the successful Lunar Prospector and Mars Pathfinder (and Sojourner) missions of the Faster-Better-Cheaper program.

(4) To lay out the concrete mission goals before actually building the CubeSat. It is nowadays easier to enter the field since one can learn from the lessons that other missions have provided. However, the critical issue is the project management and the process of learning about a CubeSat mission. It is necessary

to learn from commercial CubeSats and focus only on the payload design to make the first mission a success. One should learn the whole process that leads to the CubeSat launch to acquire know-how.

(5) To note that redundancy can be the key to a successful CubeSat mission. However, one needs to be careful about the trade-off between complexity and redundancy, as every redundancy introduced makes the system more fault-tolerant, and at the same time it makes it more complex to manage the system.

(6) To have real science objectives and to produce real data. Nowadays, it is getting harder and harder to get funded for an education-only CubeSat mission. Indeed, one cannot forget that a CubeSat mission is not only about building a CubeSat and launching it, but also about getting data and analyzing them. Nevertheless, for a newcomer who has no prior experience with CubeSats and space missions in general and who cannot resort to the help of experienced people, it might be better to focus on a small 1U mission or to gather experience in other ways. Also, it comes without saying that if a CubeSat is built by students, the likelihood to have numerous mistakes is much higher than with a full-time team. Therefore, being vigilant and debugging frequently are two musts. For what regards universities' concerns, the most important thing is the balance between costs and performance. Furthermore, a good performance always means higher costs. However, it must be noted that not all missions need a high performance, as it should not exceed the requirement of the mission.

(7) To start understanding the solutions of other teams and to learn from their lessons. Make things simpler and avoid aiming at designs which are too complex. Ambitious goals are directly proportionate to experience increase and the modernity of the design techniques, such as model-based design. Last but not least, effective team building and experienced people retention are also a key for success. All the work done should be properly documented in order to further reduce delays.

(8) To be aware that the synergy between communities is the key to promote and improve CubeSats' capabilities and to expand the nowadays relatively limited but increasing application of this technology in science. With projects like HERMES (High Energy Rapid Modular Ensemble of Satellites), we could try to follow this concept, suggesting that CubeSats incorporates the technology that could potentially lead to breakthrough discoveries. The HERMES mission is established on a novel close and synergistic collaboration between astrophysics, fundamental physics, engineering, and the industry, where all these fields are cross-fertilized and encouraged by the realization of an extremely ambitious experiment, containing the costs and the time dedicated to operations. This ambitious goal will be achieved by exploiting at most the Commercial Off-the-Shelf (COTS) components, which are currently underperforming in the space environment, but with the potential to provide high impact and radical transformations in terms of its space application.

It is important to highlight that joining the experts' community and directly interacting with scientists who have developed a successful mission surely helps the newcomers in formulating new CubeSat missions. This kind of collaboration, if done carefully, can be very helpful in framing future satellite missions to yield useful scientific results. This community of veterans and newbies may be right at the first stage of their collaboration, where the former can help the latter learn and accumulate experience on CubeSats. However, it should encompass the participation of intermediate-level players, who are neither newbies nor senior researchers. The participation of those mid-level players may help effective communication between the two groups, a sort of intermediate actor for the best results.

In joining the scientific community, we will understand the potential and progress of each player, seizing the chance to explore the progress and type of researches being carried out by each country, the recent trends of small satellite technology, the latest studies, and some other noble projects.

At the same time, it is essential not to lose sight of the importance of the trainings. Students mostly focus on theory when studying at university. However, a hands-on workshop including practice at the AIT lab. can sometimes be more useful than theory. Small satellite missions can be a good opportunity to train students and provide knowledge about satellite technology.

4 CubeSats-based International Collaboration

4.1 CubeSats Advantages for Cross-country Cooperation

The beneficial impact of CubeSats-based joint efforts can positively affect the international relations between countries of different kinds, from regions with less financial and technological means and expertise up to nations which stand at the forefront of space science innovation, as well as between eastern and western territorial sovereignties. In regard to less-developed territories, the relevance of global ties depends on multiple factors, as it enables them to learn faster with the help of international experts as well as to share costs and risks.

Cross-border collaboration made it possible for countries such as Thailand, Bangladesh, Pakistan, and Mongolia, to make the most out of the cross-border know-how sharing network and, in some cases, it even led to pioneering projects and achievements. This is for example the case of Mongolia, which launched its first Mazaalai satellite into space in 2017 in the framework of the Birds-1 constellation of satellites which involved also Japan, Bangladesh, Ghana, and Nigeria.

Therefore, the overall benefits of CubeSats-based international collaboration are as follows.

(1) Improved productivity as know-how and scientific concepts of space missions are shared between different actors striving together toward greater scientific discoveries.

(2) Fewer chances of failure when knowledge and risks are shared, especially for universities or other entities if they have already built multiple CubeSats[18,19].

(3) Countries with fewer resources can advance and learn faster from CubeSats experts.

(4) No more need to work from the ground up as lessons learned from past mistakes are shared.

(5) Higher contribution for scientific purposes rather than unnecessary technological show-off.

(6) Strengthened global ties through scientific collaboration.

Given the favorable corollary of international collaboration, CubeSats currently represent a highly attractive point of collaboration for international institutions, universities, space agencies, and in general, for those who are committed to space science studies. Many countries around the globe are still looking for technological and scientific cooperation opportunities, such as the Department of Astronautical Engineering of the University of Turkish Aeronautical Association (Turkey), which is gearing up to work on the High Energy Rapid Modular Ensemble of Satellites mission (HERMES) together with many other international actors.

4.2 Current Joint CubeSats-based Projects and Missions

Below are some examples of successful international collaboration experiences as well as of commitment to CubeSats-based knowledge-sharing models.

(1) Nations such as China, Turkey, and African countries sent their first CubeSats into space in the context of the QB50 international network of CubeSats which also involves several European countries*.

(2) The mission proposal "Deep Space Observation Forerunner (DSOF)" was recently submitted to the China National Space Administration (CNSA). Co-sponsored by Dalian University of Technology, Tsinghua University, Wuhan University, Xinjiang Technical Institute of Physics and Chemistry, Belarusian State University, and Changguang Satellite Co. Ltd., the project is based on two CubeSats, a CubeSat deployer, and four femto (10^{-15}) satellites to target the near-Earth asteroid 2016 HO_3 and the main-band comet 133P. The aim of the DSOF mission is to conduct scientific research, among others, space radiation measurement, asteroid landing, CubeSat visible/hyperspectral image acquisition, and it is one of the candidate proposals of CNSA project whose final selection has not been announced yet.

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*www.qb50.eu

(3) Thanks to international mutual support, Mongolia launched its first Mazaalai CubeSat into space on 3 June 2017.

(4) CONIDA (Peru) continuously participates in several projects worldwide, such as the Student Small Satellite, and it also collaborates with Peruvian universities working on CubeSats.

(5) In Pakistan, the Space System Lab (SSL) of the Institute of Space Technology (IST) is fully focused on CubeSats research and hitherto, IST is the only and first institute in Pakistan to have launched its own CubeSats.

(6) The SSS-2A Project is part of APSCO Student Small Satellite program and is being jointly developed by Shanghai Jiaotong University (China) and the Institute of Space Technology (Pakistan).

(7) The SSS-2B Project is also part of the same program and is being jointly developed by Tubitak-Uzay (Turkey) and GISTDA (Thailand).

(8) Aalto University (Finland) has implemented the Erasmus Mundus Space Masters as well as the Masters in Cold Climate Engineering.

(9) The Japan Aerospace Exploration Agency (JAXA) is committed to the national and international transfer of knowledge among universities and space agencies worldwide.

(10) Switzerland and EPFL (Switzerland) actively participate in chosen programs of the European Space Agency (ESA).

(11) GISTDA (Thailand) has created Space Inspirium, a modern science museum focusing on space technology and the science of the universe and aiming at knowledge sharing.

Given the proven multilateral interest and benefits of international collaboration in CubeSat development and application, many actors are looking forward to foster and enhance this kind of cooperation model to create international space missions and tighten the ties between countries worldwide.

5 Conclusions

The relevance and importance of CubeSats for the development of space studies, for advanced scientific results, and for the success of space missions, has grown to represent a critical focus in space science studies widely recognized by international scientific communities for multiple reasons.

In the first place, the marked efficiency of CubeSats in comparison to traditional satellites lies in its affordability both in terms of technological development as well as of scientific investigations. Moreover, the financial competitiveness of CubeSats implementation is also paired with the agile and time-saving technological and technical development of this kind of satellites, which can also be employed to complement the tasks carried out by traditional probes.

As a general rule, CubeSats positively differentiate themselves from traditional satellites thanks to the following features: (i) affordability; (ii) less time-consuming in terms of technical development as well as of scientific investigations; (iii) complementary to traditional probes; (iv) overall improved efficiency.

Evidence has shown that CubeSats technology-sharing entails multiple advantages for all actors involved in the process, from satellite developers to countries with fewer resources, as it decreases the chances of mission failure. Furthermore, great benefits in terms of scientific progress can derive from a technology-oriented cooperation. In fact, given the great complexity of space science-related questions and challenges, global technology collaboration can serve as a springboard for deeper scientific research and as a determinant to achieve competitive scientific outcomes.

For these main reasons, CubeSats currently constitute a valid, highly efficient option which allows scientists to fully focus on CubeSats' potential scientific and engineering applications, rather than on their preliminary development and project. As a matter of fact, the technical development of CubeSats bears no secrets as big as the mysteries of science, which, on the other hand, do still need joint efforts to be properly unlocked. In order to do so and thanks to the favorable common ground provided by CubeSats' shareable advantages, international actors of different kinds are prompted to work together, decrease international competition, and get rid of any eventual

CubeSats race for the sake of science.

As missions and experiments carried out in the outer space are becoming more and more essential to solve many earthly problems, such as resource management, environmental problems, and disaster management, CubeSats can benefit humanity and therefore, young scientists and engineers should be motivated to research and develop new CubeSat missions.

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