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Evolution from education to practical use in University of Tokyo's nano-satellite activities

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A B S T R A C T

The paper overviews recent nano-satellite development activities of University of Tokyo, Intelligent Space Systems Laboratory (ISSL). Development of real satellites and actually launching them provides excellent materials for space engineering education as well as project management, which is rather difficult to teach in usual class lectures. In addition, it may lead to a new way of space development with its cheap and quick access to space. Two educational CubeSats were launched successfully in 2003 and 2005, and they have been surviving in space more than 5 years, which showed that the COTS (commercial off the shelf) can be reliably used in space if the system is designed appropriately. Based on the experiences and technologies obtained in CubeSat projects, ISSL initiated practical applications of nano-satellite, starting with PRISM, 8 kg remote sensing satellite aiming for 30 m ground resolution and Nano-JASMINE, 20 kg astrometry satellite, which will be launched in 2009 and 2010, respectively.

In order to support these kinds of student-oriented activities in Japan, University Space Engineering Consortium (UNISEC) was founded in 2002 by the author's group, which has had large effect of further facilitating students' space-related activities in Japan. Significance and history of such activities are reviewed briefly, followed by the objectives and future vision of such nano-satellite activities.

1. Introduction

In recent years, a number of Japanese universities have been working on educational space engineering projects, practical student projects based on manufacturing nano-satellites and hybrid rockets. The first big wave was that a group of universities including the University of Tokyo, Tokyo Institute of Technology, Kyushu University, Nihon University, Tohoku University and Soka University, etc., have taken part in a project to launch nano-satellite models called CanSats onboard rockets and conduct experiments during their descent since 1999. Based on the experience and technology taken away from this project, educational and engineering CubeSat (10 cm^3, 1 kg nano-satellite) and larger satellite projects have been developed at a number of universities with the aim of producing an orbiting satellite. Taking part in space exploration using satellites made by university students themselves is becoming a major trend.

Two CubeSats, 1 kg nano-satellites, made by University of Tokyo and Tokyo Institute of Technology were launched in June 2003, since which time they have remained in use for more than 5 years. It can be said that this was a significant milestone in that it demonstrates that university students can make a satellite themselves. A large number of similar satellite projects have also sprung up elsewhere, such as the QPS project (Kyushu University), remote sensing agricultural satellite project (Hokkaido

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Institute of Technology), mother–daughter tether satellites (Kagawa University), or lightning observation science satellite SPRITE (Tohoku University), to name a few. Aided by international cooperation and collaboration with small to medium scale companies in the private sector, there is an ongoing search for opportunities to manufacture and launch satellites made actively and independently by students themselves.

University of Tokyo, ISSL have initiated the next step; "practical use of nano-satellites", starting with their third satellite PRISM, 8 kg satellite with remote sensing mission. In this satellite, by developing extensible boom with lens at its end, the optical system is expected to obtain 30 m resolution ground images. FM will be completed by mid-2008 in order to be ready for the launch using H-IIA launcher of JAXA, Japan in early 2009. The fourth satellite Nano-JASMINE, 20 kg astrometry satellite, is also under development in collaboration with National Astronomical Observatory of Japan, with a mission of generating a precise three-dimensional map of starts using near infrared CCD sensor in TDI (time delay and integration) mode. Nano-JASMINE is now at EM (Engineering Model) phase and planned to be launched in 2010 using Ukrainian-Brazilian rocket named CYCLONE-4. Another unique satellite named PETSAT, a novel satellite consisting of modular, plug-in panels has been developed together with small industries, and now is waiting for final brush-ups and launch. In these projects, we have been challenging the question of how we can realize practical missions out of less than 20 kg nano-satellites. We expect that these three satellites will demonstrate that the practical missions should be possible by blending good missions and new and well-considered technologies.

In addition to yielding outstanding educational results, activities such as these show that universities are on the verge of having the capability to manufacture and launch satellites in an attempt to expand the scope of space exploration, a field that has tended to become increasingly narrow. The effects of this are expected to include groundbreaking ideas for missions and satellite technology being uncovered thanks to the participation of researchers from a wide range of fields and opportunities being provided to quickly test cutting edge technology developed by national research institutions and manufacturers. There are high hopes that this will make a major contribution and help stimulate Japanese space exploration as a whole, which is currently stalled somewhat. Similar student activities emerged and are expanding in the field of hybrid and other type of rocket development.

A university/college community named University Space Engineering Consortium (UNISEC) was founded in 2002 and got NPO (Non-Profit Organization) status in 2003, whose objectives include (1) human resource training & development especially in the field of space development and utilization, and (2) technology seeds generation in the field of nano-satellite and hybrid rocket. Its unique characteristic is that "making something which reliably works in the real world", not simulation study nor mere theoretical research, is respected in UNISEC community. UNISEC contributed much to further facilitating university space-related activities, with currently more than 400 students from 34 universities/colleges who are so enthusiastically developing nano-satellites and/or rockets.

2. The educational significance of university nano-satellite programs

Nano-satellites offer groundbreaking opportunities for the world of space engineering education. By enabling students to experience one complete cycle within a short-term space project lasting 1–2 years, that is everything from coming up with an idea to investigating basic ideas, designing, manufacturing, conducting ground tests, providing feedback on the results, launching, operating and analyzing results from the satellite, they can, for instance, gain experience of which factors need to be taken into consideration at each stage. Half-baked designs, manufacturing or experiments will eventually result in failure afterwards. In terms of engineering, we can complete education only after students can verify how the devices they have designed and manufactured actually behave in a real environment and can observe the results. Teachers merely grading students' designs on paper neither satisfies students nor represents "evaluation" in the true sense of the word. The harsh realities of feedback from the real world make for the ultimate teacher. Designs on paper always say how something *should* behave. In reality however, things rarely go according to calculations. It is important for students to learn about the harsh reality and reflect that knowledge in their next project. Although failures leave students feeling really frustrated, this helps them grow and develop new technology out of their determination not to fail again. Students should learn to experience a great many failures over the course of a minor project. After all, when it comes to a major project costing tens of billions of yen, failure is unacceptable. Failures should be experienced while the project cost is still small.

Another important part of education is practical training in disciplines such as project management and teamwork, which are essential qualities in the field of space development. Through a process of trial and error, students learn how to manage time, money, risk and human resources, how to hold effective meetings and how to manage and use documents. They will not acquire these skills simply by being taught "this is what you should do" in a lecture. Practical experience is the most important thing; you can clearly see students' skills improving over the course of any one project.

Although the majority of Japanese universities have been building up satellite design capabilities through the Satellite Design Contest (sponsored by three academic societies) since it started in 1993, these capabilities remain confined to designs on the drawing board rather than going on to be made into actual satellites. The CanSat project [1] however, which we will look at next, has enabled students' enthusiasm to blossom into real satellites.

3. The CanSat project for initial training

The CanSat project is a program that was put forward at the University Space Systems Symposium (USSS) in 1998 by Professor Bob Twiggs from Stanford University. The initial plan was to get individual universities to make satellites with the size of a 350 ml juice-can and then launch them all into orbit. Due to difficulties securing a means of launching the satellites into orbit however, this was revised to a plan called ARLISS (A Rocket Launch for International Student Satellites) involving launching the satellites to an altitude of approximately 4 km using solid rockets provided by amateur rocket groups. Launch tests have been held in the Black Rock Desert in the US state of Nevada annually since 1999. Initially, the only participants from Japan were University of Tokyo and Tokyo Institute of Technology, but 2007 saw a total of nine Japanese universities and one high school take part in what was a major experiment involving the launch of 35 rockets. Fig. 1 shows the University of Tokyo's three CanSat satellites from the first year.

After being released from a rocket at an altitude of approximately 4 km, the CanSats open their parachutes and then take around 15–20 min to descend to the earth's surface. During this time a range of experiments are carried out, including communication experiments with earth stations on the ground and demonstration experiments to test satellite equipment at the stage prior to being launched into orbit, all of which have enabled us to obtain significant results. Individual universities have also conducted their own elaborate experiments, including experiments to obtain images from cameras pointed in a fixed direction, formation flight experiments involving multiple satellites and tethered satellite control, various types of rover experiments, differential GPS navigation, etc., as each university has continued to strive to improve satellite technology within its own specialist field. The event has featured a "Comeback Competition" since 2001 to see which CanSat can land closest to a specified destination once released from rocket with no outside assistance, just using GPS and parafoil or roving capabilities. This has increased student's motivation even further, and also improved the level of technology.

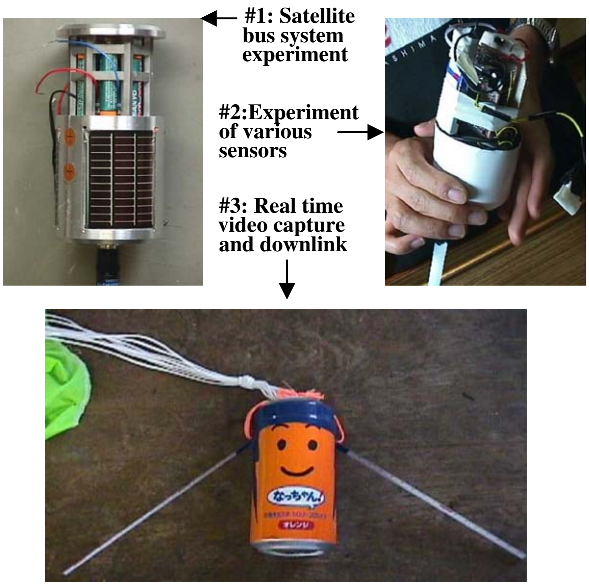

Fig. 1. The University of Tokyo's initial three CanSats from 1999 (the first year of ARLISS).

The primary objective of this competition is to provide students with a more severe problem of system design and integration with a clear "evaluation function". The onboard system should have almost all the satellite bus subsystems, including, computer, memory, communication system, battery, sensors/actuators, and the structure/mechanism, and the mission of the comeback CanSat (called "comebacker", hereafter) can only be achieved when all the subsystems work correctly. The comebacker cannot receive any maintenance once it is loaded in a rocket, and the operations should be fully autonomous. The comebacker should be tolerant against the launch acceleration of about 8 g and the environment of about 25 g rms random vibration, which requires substantial vibration test before launch. Moreover, the comebacker's system requires skills and knowledge in various research fields such as aerodynamics, control system design, structure/ mechanisms, electronics and RF communication, which provides a good opportunity to train the skills on systems integration. The competition has been held annually since 2001 as one of ARLISS experiments. The first Japanese domestic competition using the thermal balloon for lifting the comebackers was held in 2002 with a great success. Currently, Noshiro Space Event, held annually in August, provides an occasion for domestic comeback competition, and more and more universities/colleges are developing their own unique comebackers. In 2002, fly-back type such as the left figure in Fig. 2 showed excellent performance as 45 m to the target, but the current world record holder is a rover type (right figure in Fig. 2) which achieved "6 m to the target" milestone in 2006. Fixed winged type combackers also appeared in 2007, and we can expect other unique ideas on how to realize the goal of "reaching a certain target point" in near future. In 2008, we will have tenth memorial ARLISS event on September 15–20.

4. CubeSat: real orbital satellite project

4.1. Concept of CubeSat

The next step was the development of an orbiting satellite. It was at this stage that the CubeSat concept

Fig. 2. Fly-back type (left) and rover type comebackers.

emerged. CubeSat is a project put forward by Professor Bob Twiggs from Stanford University involving 10 cm cubic standard sized nano-satellites weighing 1 kg or less. Although the project's primary objective was educational, due to the fact that CubeSat satellites can be developed inexpensively in the exceptionally short space of time of one to one and a half years, there are high hopes that they will pave the way for a new dimension in space exploration as a platform for quickly conducting tests on new technology in space and for space business. Although there are currently at least 100 universities, venture companies and even space agencies such as NASA around the world working on independent projects, University of Tokyo and Tokyo Institute of Technology were the first to complete their projects, becoming the first to launch CubeSat satellites in June 2003 (Fig. 3). University of Tokyo also went on to successfully launch a second satellite in 2005.

4.2. University of Tokyo's CubeSat XI-IV

As one example, University of Tokyo's CubeSat, which is called "XI-IV" (pronounced "sai four", short for X-factor Investigator 4) is explained in a little more detail to show the technology level of CubeSat [2]. Its missions include space engineering education, as mentioned previously, and testing micro/nano-satellite bus technology in orbit. With the exception of its solar batteries, it exclusively uses commercially available products and has the important mission of both verifying how they behave in orbit and lays the foundations for future micro/nano-satellite development. University of Tokyo is looking into remote sensing as one effective mission that could be performed by micro/nano-satellite. As the first step towards this goal, CubeSat XI was also assigned an advanced mission entailing obtaining and downlinking images of planet Earth using a miniature CMOS camera.

The specifications of CubeSat XI-IV, which was designed for the initial launch, are detailed in Table 1. Of all the satellites whose size and weight has been disclosed, it is the smallest and lightest in the world. All of the components are commercially available products apart from the solar batteries, meaning that it was developed at an exceedingly low cost. All the design, fabrication, integration, ground tests, launch procurement, and orbital operations are performed solely by about 20 students.

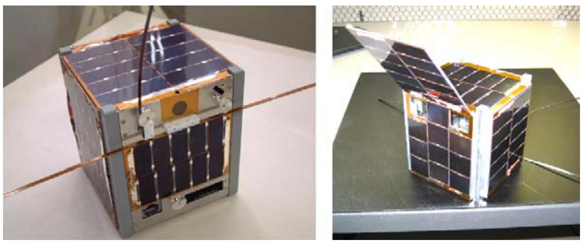

Fig. 3. First CubeSats in 2003: University of Tokyo's XI-IV and Tokyo Institute of Technology's CUTE-1 (right).

Table 1
Specifications of University of Tokyo's "XI-IV".

Size	$10 \times 10 \times 10\,cm^3$
Mass	1 kg
C&DH system	
OBC	PIC16LF877, 8bit, 4 MHz
Storage	EEPROM 256 kbyte
Communication sys	
Uplink	144 MHz amateur band, FM, 1200 bps
Telemetry downlink	430 MHz amateur band, FM, 1200 bps, 0.8 W
Beacon downlink	430 MHz amateur band, CW, 80 mW
Antenna	Monopole (up)
	Dipole (down)
Power supply system	
Solar batteries	Mono-crystal silicone, 1.1 W (average)
Secondary batteries	Lithium ion batteries, 6.2 AH
Attitude control	Passive magnetic field aligned control
Sensors	Heat, voltage, current, CMOS camera

Fig. 4. Examples of earth photos taken by XI-IV.

XI-IV and CUTE-1 were launched together by Russian rocket ROCKOT in June 2003, and has survived in orbit for more than 5 years, which has validated the two universities nano-satellite system's architecture based on COTS parts as well as proved the feasibility that even university students can develop real satellites.

The photos of the Earth taken by XI-IV (Fig. 4), which exceeds 300 in 5 years, also has shown the possibility of usage of such Nano-satellites for practical applications such as weather forcast.

4.3. Follow-on nano-satellite projects in 1st phase

University of Tokyo launched their second CubeSat XI-V, on another Russian Rocket COSMOS, in international collaboration framework with ESA. XI-V is of almost the same design as XI-IV, except for the enhanced camera capability and a new mission of in-orbit test and demonstration of CIGS (copper indium gallium diSelenide) solar cells developed by JAXA funded by NEDO, which is said to be very tolerant against radiation. The in-orbit test result until now is very encouraging, which shows the promising applications of nano-satellites to quick and low-cost in-orbit test bench for new technologies, parts and equipment, which otherwise should wait for 4 or 6 years to be tested in space in the conventional space development framework.

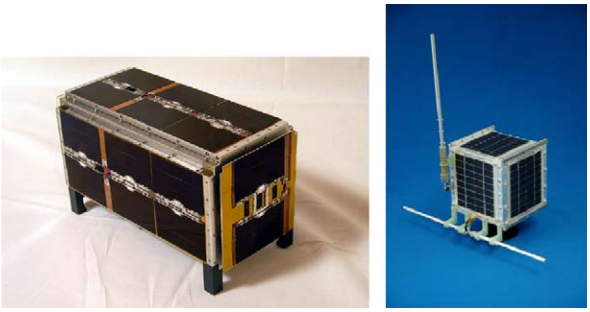

Fig. 5. Satellites in 2006; CUTE-1.7+APD (left) and HIT-SAT.

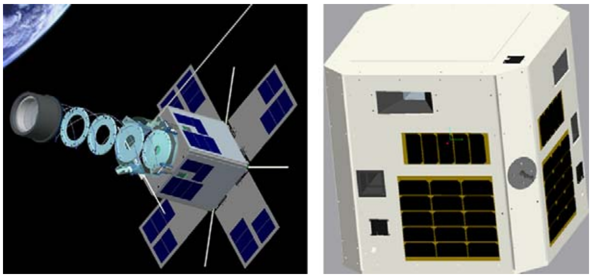

Fig. 6. University of Tokyo's 2nd generation satellites: PRISM (left) and Nano-JASMINE.

Tokyo Institute of Technology launched their second satellite named CUTE-1.7 and APD (Fig. 5, left) on JAXA/ISAS's M-V rocket in February 2006, and PDA based C&DH system and other new bus technologies have been tested in space. It has real science mission such as gamma ray burst detection using Avalanche photo diode, and also came one step closer to the real application of nano-satellite. On another M-V rocket, Hokkaido Institute of Technology launched their first satellite named HIT-SAT (Fig. 5, right) in September 2006, which tested sun-oriented attitude control system, amateur communication system and other bus technologies.

5. Second phase: practical applications of nano-satellites by University of Tokyo

Stimulated by the success of these 1st phase nano-satellite developments and launches, more and more universities are currently performing their satellite projects. Such universities or colleges that have not launched satellites yet are mainly pursuing rather educational objectives with the typical main mission of demonstration of their own bus technologies in orbit, while the universities which have already experienced launch and real satellite operation started to pursue their own characteristic missions.

University of Tokyo is now aiming for practical applications of nano-satellites in several directions; remote sensing, space science and in-orbit demonstration of new technologies. XI-V is one example of the last direction. University of Tokyo's third satellite, named PRISM [3] (Fig. 6, left), 8 kg satellite, aims for remote sensing with the target ground resolution of 30 m using a refractive optical system with 50 cm focal length. The key technology is an extensible boom with a lens at its end, and bus technology such as communication system, power system and attitude control system is enhanced to support remote sensing mission. The fourth satellite Nano-JASMINE [4,5] (Fig. 6, right), 20 kg satellite, which is being developed in collaboration with Astronomical Observatory of Japan, has "astrometry mission" to make a 3D precise atlas for more than 100,000 stars in the sky. The requirement for attitude and temperature stability is quite severe, which has been achieved by special attitude control system and thermal/structural design. The technologies being developed will be good basis for a high-performance satellite bus for future space science applications.

As to a research on new satellite architecture, plug-in, modular, panel-shaped satellite named PETSET [6] has been studied with governmental funding, and a prototype model was developed in collaboration with small private companies. In this concept, a satellite is made of several Functional Panels such as Communication panel, Attitude control panel, Thruster panel, and Mission Panel, each of which has a special dedicated function. By connecting these panels by reliable connection mechanism in "plug-in" fashion, the total integrated system as a whole has a satellite function. Various combinations of functional panels (e.g., one communication panel+three attitude control panels+two thruster panels, etc.) provide flexibility to deal with various mission requirements, even though the basic panels are the same for various missions. (Fig. 7).

Fig. 8 shows the roadmap of University of Tokyo's nano-satellite development activities. The most important activity now is recognized to be showing/proving that nano-satellites are "practically useful", i.e., a certain practical missions, even if they are not the same level as large satellites' ones, and that they can be achieved within the limit of nano-satellite resources. In ISSL, missions suitable for nano-satellites have been searched.

6. Nano/micro-satellites of other Japanese universities

Tokyo Institute of Technology is pursuing space science mission in the same direction as CUTE-1.7+APD. They

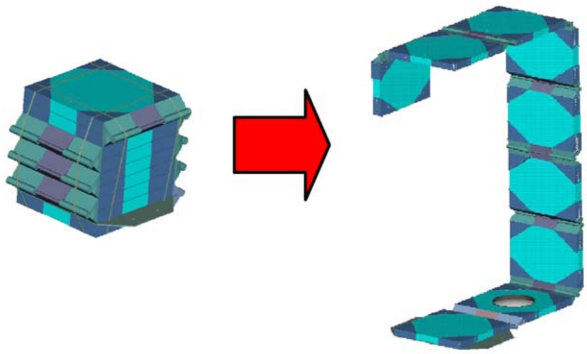

Fig. 7. Concept of PETSAT before deployment (left) and after deployment (right).

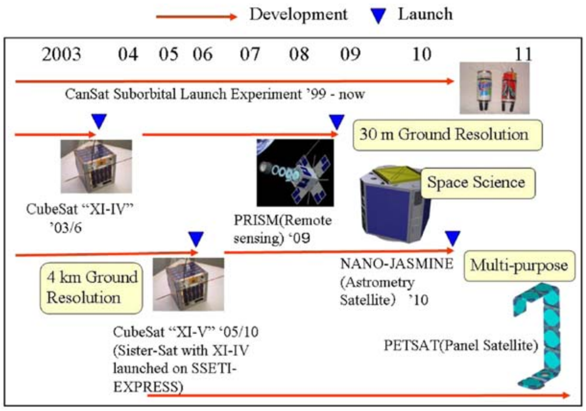

Fig. 8. Nano-satellite development roadmap of University of Tokyo.

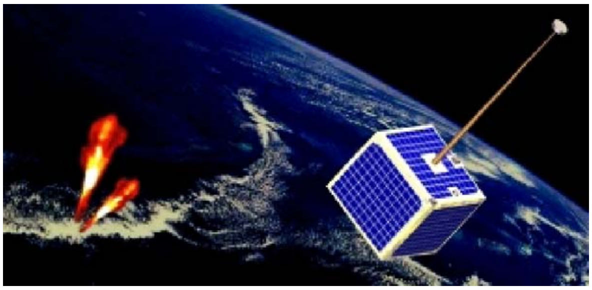

Fig. 9. Image of SPRITE-SAT and SPRITE phenomenon.

have developed enhanced version CUTE-1.7 +APD II, which was launched on Indian PSLV in April 2008.

Tohoku University is another very active university who is pursuing space science mission. SPRITE-SAT, 50 kg, 50 cm cubic satellite, is their first satellite which observe SPRITE phenomena in ultra-high altitude atmosphere together with gamma ray to find out its generation mechanism (Fig. 9).

Kagawa University is developing small satellite named STARS for technical verification of a tethered space robot. Two satellites, mother and daughter satellites, are connected by a tether of several meter length, and the daughter satellite performs robotic motion using tether tension, operated by the mother satellite. Each satellite is roughly 16 cm cubic with 3.5 kg weight (Fig. 10).

Hokkaido Institute of Technology is now developing their second satellite Taiki, which aims for remote sensing of agricultural fields using hyper-spectral camera.

Nihon University has developed their first CubeSat named SEEDS. After the loss of their original SEEDS by the accident of the Dnepr rocket failure in July 2006, they have been refurbishing their backup model, which was launched successfully in April 2008. Its mission include bus technology demonstration. Tokyo Metropolitan College of Aeronautical Engineering is developing their first 15 cm cubic, 3 kg satellite named KKS-1. It should be noted that even 15 year old students are involved in the satellite project (Fig. 11).

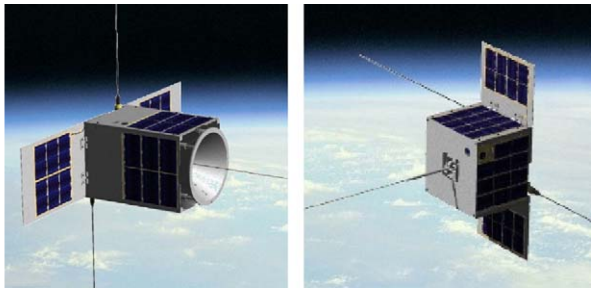

Fig. 10. Mother and daughter satellites of STARS.

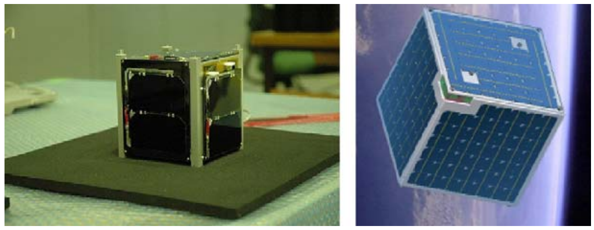

Fig. 11. Nihon University SEEDS (left) and KKS-1 by Tokyo Metropolitan College of Aeronautical Engineering.

These enlarging university activities has been stimulating JAXA, which established H-IIA piggy-back co-launch framework in 2006, and 6 micro/nano-satellites including university/college's 4 satellites, PRISM, SPRITE-SAT, STARS and KKS-1, have been selected as the first passenger group to be launched together with JAXA's GOSAT in early 2009. Additional four university satellites were selected in 2008 for piggy-back satellites, to be launched together with the main satellite Planet-C, a Venus exploration spacecraft in 2010. Among these four university satellites, one satellite named UNITEC-1 plans to be the first university satellite which leaves Earth gravitational fields into the deep space.

7. Ground station network

Many Japanese universities who have amateur frequency ground stations jointly started developing ground station network (GSN), by connecting their ground station computers via internet to enable remote control of ground stations as well as real-time transfer of the downlinked data. GSN should be very helpful for the satellite operating universities, because (1) it provides far more frequent satellite operation windows because the satellite can be operated even it flies over other universities, (2) other universities' ground stations can be back-ups in case its own ground station system fails or weather condition (such as typhoons) prohibits normal operations, (3) the data obtained by satellite can be downlinked at the nearest ground station to more quickly respond to the urgent phenomena. Since 2004 more than 8 universities in Japan and 3 overseas universities (Lurea University, University of Wurzburg, and CalPoly) have been participating in this project. Easy to use software has been developed by University of Tokyo and distributed, and various experiments based on this software have been performed such as satellite hand-over experiments, quick image download using multiple ground stations, etc [7].

This GSN concept is now recognized as an international educational program by ISEB (International Space Education Board) in the name of GENSO (Ground-station Educational Network for Satellite Operation) in 2006, and more and more universities in different countries all over the world are now becoming members. Japan has been contributing significantly to this project by providing core software as well as by leading the experiments.

8. University Space Engineering Consortium (UNISEC)

Micro/nano-satellite and small rocket development activities such as these are in full flight not only at the above-mentioned universities but at more than 30 universities around Japan. To support and continue to improve on university-based activities like these, we believe that broad-ranging support from the government, space agencies and manufacturers, covering everything from funding to the provision of technology, testing equipment and components, is vitally important, as is procedural guidance relating to areas such as securing frequencies and exporting satellites. Based on our experience with CubeSat, it has become apparent that the ability to secure frequencies and quickly arrange the launch in particular is a major priority for the nano-satellite projects. From the point of view of universities too, it has become essential to step up cooperation in areas such as exchanging technology, transferring experience and expertise, jointly developing and purchasing equipment, conducting joint experiments and sharing the burden of development.

The University Space Engineering Consortium (UNISEC, http://www.unisec.jp) was established in 2002 to act as a support community to help achieve these objectives, going on to become certified as an NPO by the Tokyo Metropolitan Government in February 2003. UNISEC currently consists of 43 member laboratories and groups from 34 different universities/colleges (as of April 2008) and is developing into a major organization with over 157 individual and group members available to provide support. We are continuing to strive to step up cooperation not only between universities but also with the private sector and national research institutions and to get members of the general public who are interested in space involved in an attempt to build up a large community. We hope that people understand the purpose of our activities and ask for further support from all those involved. As universities, we intend to continue to work tirelessly to improve our technical capabilities and to make every effort to create universities or enterprises capable of supplying a constant stream of satellites or rockets that can be put to practical use.

9. Conclusions

University nano-satellite development activities have been identified to have not only educational contributions but also the potential to open a new way of space development, by providing far lower cost and quicker access to space. Nano-satellites have the potential to not only explore technology but to pave the way for entirely new categories of space user, like the study groups to look into ways in which people in professions previously unrelated to space could make use of nano-satellites. However, it should be kept in mind that "micro space systems" such as nano-satellites cannot perform the same things as "big space systems". The important thing is to retain the approach of striving to see how much is possible within the micro-framework, making sure that the satellites are not made bigger just to improve their capabilities. This will ensure that nano-satellites maintain the flexibility offered by universities and pave the way for a new era in space exploration, breaking away from the faltering giant that it is today.

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