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International network operations of five CubeSats constellation

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ABSTRACT

Kyushu Institute of Technology initiated Joint Global Multi-National Birds (aka, BIRDS) project in 2015. It is a constellation of five 1U CubeSats built by a group of students from Japan, Ghana, Mongolia, Nigeria, Bangladesh and Thailand. The constellation will be operated via a network of seven ground stations distributed worldwide including the one in Taiwan. Its prime mission is to "By successfully building and operating the first satellite of the country, make the first step toward indigenous space program". The mission success criteria is that after the students graduate, they succeed in developing and operating the second satellite in their home country. Because of this, the educational aspect of the BIRDS project was carefully designed so that the students gain enough in-depth training to initiate their own space program with the minimum cost utilizing lean satellite approach. The ground station network serves as an important asset to promote the cross-border inter-university space research and education collaboration that the students utilize after they return their home country. The BIRDS project will demonstrates the network operation of a CubeSat constellation via UHF/VHF ground station, which is easily expanded to other frequency ranges in future.

1. INTRODUCTION

Recent explosive growth of small satellite programs worldwide is clear evidence that the barrier to space is falling. Figure 1 shows the number of small satellites launched per year since 2003. We see an explosive growth in 1 to 10 kg range for the past three years, most of which are CubeSats.

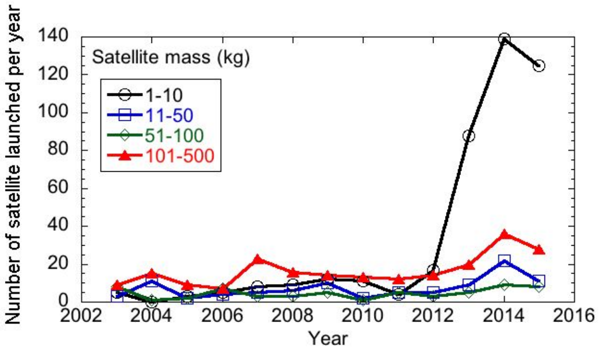

Figure 1: Trend of small satellite launch

CubeSat activities have proliferated worldwide. Table 1 lists the break-ups of countries who own the 1-10kg satellites shown in Fig.1. From 2003 to 2012, 74 satellites ranging from 1 to 10kg mass were launched. The number of countries that owned those satellites was 21. From 2013 to 2015, the number of 1 to 10kg satellites launched was 350. Among those, 262 satellites belonged to US, due to the large number of satellites launched by PlanetLab constellation. Still, there were satellites launched by other countries. During the past three years, 18 countries joined as the owners of 1 to 10kg satellites.

In Table 1 we see some countries Peru, Equador, Columbia, Vietnam and others who launched CubeSats as the country's first satellite. Low-cost nature of CubeSat and easy access to piggy-back launch make CubeSats as the ideal platform to enter the space sector.

Table 1: Countries that launched 1-10kg satellites

Country	Year 2003-2012	Year 2002-2015
USA	23	285
Japan	16	24
China	3	19
Germany	5	11
Denmark	3	9
Canada	3	7
UK		5
Norway	2	4
Peru		4
Singapore		4
India	3	3
Italy	3	3
Argentina	1	3
France	1	3
Poland	1	3
Spain	1	3
Brazil		3
South Korea		3
Switzerland	2	2
Netherlands	1	2
Turkey	1	2
Vietnam	1	2
Belgium		2
Ecuador		2
Lithuania		2
Colombia	1	1
Hungary	1	1
Romania	1	1
Russia	1	1
Austria		1
Estonia		1
Greece		1
Iraq		1
Israel		1
Pakistan		1
South Africa		1
Taiwan		1
Ukraine		1
Uruguay		1

There are various kinds of CubeSats mission ranging from commercial to personal use. Historically, small satellites have been used as a platform to do hands-on training of engineers. There are increasing number of countries who wish to utilize small satellites, especially CubeSat for space-related capacity building and human resource development. It is especially true for non-space faring countries who want to build a self-sustainable space program.

Space-related capacity building and human resource development is carried out by a combination of domestic and international activities. At least one institution is responsible to foster the space program and human resources. In terms of what type of organization plays that role, there are three approaches, agency-based, company-based and university-based.

Comparison of the three approaches can be found in Ref. [1]. Each approach has advantages and disadvantages. Examples of agency-based approaches can be found in numerous countries, such as the Bolivian Space Agency (ABE) in Bolivia, National Research and Development Agency (NASRDA), etc. The company-based approaches is not common but still exists. Examples are RENATELSAT in the Democratic Republic of the Congo or Sequoia Space in Colombia. A successful example of university-based approaches is found in Singapore, where Nanyang Technological University led the initial space program. In the present paper, a CubeSat constellation is introduced as a method of space-related capacity building and human resource development. The constellation aims at starting a tangible space program through university-based approach.

Kyushu Institute of Technology (Kyutech) runs a joint United Nations/Japan long-term fellowship program known as Post-graduate study on Nano-Satellite Technologies (PNST). The program was initiated in 2010 under the name Doctor on Nano-Satellite Technologies (DNST), which was expanded and renamed to PNST in 2013, and continues to offer up to six fellowships per year (two Masters, four Doctoral) to aspiring post-graduate level students interested in capacity building for basic space technology development. All PNST fellowship students enroll in the English-based Space Engineering International Course (SEIC) at Kyutech, which was launched in April 2013. A detailed account of the development and particulars of DNST, PNST, and SEIC by the United Nations/Kyutech can be found in Ref.[2].

As the result of PNST/SEIC, Kyutech has attracted a large number of foreign students in the past several years. Table 2 lists the number of students studying at SEIC and their home countries as of October 2015. It has quite diversified population made of 51 students from 19 countries. Most of the foreign students are from so-called non-space-faring countries. SEIC is made of four components, lecture, project, research, and hands-on.

Table 2: Student composition of Kyutech/SEIC as of October 2015

Country	Number of students	Country	Number of students	Country	Number of students
Japan	18	Egypt	2	Romania	1
Nigeria	4	Mexico	2	Malaysia	1
Vietnam	4	Algeria	1	Palestine	1
Ghana	3	Indonesia	1	Turkey	1
Mongolia	3	Columbia	1	Costa Rica	1
Bangladesh	3	Thailand	1		
Ukraine	2	Philippine	1		

It is our belief that one cannot build a satellite by reading books. Therefore, SEIC students are encouraged to join on-going space projects. There have been two satellite projects SEIC students joined, HORYU-IV and SHINEN-2. HORYU-IV project started in 2013 and the satellite was launched on February 17, 2016. Since then, the satellite is operating successfully. The HORYU-IV project involved staffs and students from 18 countries (see photo in Fig.2) . SHINEN-2 project also started in 2013 and the satellite was launched on December 3, 2014 to interplanetary orbit. The satellite succeeded in long-distance communication over 2,310,000km via UHF/VHF amateur radio band. SHINEN-2 project involved 3 foreign students.

Figure 2: HORYU-IV development team

In 2015, Kyutech launched JGMNB (Joint Global Multi-National Birds) project, in short BIRDS project. The project is made of 15 students from 6 countries supervised by 4 Kyutech faculty members (see photo in Fig. 3)

The BIRDS project is a constellation of five 1U CubeSats to be released from International Space Station. The target launch date is 2017. The participants to the JGMNB project are, All Nations University College (ANUC) in Ghana, National University of Mongolia (NUM) in Mongolia, Federal University of Technology Acure (FUTA) in Nigeria, Brac University in Bangladesh, King Mongkut's University of Technology North Bangkok (KMUTNB) in Thailand, National Cheng Kung University (NCKU) in Taiwan.

The five satellites are exactly the same design, including their uplink/downlink frequencies except the call sign. The satellites capture the Earth image by a five million pixel camera and transmit music songs for outreach purpose. The constellation is operated by 7 ground stations located at each partner institution. Each ground station is connected to an operation server and receives the operation schedule, the orbit information and the command set to be uplinked.

Figure 3: BIRDS development team

The purpose of the present paper is to present the BIRDS project in terms of capacity building and human resource development in non-space faring countries. BIRDS project is not one-time satellite project. It is intended to serve as the basis of cross-border international university collaboration for space research and education. Human network and physical network of ground station will play key roles to further the collaboration. This paper is made of four parts. The second part describes the satellite architecture and its mission. The third part describes the educational aspect of the project. The fourth part describes the network operation of the constellation and its future utilization plan. The fifth part gives conclusion.

2. BIRDS ARCHITECTURE AND MISSION

The prime mission of BIRDS project is to "By successfully building and operating the first satellite of the country, make the first step toward indigenous space program". Each satellite will be owned by Kyutech, ANUC, NUM, FUTA and Brac. For Ghana, Mongolia and Bangladesh, the BIRDS satellite is indeed the first satellite of each country. For FUTA, it is the first university satellite of Nigeria.

The mission objectives are

- Learn the entire processes of a satellite program from beginning to end
- Lay down foundation of sustainable space program by accumulating human resource in universities and launching a university space research and education program
- Create international human networks to assist the infant space programs each other

The BIRDS project aims at fostering university space research and education bases in non-space faring countries. Advantages of university-based approach toward space-related capacity building and human resource development are

- Less susceptible to abrupt loss of funding due to change in government policy or political instability (especially private universities)
- Lean satellite project cycle, including launch and operation, can be matched to degree timelines
- Ease of information sharing in academic environment
- Inexpensive labor

There are disadvantages, though, such as

- Low ceiling (program likely will not extend beyond research and development satellites)
- Reduced quality and mission value compared to professional projects
- Increased likelihood of mission failure

Kyutech offered training opportunities to the partners stressing the following advantages of university training environment,

- Lean satellite project cycle, including launch and operation, can be matched to degree timelines
- Learning from mistakes is encouraged
- Fully hands-on and autonomous
- Wide international appeal and can more easily include non-engineers
- Continuous pipeline

In the system life cycle, all the fifteen students act as one team up to the end of design and its verification. They are responsible from definition of satellite science missions under constraints. Major constraints given are the following,

1. Science missions comply with the top-level mission objectives
2. The overall system life cycle is 2 years from the project kick-off in October 2015 to match the degree timeline of two years (Master course)
3. Five identical 1U CubeSats released from ISS.
4. Operated by UHF/VHF amateur band from each member countries

The students define the science missions and design the satellites. A prototype, Engineering Model (EM), is assembled, integrated and tested for space environments. The design and its verification results are examined at Critical Design Review (CDR). Once the design is fixed and the project enters the flight model (FM) phase, the team will be divided into five groups made of members from the same country. They are responsible of assembly, integration and testing of flight model of each country.

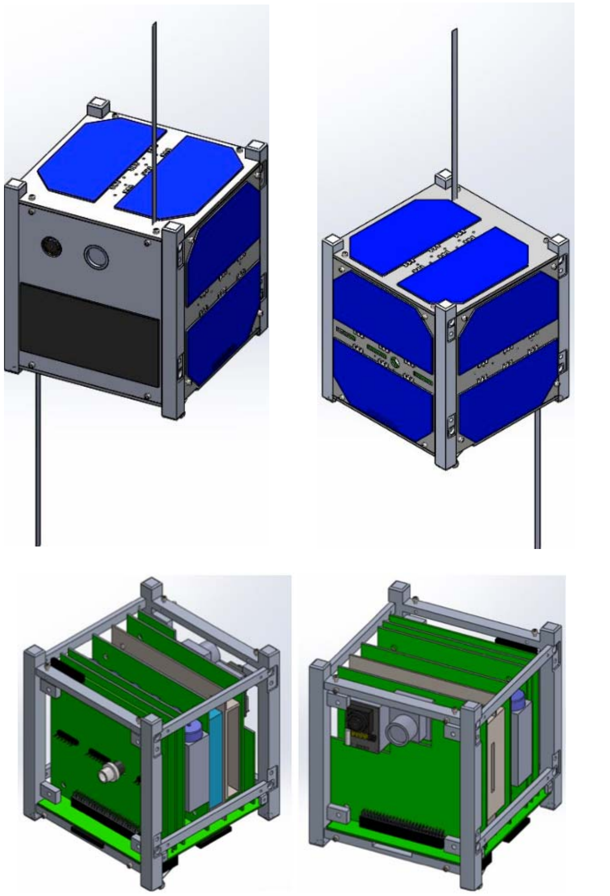

Figure 4: BIRDS CAD image

Figure 4 shows a CAD image of a BIRDS satellite. The satellite is based on so-called backplane design. The satellite is made of 7 internal panels. Among the 7 internal panels, 5 are PCB connected to the backplane via a 50pin connector. The satellite basic functions, command & data handling (C&DH), communication (COM) and electrical power system (EPS) are integrated into a single board. The electrical design inherits the flight-proven HORYU-II and HORYU-IV design. There is one PCB that carries mission payloads. The external panels are made of 5 solar panels and 1 antenna panel with a UHF patch antenna. The satellite attitude control is done by a combination of permanent magnet and hysteresis damper. Four solar panels are directly attached to the back plane via connector and the solar panel at the top is attached to the front internal panel via a connector.

The satellite design emphasizes modularity and harnessless. Harnessless design makes the satellite easy to assemble and decrease the risk of workmanship error. The modularity design makes the satellite functionality easy to be upgraded by replacing some of the internal boards.

The satellite carries the following science mission

1. Taking photographs of homeland via onboard cameras using 2 cameras (wide-view and narrow-view) (CAM)

2. Detecting single-event-latchup in orbit (SEL)

3. Determining precise satellite locations (POS)

4. Deriving atmospheric density distribution (ATM)

5. Demonstrating ground station network for CubeSat constellation (NET)

and the following outreach mission

6. Exchanging songs via satellites through UHF amateur radio band (SNG)

The success of science missions rely on the success of the NET mission, the ground station network. Each satellite will carry a 5 million camera and a back-up VGA camera. The captured image is compressed to a JPEG format in orbit and transmitted via 9600bps UHF transmitter. Each file size is expected to be 1 to 5 Mbytes. To increase the amount of data to be downlinked per day, we connect 7 ground stations as shown in Fig. 5. Based on the simulation, each satellite is expected to have an average of 2.4 hours of downlink window each day. If we have only one ground station, the window time is limited to 35 to 65 minutes, 50 minutes on average. Therefore having 7 ground stations, we increase the window time by 3 times.

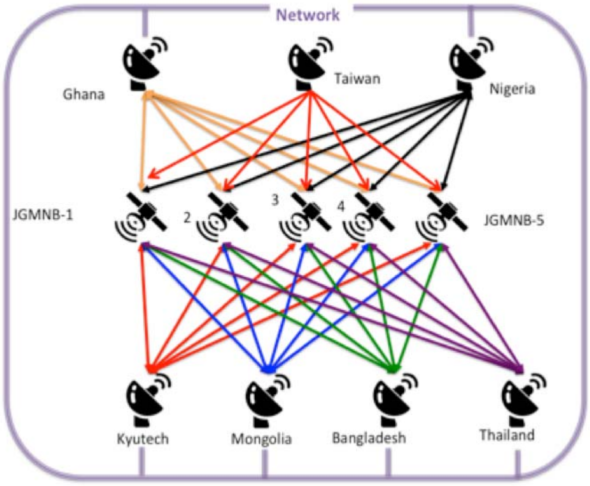

Figure 5: Concept of ground station network

The POS mission is carried out by detecting the radio signal time delay among three different ground stations and triangulating the satellite position. When a satellite flies over China, there is a chance of detecting the satellite signal simultaneously over by as many as 5 ground stations shown in Fig. 6. POS mission needs 3 or more ground stations receive the signal simultaneously for 2 minutes or longer. Fig.7 shows an example that a satellite is first viewed by Bangladesh, Thailand and Taiwan ground stations, and later by Taiwan, Japan and Mongolia ground stations. We need to connect the distant ground stations via network and synchronize their timing. We time-stamp the IQ signal recorded at each ground station by GPS clock signal. The ATM mission relies on the POS mission as it calculate the atmospheric density by constantly updating TLE using the positions identified by POS.

Figure 6: POS mission overview

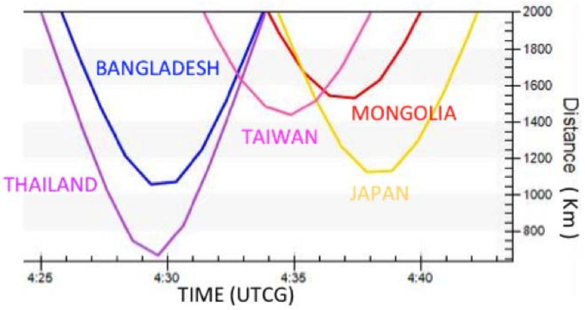

Figure 7: Satellite view by multiple ground stations

The SNG mission uses Yamaha Voice Synthesizer (EVY1 Vocaloid) onboard the satellite. The EVY1 module converts the MIDI file into audio signal that is fed into the UHF transmitter. The EVY1 not only can play melody but also can sing a song. The user can hear the song directly from UHF transceiver on the ground. The EVY1 is already onboard HORYU-IV and we already played music (see Fig.8). It is a powerful outreach tool to let children to think about the mystery of song coming from space. For HORYU-IV, the mission is limited to downlink only. For BIRDS, uplink of song MIDI files will be tried. If successful, exchange of music between different continents via UHF amateur band becomes possible.

Figure 8: Outreach event using Vocaloid synthesizer of HORYU-IV

3. EDUCATIONAL ASPECTS OF BIRDS PROJECT

A short-tem goal of BIRDS project is to actually build and operate satellites, which give the students tremendous confidence that they can do it. Giving confidence is not enough, though. The project needs to make sure that the students, once they return home, can initiate their own space program. In that sense, the mission is accomplished when the former students successfully build and operate the second satellite in their home countries. Many space-related capacity building programs often failed in this point. Agencies, companies, universities invite a group of engineers for long-term training. The engineers build and operate a satellite themselves with assistance of the host institution. Although there are successful examples, such as South Korean trained in Surrey, in many cases trainees see hard time once they return the home countries.

There are several reasons why it didn't go well. The satellite they were trained was simply too complicated, e.g. a GEO communication satellite, to learn the overall picture of the satellite development. The support from the home country was not continuous due to political and/or economic disturbance. The depth of training was not deep enough for students to learn the critical points of satellite development.

The BIRDS project intends to let students learn the entire processes of a satellite program from beginning to end. It is not possible to teach each student all the sub-systems of a satellite. It is not technology we teach. It is process. Students learn what is necessary at each phase of satellite development, what kinds of decision they have to make and how to make the decision, how risks are evaluated and dealt with. Each student learns a particular aspect of satellite technology. But more important is to judge what component they should buy and what component they should develop in-house, how and where to procure the component, how to integrate various sub-systems into one system, and how to verify the system.

Therefore, experiencing the entire process of the satellite development and operation, witnessing each decision process and making decisions by themselves are critical. As a team they are given the full responsibility of the program under supervision of faculty members.

Another important point is to fit the project within the degree timeline. A master program is two years. Therefore, the satellite must be simple enough to be finished in two years and the launch slot must be secured.

Based on these two points, 1U CubeSat has been chosen as a platform because of its simplicity. ISS release has been chosen as the launch method to secure the solid launch slot so that we can finish the operation by the end of the second year.

We often witness a national space program suffers disruption because of political and economical disturbance. University space program is relatively immune to the external disturbances. After all, as long as a university professor keeps his/her position with his/her laboratory and students, the satellite project can continue. Many countries' space programs have their origin in university space program. In fact, Japanese space program originated from University of Tokyo that launched the country's first satellite, Osumi, in 1970. The university space program has its ceiling. It cannot grow forever. At one time, they have to hand over the national space program to the government or companies. But to start with the minimum budget from scratch, a university is an ideal place. This is another reason why CubeSat was chosen as a training platform. The space program to be maintained at a university must be affordable enough at university budget level.

Even after handing over the big projects to the outside body, the university still can continue its own space research and education. Thanks to CubeSat technologies, nowadays it is possible for universities to carry out real satellite missions and conduct cutting edge researches in orbit.

To build the second satellite in their home countries, the satellite they learn during training must be simple enough and easy to reproduce in the home countries. In BIRDS project, the modularized design using the backplane was adopted. In their home country, the students do not have to start the satellite design from scratch. They identify which subsystem they need to replace for their next mission. Once it is identified, only the board that contains the subsystem is replaced and the second satellite is built easily. All the parts/components used in the BIRDS project are COTS based except solar cells. They are free from export control, easy to procure in the students' home country.

The BIRDS project is a part of intensive two-year training program carried out by SEIC. Because the training is done in university environment, the students are encouraged to do everything by themselves. Mistakes are allowed as long as lessons are learned. The students are supposed to operate all the facilities necessary for testing. They are supposed to find and procure parts/components themselves. If things are broken, they are supposed to fix it by themselves. Challenge is allowed as long as the risk associated is evaluated properly. Through these learning processes, the students will obtain in-depth experience of satellite development.

The BIRDS project experiments the lean satellite approach. See Ref. [3] for the detail of the lean satellite approach. Lean satellites seek to deliver value to the customer (the end-user or the purchaser) or the stakeholder at minimum cost and in the shortest possible schedule by minimizing waste. When the students continue the space program in their home country, they have to adopt a lean approach so that the program can run with a small team and a minimum cost. To do so, the waste associated with the satellite development has to be minimized as much as possible and the students have to learn the virtue of waste minimization through real experience. In the BIRDS project, all the fifteen students members are placed in one room where the satellite assembly, integration and testing rooms are located in the same building. Even the ground station is located in the next building. The overall satellite development activity can be done within a radius of 30 m that significantly reduce the waste associated with transportation and communication. The students are encouraged not to use e-mail unless they need to broadcast to all the team members. Face-to-face communication is the most important method of the communication.

The BIRDS project intends to foster the cross-border inter-university network. The network is formulated in two ways, human network and ground station network. The human network is the most important framework. Mutual trust is built by going through the hardship together and achieving something together. After going through intensive two-years training, the students will learn the importance and merits of teamwork and cooperation in space projects. The space programs the students wills start in their home country are still at infant stage. The human network the students build during the BIRDS project will assist the infant space programs survive the hard time.

The ground station network can act as the backbone of the inter-university network. Using the ground station network, even when a university has no satellite orbiting in space, the university still can join the space research and education by participating in the operation of the satellites launched by partner universities. It can also join the project by providing a part of mission payloads. The data can be shared among the partners. Space research using a small satellite constellation can generate results not possible by traditional large/medium/small satellites operating as a single satellite. Having a networked ground station distributed over the world makes planning of constellation missions easy. The partner universities can propose other partners to join a constellation mission utilizing the ground station network. The ground station network is the key to maintain the inter-university collaboration and the quality of space research conducted at each partner university.

4. INTERNATIONAL NETWORK OPERATION

A constellation of CubeSats enables mission that is impossible by a single satellite. In addition, a system made of multiple satellites is inherently robust against failures of individual satellites. Communication time with a ground station, however, may limit the application of constellation. Unless its orbit is carefully chosen, which is not easy for CubeSats relying on piggy-back launch, for most of the cases, the total duration of communication time with the ground station is limited to one hour per day at most. The solutions to this problem are the following: (1) Distribute ground stations globally, (2) Increase the communication speed, (3) Use a relay satellite. The BIRDS project intendt to experiment operation of CubeSat constellation via a network of globally distributed ground stations.

As shown in Fig. 5, the BIRDS constellation will be operated by 7 UHF/VHF ground stations distributed worldwide. The five BIRDS satellites are exactly the same design, including their uplink/downlink frequencies, although the call sign is different. Each ground station is connected to an operation server and receives the operation schedule, the orbit information and the command set to be uplinked. The data downlinked are transferred to the archive server. Satellite operation over a ground station is handed over to the next ground station available.

Figs. 9 shows basic schematics of the network operation. Each ground station has autonomy or acts as a part of the network. During the network operation, one ground station acts as Mission Control Center where the satellite operation is planned and the mission data is processed. The orbital dynamics is analyzed at the mission control center. Each ground station is given its task, which satellite to track and when.

Between the Mission Operation Center and the Antenna Operator Sites, there is a cloud server. The server handles the data transfer between the Antenna Operator Sites and the Mission Operation Center. At the same, the server relays the antenna schedule to each Antenna Operator Site and access to the antenna system at each site.

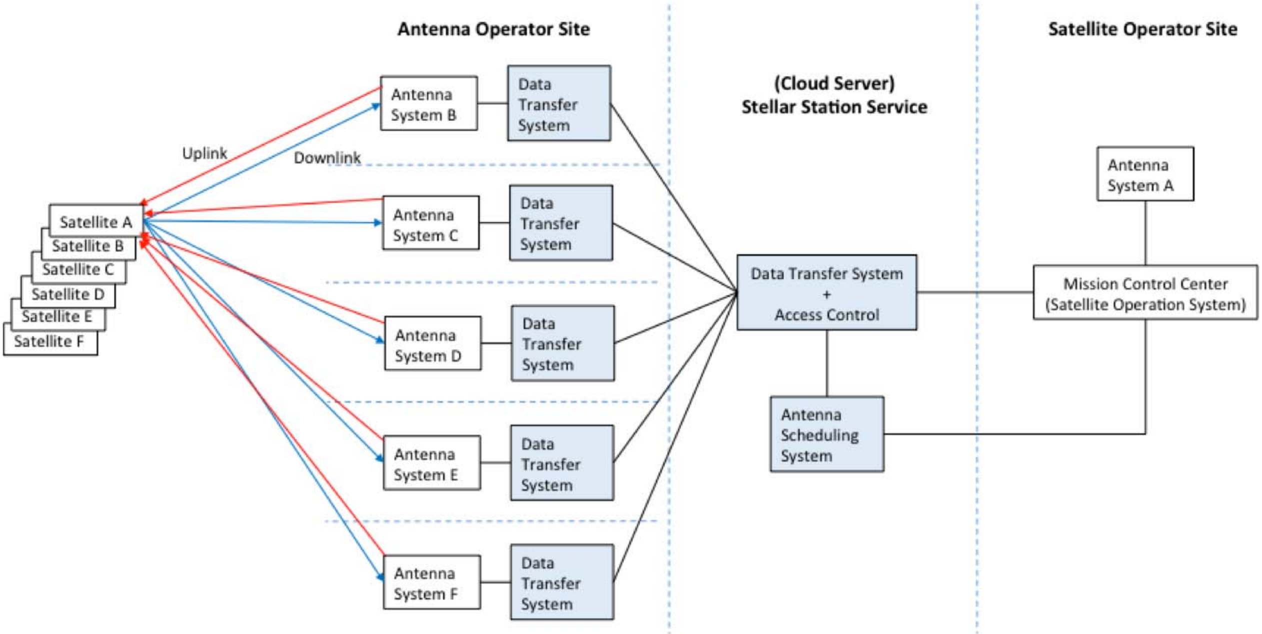

Figure 9: Schematic of network operation

If successful, this system demonstrates utility of low-cost UHF/VHF ground station network to operate CubeSat constellations. The system can be easily expanded to accommodate other types of satellite constellation, as well as other frequency ranges, such as S-band or higher.

5. CONCLUSION

Kyushu Institute of Technology initiated JGMNB (Joint Global Multi-National Birds, aka BIRDS) project in 2015. It is a constellation of five 1U CubeSats to be released from International Space Station. Its prime mission is to "By successfully building and operating the first satellite of the country, make the first step toward indigenous space program". The three satellites among the BIRDS constellation are the country's first satellite for Ghana, Mongolia and Bangladesh.

The mission success criteria of the BIRDS project is that after the students graduate, they succeed in developing and operating the second satellite in their home country. Because of this, the educational aspect of the BIRDS project was carefully designed so that the students gain enough in-depth training to initiate their own space program with the minimum cost utilizing lean satellite approach.

The satellite science missions rely on network operation connecting the ground stations in seven countries. The ground station network serves as an important asset to promote the cross-border inter-university space research and education collaboration that the students utilize after they return their home country.

The BIRDS project tries to demonstrate the network operation of a CubeSat constellation via UHF/VHF ground station. If successful, the network methodology will be easily expanded to other frequency ranges.

As of June 2016, the satellite is going through qualification tests using EM (see Fig.10). From July 2016, the student group is split into five small sub-groups made of the students from the same country. They will go through on-the-job training of the assembly, integration and testing using the flight model.

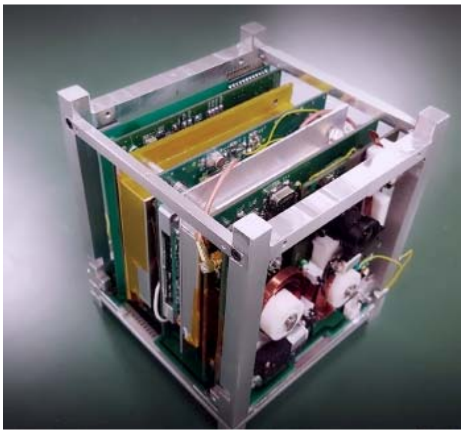

Figure 10: BIRDS Engineering Model

At the same time, preparation of network operation is underway. The key tasks are development of an operation planning tool and a networking software, hardware/software compatibility at each ground station, avoiding cross-talk among the satellites, and verification of the overall end-to-end communication and operation before launch.

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