SSC21-WKIII-03

An Overview of the BIRDS-4 Satellite Project and the First Satellite of Paraguay

Adolfo Javier Jara Cespedes, Izrael Zenar Casople Bautista, BIRDS-4 Project Members, George Maeda, Sankyun Kim, Hirokazu Masui, Takashi Yamauchi, Mengu Cho
Laboratory of Lean Satellite Enterprises and In-Orbit Experiments (LaSEINE), Kyushu Institute of Technology
1-1, Sensui-Cho, Tobata Ward, Kitakyushu City, Japan; +81 80 9109 6222
javier.jara-cespedes758@mail.kyutech.jp

ABSTRACT

The Joint Global Multi-National Birds or BIRDS program, is a multinational small satellite project led by Kyushu Institute of Technology (Japan). The BIRDS program gives to non-space faring nations the opportunity to design, integrate, build, test, launch, and operate their country's first satellite. This paper focuses on BIRDS-4, a constellation of three 1U CubeSats belonging to Paraguay (GuaraniSat-1: Paraguay's first satellite), Philippines (Maya-2), and Japan (Tsuru). BIRDS-4 members are graduate students enrolled in Space Engineering International Course (SEIC) at Kyushu Institute of Technology. This constellation will execute nine missions such as Earth Imaging, Total Ionization Dose measurements, evaluation of Perovskite solar cell performance in space, and the use of "Satellite Structure as Antenna" for CW transmission. More importantly, the satellite will conduct a Store-and-Forward mission to test the technical viability of the chosen hardware, such that if proven successful, will be used for future satellite missions to gather data in remote areas. The satellites were launched on February 22, 2021 and deployed from the International Space Station on March 14, 2021. This paper describes the background, missions, stakeholders, lessons learned, and initial operational results after the deployment from ISS. Finally, this paper shall discuss the significance of this satellite for Paraguay, which has been a non-space-faring nation up until now.

INTRODUCTION

The Joint Global Multi-National Birds or BIRDS program, is a multinational small satellite project led by Kyushu Institute of Technology (Japan). The BIRDS program gives non-space faring nations the opportunity to design, integrate, build, test, launch, and operate their country's first satellite. The mission statement of BIRDS project is to make the first step towards indigenous space program for each country by successfully building and operating the first satellite of the nation.

The BIRDS-1 project is a constellation of five CubeSats belonging to Ghana, Mongolia, Bangladesh, and Nigeria [1]. The BIRDS-1 was deployed in orbit on the of 7th July 2017 from the ISS. BIRDS-2 project is a constellation of three CubeSats belonging to Malaysia, Bhutan, and Philippines [2]. BIRDS-2 was deployed to orbit on August 10th, 2018. BIRDS-3 project is a constellation of three CubeSats belonging to Sri Lanka, Nepal, and Japan [3]. BIRDS-3 CubeSats was deployed to the orbit on 17th June 2019 from International Space Station (ISS). BIRDS-4 project is a constellation of three CubeSats belonging to Paraguay, Philippines, and Japan. BIRDS-4 CubeSats was deployed to the orbit on 14th March 2021 from International Space Station (ISS).

In the BIRDS-4 project, Paraguay participated as one of the non-space faring countries while the Philippines aimed to improve space activities after launching Maya-1 (as part of the BIRDS-2) in 2018 [2]. The project aims to build Paraguay's first satellite, named as "GuaraniSat-1" while improving the standardized bus system for future missions and provide continuation to the satellite development of the Philippines and Japan as well as the previous missions from BIRDS-1, 2 and 3. The stakeholder of Paraguay's first satellite, GuaraniSat-1 is the Paraguayan Space Agency (AEP) located in Asunción, Paraguay. While the stakeholder of Philippines' satellite, Maya-2, is the University of Philippines - Diliman located in Quezon City, Philippines.

As the BIRDS-4 project is initiated in November 2018 and the flight models deployed in March 2021, this paper is provided to explain the satellites; covering the aspects of design, missions, initial operational results, and lessons learned after deployment from ISS. A photo of the flight models of BIRDS-4 is shown in Figure 1.

Figure 1: The photo of flight models of BIRDS-4 taken in January 27, 2020

Project Team

The BIRDS-4 team is made up of 14 students representing the countries of Japan, Paraguay, and the Philippines. Both Filipinos and Paraguayans represent their own country, while the Japanese team has a wide range of nationalities, in addition to the 4 Japanese members, students from Egypt, France, Nepal, Sudan and Turkey are also part of the team. All students are enrolled in the Space Engineering International Course (SEIC) in either Master or Doctoral degree. Through the BIRDS projects the students experience the entire life cycle of satellite building. From mission definition up to operation. Figure 2 shows the BIRDS-4 team that includes the fourteen Kyutech students and teachers. The principal investigator of the project is Professor Mengu Cho.

Figure 2: BIRDS-4 Team

SYSTEM OVERVIEW

CubeSat Description

The satellites of the BIRDS-4 constellation are based on the 1U CubeSat standard. The external dimensions of a CubeSat are 114.5mm x 107.8mm x 104mm with an average mass of 1.3 Kg. Figure 3 shows the CAD model of the BIRDS-4 CubeSats with the respective axis definition. All printed circuit boards (PCBs) are connected to a backplane board via 50-pin connectors. BIRDS-4 has nine missions in total which will be described in the following sections.

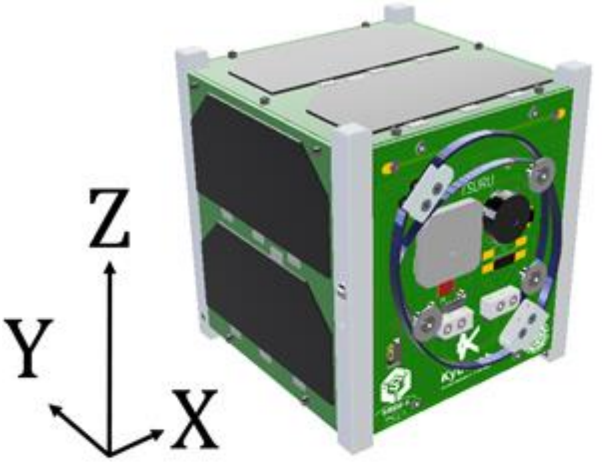


Figure 3: External view of the BIRDS-4 CubeSat

Bus System

The BIRDS-4 bus system is based on the BIRDS-1, BIRDS-2 and BIRDS-3 bus systems. The bus system consists of the Front Access Board (FAB), the Electrical Power System (EPS), the On Board Computer (OBC), the Communication (COM) and the Rear Access Board (RAB). Figure 4 shows the bus configuration.

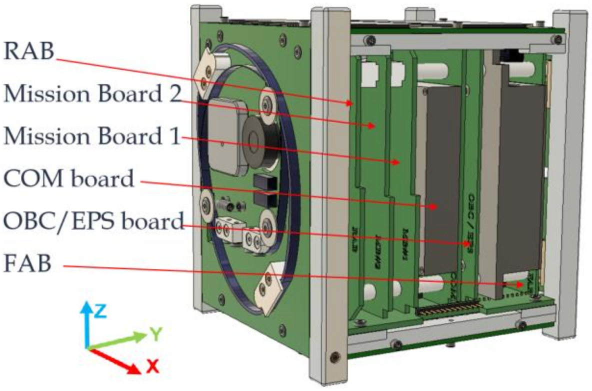


Figure 4: Bus Configuration

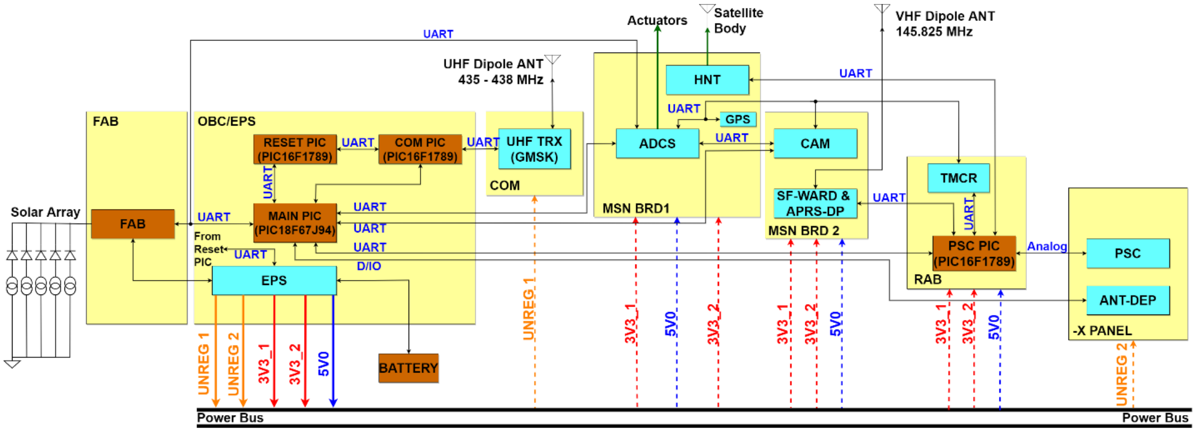


Figure 5: System block diagram

The system block diagram is shown in Figure 5. The microcontrollers used in the bus system are from the PIC family made by Microchip.

The FAB board uses a PIC16F1789 that fulfills the function of collecting housekeeping data from solar panels and battery. The FAB PIC receives commands and sends housekeeping data to the Main PIC using the UART communication protocol. The FAB has a kill switch that is controlled by the FAB PIC and Main PIC. Main PIC collects FAB PIC data every 90 seconds in normal sampling mode and every 5 seconds during high sampling mode operation.

The OBC includes the main PIC and a Reset PIC enabled as a watchdog. The main PIC is a PIC18F67J94, which works as the brain of the CubeSat and its functions are to collect and store the housekeeping data, send the command for the antenna deployment, process the uplink commands, and execute the missions accordingly. The main PIC has a 1Gb MT25QL01Gb flash memory that is divided according to the needs of each mission. A PIC16F1789 is used as a RESET PIC. The RESET PIC keeps the count of the time elapsed since the deployment into the orbit, resets the Main PIC in case of a single event latch up and monitors the power lines current consumption. The main PIC and the reset PIC communicate through UART.

COM has a PIC16F1789 microcontroller located in OBC board. COM PIC functions are to receive the command from the ground station, send those commands to Main PIC, create the CW format, and transmit. COM PIC communicates with Main PIC through UART protocol. COM PIC has its own flash memory which is a MTQ25QL01Gb 1Gb. A dipole antenna is in –Y panel. The telemetry data and CW data are sent to ground station by communicating through this antenna. The frequencies used for uplink and downlink are in the amateur radio band. The downlink frequency is 437.375 MHz.

A shared memory system through multiplexers and SPI interface is used to transfer large data volumes between COM PIC, Mission Board II and Main PIC. The shared memories block diagram is shown in Figure 6.

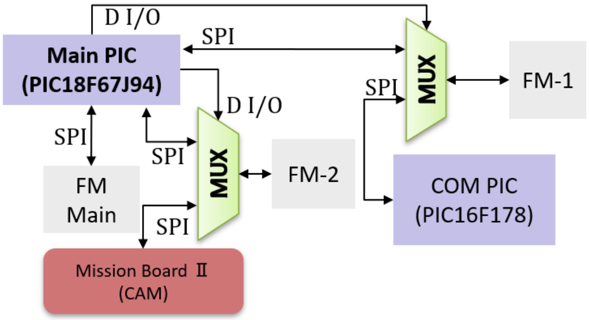


Figure 6: Shared memories block diagram

Solar panels placed on five sides of the CubeSat are responsible for the power generation, one solar panel has two cells connected in series. The energy generated is stored in six rechargeable Eneloop NiMH batteries with a capacity of 1900 mAh per battery arranged in a 3-series 2-parallel configuration. The total power generation per orbit is 1411 mWh. The power generation calculation is shown in Table 1.

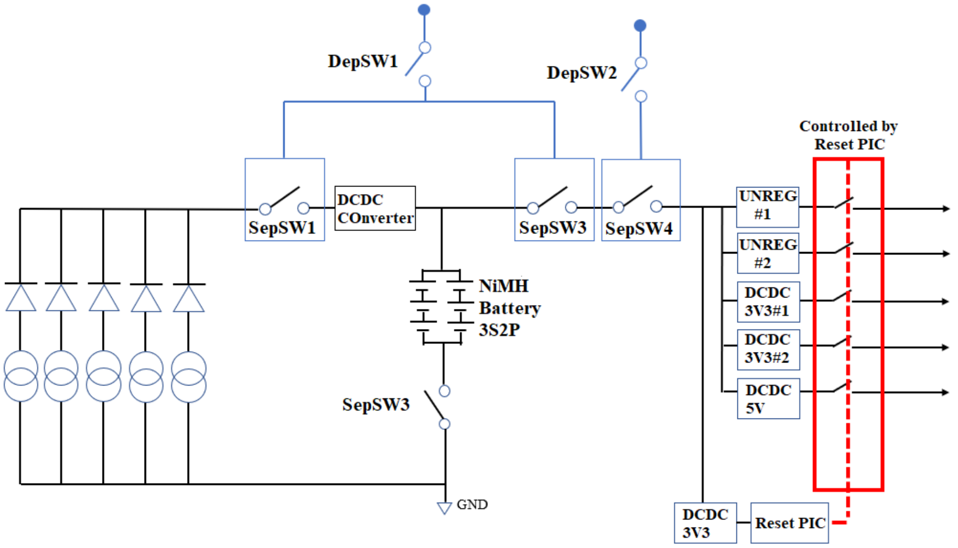


Figure 7: Eps block diagram with power distribution

Table 1: Power generation calculation

Parameters	Value
Total generated energy (MATLAB simulation)	2184 mWh
Power loss in blocking diode	360 mWh
BCR efficiency (based on buck-boost DC/DC converter specifications)	80%
Total energy available per orbit after BCR	1411 mWh

TPS63020-Q1 voltage regulators are used to convert battery voltage and provide power to all missions and satellite subsystems. The power lines of the CubeSat are controlled by the Reset PIC. Two 3.3V lines, one 5V line and two unregulated lines are used. The unregulated lines are used for the deployment of the antennas and for the supply of the COM transceiver. Power distribution block diagram is shown in Figure 7. The antennas are deployed 30 minutes after the satellite deployment into orbit from the ISS. The RAB is used for programing and monitoring each mission microcontrollers. The FAB is used for programing and monitoring the Main PIC, FAB PIC, RESET PIC and COM PIC.

MISSIONS OVERVIEW

Missions Description

BIRDS-4 has nine missions. They are the Imaging Mission (CAM), Automatic Packet Reporting System and Digipeater Mission (APRS-DP), Store and Forward of Weather and Reinfestation Data using CubeSats (SF-WARD), Satellite Structure as Antenna Mission (HNT), Total Ionizing Dose Measurement of COTS and Onboard Rad-Hard Components Mission (TMCR), Latch-up Detection and Protection Mission (LDAP), Perovskite Solar Cell Mission (PSC), Attitude Determination and Control Mission (ADCS) and Glue Mission (Glue). There are two mission boards in BIRDS-4 CubeSats, they are named as Mission Board I and Mission Board II. The nine missions are described below.

Imaging Mission (CAM)

With the goal to take images of the participating countries, the commercial-of-the-shelf camera module was selected based on its heritage from existing satellites and its power consumption requirement. The OV5642 camera module utilizes a color image sensor with a low voltage, high-performance, 1/4-inch 5-megapixel CMOS image sensor that provides the full functionality of a single chip 5 megapixel with active array size of 2592x1944. In addition, the camera is controlled by a microcontroller unit (ATMEGA 2560V) which is responsible for the communication with the satellite's On Board Computer (OBC) and saving the image data in a non-volatile 1Gbit flash memory (MT25QL01GBQ). The above mentioned camera, microcontroller and flash memory have their flight heritage as the same components were used by the BIRS-3 satellites. Although the camera module includes an M12 lens with a field of view of 90 degrees, a different M12 lens was used. Such lens has the following specifications: focal length of 2.9mm, F2.0, 1/2.5", image height 7.30mm, and with IR cut filter.

Table 2: Camera mission parameters

Parameters	Value
Camera Resolution	5 MP (max)
FOV (D/H/V)	125º / 100º / 75º
Ground Swath	1008 km / 806.4 km / 604.8 km @ 400km altitude
Ground Resolution	Approximately 300m

The software is designed so that the imaging payload can take images at different resolutions (320x240, 640x480, 1280x960, 2048x1536 and 2592x1944) and different compression quality (high, normal, and low). The imaging mission is executed when the camera payload receives a command from the ground station through the COM PIC and Main PIC. Imaging mission hardware is shown in Figure 8.

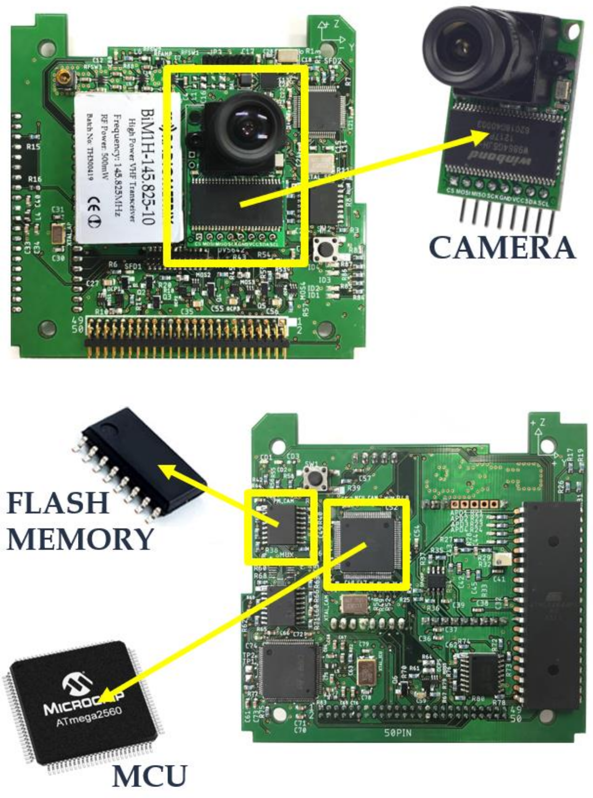


Figure 8: Imaging Mission Hardware.

Automatic Packet Reporting System (APRS)

In Automatic Packet Reporting System (APRS) mission, the satellite receives APRS messages from the amateur community and digipeats it back to ground. The mission aims to provide amateur radio service to amateur radio community and to demonstrate functionality of APRS digipeating using low-cost commercial off the shelf (COTS) components. The payload is composed of a Terminal Node Controller (TNC) connected to a 500mW radio transceiver tuned at 145.825 MHz amateur radio band. Both are COTS components from Byonics and Radiometrix, respectively. A dipole antenna is used in the mission. The antenna design makes use of a strip line to connect its elements to its feedline. End-to-end ground testing showed that the payload radio sensitivity is at -95 dBm and uplink success is achieved up to 130 dB total effective attenuation. This provides margin for communication in space. APRS-DP block Diagrams is shown in Figure 9.

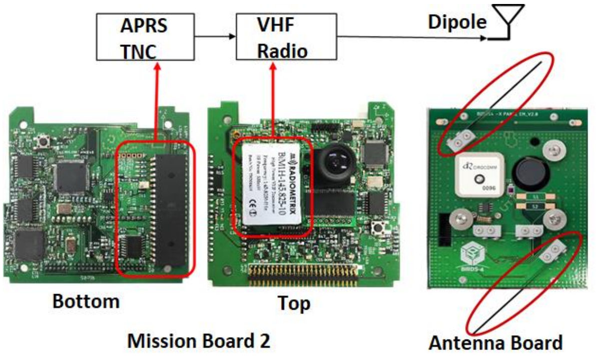


Figure 9: Mission Board 2 with APRS-Module, Transceiver, and the VHF dipole antenna.

Store-and-Forward mission (SF)

This mission´s purpose is to demonstrate a data/message store-and-forward (S&F) system in line with the Universal Amateur Radio Text and E-mail messaging. This mission aims to investigate technical challenges through experiments on appropriate data format, multiple access scheme, file-handling protocol while complying with limited operational time and power constraints using the APRS protocol. To do this, it uses the same transceiver as the APRS mission.

Attitude Determination and Control Mission (ADCS)

ADCS mission´s purpose is the demonstration of active attitude stabilization control and 3-axis satellite attitude pointing control. ARM STM32F446RE is used as the microcontroller (MCU), the ADCS includes a L3GD20 Gyroscope, MMC5883MA magnetometer, Venus838FLPx-L GPS chip and A3901 Driver ICs. Mission Board 1 with ADCS components is shown in Figure 10.

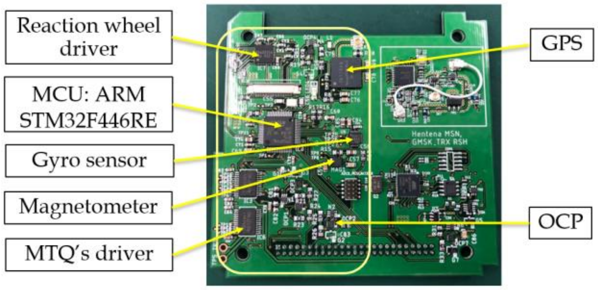


Figure 10: Mission Board 1 with ADCS components.

ADCS MCU collects data from magnetometer, gyroscope, and GPS chip. The magnetometer communicates with the ADCS MCU using I2C protocol, gyroscope communicates using SPI interface and GPS chip communicates using UART protocol. ADCS MCU sends the data collected from the sensors to Main PIC via UART. For the active stabilization, magnetic torquers (MTQ) and a Reaction wheel (+Z axis) are used as the actuators. The current in magnetic torquers are controlled by Driver ICs. Control algorithm used is B-dot algorithm. Magnetic torquers coils are attached to the Printed Circuit Boards (PCB) of -X, -Y and -Z sides of the CubeSats. -X and -Z are solar panels boards while -Y is Mission Board 1 (MB1). Figure 11 shows the magnetic torquer coil attached to -Z PCB. Each MTQ has 1130 turns, a weight of 49 g and a current consumption of 0.05 A for a design torque of 1.1×10^{-5} Nm.

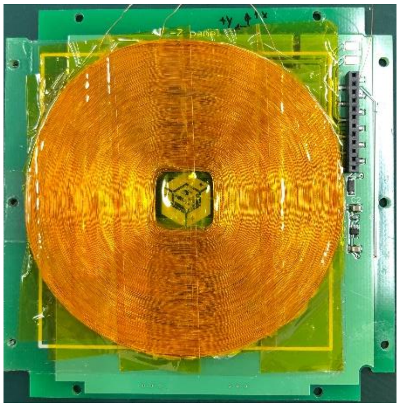


Figure 11: Magnetic torquer coil attached to -Z PCB.

Perovskite Solar cell mission (PSC)

For this mission, each satellite is attached with two samples of perovskite solar cell, Figure 12. The hole transport material varies for each satellite as follows: Guaranisat-1 has Carbon, Maya-2 has Spiro-OMeTAD [2,2′,7,7′-tetrakis (N, N-di-p-methoxyphenyl-amine) 9,9′-spirobifluorene] and Tsuru has CuSCN [Copper(I) thiocyanate].

Figure 12: Samples of perovskite solar cell attached to each satellite.

In the Rear access board (RAB) of the satellite, a solar cell circuit measures the current and voltage characteristics of the PSCs as well as the temperature and irradiance from the sun. These data are saved in the local flash memory and later downloaded by the ground station for analysis.

Total Ionizing Dose Measurement of COTS and Onboard Rad-Hard Components Mission (TMCR)

The objective of the TMCR mission is to verify the accuracy of ground test that simulates exposure of COTS components to space radiation. Using three devices: One IRL620 and two IRLML6402, the change in current consumption of these devices as they are exposed to radiation is monitored. The same microcontroller and flash memory as the PSC mission is used for this mission.

Latch-up Detection and Protection Mission (LDAP)

Cosmic rays and high energy particles in space could sometimes trigger single latch-up event which changes the status of digital devices from 0 to 1 and vice versa. A latch-up detection device has been fabricated by the Nanyang Technological University (NTU) and its effectiveness will be demonstrated through this mission. A latch-up prone device, AD7888ARZ, will be monitored by the latch-up detection and protection (LDAP) made by NTU.

Satellite Structure as Antenna Mission (HNT)

This mission explores the feasibility of using the satellite structure to serve as antenna element to transmit CW/Morse code signals from the satellite. Through this mission, a new antennas design is explored and opens a possibility of avoiding the use of deployable antennas. To do this, some parts of the structure are replaced with Polyether ether ketone or PEEK material, as shown in Figure 13.

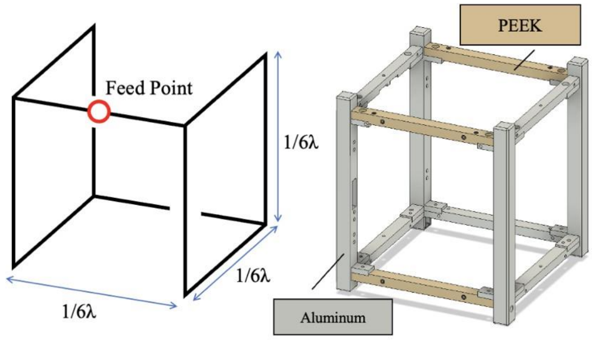


Figure 13: Structure loop of hentenna and BIRDS-4 structure.

The BIRDS-4 hentenna is designed to transmit in the amateur satellite UHF band (435-438 MHz) with its dimensions and matching circuit. The antenna is connected to a different CW transmitter than CW beacon transmitter for bus system, but the transmitting power is same. The HNT mission is turn on by command and transmitted at the timing shown in Figure 14. The antenna performance will be relative measured by receiving signal strength on the ground.

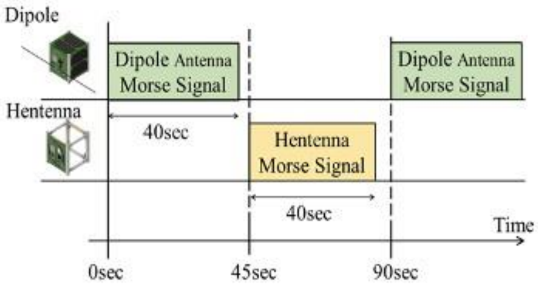


Figure 14: Hentenna transmission timing.

INITIAL OPERATIONAL RESULTS

First 72 hours of operation

After satellites deployment from ISS, the CW signals from Tsuru and GuaraniSat-1 were received by Kyutech Ground Station (GS). The received CW signals indicated 4.10V for TSURU battery and 4.02V for GuaraniSat-1 battery. Uplink and downlink were successful with both satellites, even at low elevation (less than 5 degrees). Maya-2 CW signal was received first by Philippines GS, indicating a low battery level (2.95 V), later the signal of Maya-2 was received in Thailand (March 14), Brazil (March 16) and Paraguay (March 18). The satellites executed CAM mission during deployment and Tsuru was able to take a 320x240 resolution image that contains a portion of ISS and the earth. The photo taken during deployment is shown in Figure 15.

Figure 15: Tsuru 320x240 resolution image taken during deployment.

Tsuru battery voltage and current values collected every 10 seconds during two orbits is shown in Figure 16. During sunlight, the battery charging current is in the order of 600mA to 700mA and the voltage is around 4.2V, all subsystems and missions are supplied by solar cells. During eclipse, batteries are used to power subsystems and missions. The system nominal current consumption is around 250mA to 280mA, reaching 400mA during CW transmission. According to Tsuru on orbit data the voltage has not go below 3.9V and battery always recover its full charge condition.

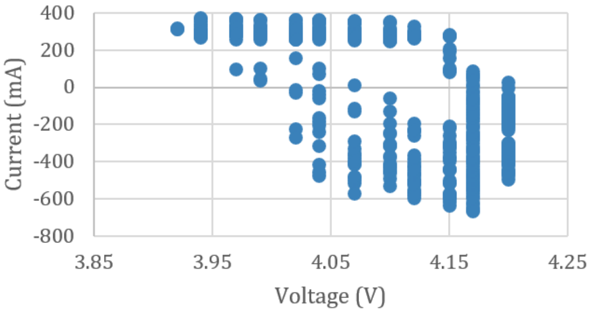


Figure 16: Tsuru Battery voltage vs current.

GuaraniSat-1 battery voltage and current values collected every 90 seconds is shown in Figure 17. During sunlight, the battery charging current is in the order of 400mA and the voltage is around 4.1V. GuaraniSat-1 data shows a less charging capacity in comparison with Tsuru satellite. Subsequent analysis of CW data confirmed no power generation by +Z panel.

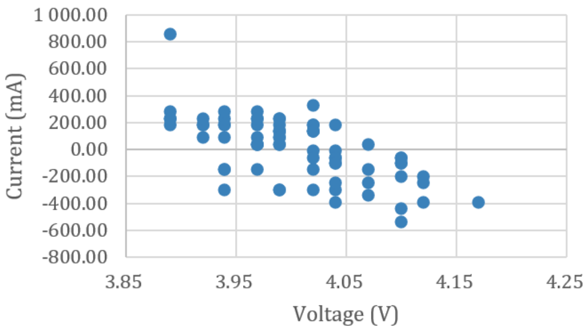


Figure 17: GuaraniSat-1 Battery voltage vs current.

Guaranisat-1 had a decline in voltage over 3 days of operation. 72 hours after deployment the satellite stopped transmitting after downloading data. The last logged voltage was 3.38V

Energy Generation/Consumption Summary is shown in Table 3. It shows that is necessary for 5 panels to work to keep the energy balance of the satellite at a safe surplus.

Table 3: Energy generation/consumption summary

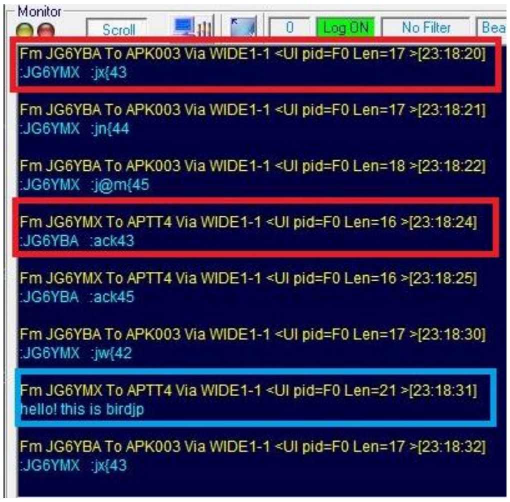
	Energy generation			Energy consumption per orbit
	5 panels	4 panels	3 panels	
MATLAB Calculation	1411	1178	821	1438 mWh
BIRDS-4 satellites	1513	1210	953	1483 mWh (w/ heater)

First 2 months of operation

During the first two months of operation Tsuru satellite was able to execute CAM mission and take pictures from space at different resolutions. The Figure 18 shows a 1280x960 resolution image taken over South America. A noticeable area in the image shows the Parana river, portion of which crosses Paraguay. The command to take this image was sent from Paraguay, which is part of the BIRDS network of ground stations along with 15 other countries [4].

Figure 18: Tsuru 1280x960 resolution image taken over South America.

The APRS mission payload was successfully activated in Tsuru satellite. It is confirmed by the received beacon shown in Figure 19, transmitted every 40 seconds, in the ground station. A successful uplink was also confirmed when ACK messages were received from the payload. The team has yet to demonstrate its digipeating capability.



```
Fm JG6YBA To APK003 Via WIDE1-1 <UI pid=F0 Len=17 >[23:18:20]
:JG6YMX  :jx{43

Fm JG6YBA To APK003 Via WIDE1-1 <UI pid=F0 Len=17 >[23:18:21]
:JG6YMX  :jn{44

Fm JG6YBA To APK003 Via WIDE1-1 <UI pid=F0 Len=18 >[23:18:22]
:JG6YMX  :j@m{45

Fm JG6YMX To APTT4 Via WIDE1-1 <UI pid=F0 Len=16 >[23:18:24]
:JG6YBA  :ack43

Fm JG6YMX To APTT4 Via WIDE1-1 <UI pid=F0 Len=16 >[23:18:25]
:JG6YBA  :ack45

Fm JG6YBA To APK003 Via WIDE1-1 <UI pid=F0 Len=17 >[23:18:30]
:JG6YMX  :jw{42

Fm JG6YMX To APTT4 Via WIDE1-1 <UI pid=F0 Len=21 >[23:18:31]
hello! this is birdjp

Fm JG6YBA To APK003 Via WIDE1-1 <UI pid=F0 Len=17 >[23:18:32]
:JG6YMX  :jx{43
```

Figure 19: APRS mission acknowledge confirmation and beacon received by the Ground Station.

Since the deployment of the satellite on March 13, 2021, the on-orbit behavior of +X panel with the Cemedine EP007 adhesive is being monitored. The panel current and voltage values are being observed. So far, no abnormal values have been observed. All values are close to ground test data.

As an initial operation, the transmitter of Hentenna was turned on for the first time on March 19, 2021, and it was confirmed that Hentenna was operating in outer space. The Morse code sent by HNT mission was received for the Ground Station on March 19th, 2021, 18:54 (JST), Elevation: 18deg

The initial data of the current consumption of the COTS components being tested for space radiation hardness were gathered. It is expected that these measurements will increase over time indicating degradation of the FETs due to space radiation. The IRF620 averaged 9.51mA, while the IRLML6402 averaged 30.12 and 30.24mA, for each device respectively.

A total of 4 days of operation for the LDAP mission has been done but no latch-up has been recorded yet. Longer mission execution time is necessary since this mission is based on probability that a high energy particle would hit the SEL sensitive device.

After 1 month of operation in space, data has been gathered from the Perovskite solar cell (PSC) attached to the Tsuru satellite. This PSC is made with Copper(I) thiocyanate or CuSCN as the hole transport material. The first results shows that PSCs can work in space and degradation will be monitored through the satellite's lifetime.From the housekeeping data of the satellites, the magnetometer and gyroscope data were analyzed to see how the attitude of the satellites changed during its first 2 months of operation. The active attitude control will be initiated later in the satellite's operation to learn about how effective the magnetorquers fabricated and COTS reaction wheel are in controlling the satellite and stabilizing its attitude.

LESSONS LEARNED

Important lessons learned by the team before the satellite delivery and during operation should be accounted and passed down to the next satellite project. These include the following:

- Frequency coordination. This is a technical and regulatory process which involves communication with various organizations in order to operate on a particular frequency. As this process takes time, documentation should be processed as early as possible to get frequency license. Delays in frequency license often leads to miss the satellite launch schedule.

- Power budget calculation. A balance between power consumption and power generation must be achieved at the very least. All subsystems and payload consumptions must be considered during nominal and mission execution conditions. Also, ensure that the generated power by the solar panels should have enough margin to charge the battery and deliver power to the load even in scenarios where some solar panels have issues.

- Long duration test. This test is an emulation of how the satellite should operate in orbit. Therefore, the entire test should not only focus on the individual mission execution, but more importantly the system performance as a whole. In cases where software-related issues in subsystem level, mission level or system level are encountered, these should be addressed and fixed. Another run of long duration test is recommended.

- Flight software. When the result of the long duration test meets the requirements, flight software is considered final. No more modification after should be done as it may affect the satellite operation.

- Satellite operation. The first 72 hours of satellite operation must be focused more on satellite health monitoring. Comparison between the collected on-orbit data, ground data from long duration test and data from heritage satellite (if applicable) is strongly recommended for early anomaly detection. Any anomaly needs further investigation using back-up satellite for root cause analysis and immediate fix.

SIGNIFICANCE OF THIS SATELLITE FOR PARAGUAY

Paraguay is the last country in the south-american region to have a presence in space. Until recently it did not have the minimum capacities and infrastructures for the development of space sciences and technologies in the country, necessary conditions to aspire to contribute to economic, scientific, and social development through a sustainable space program.

Having the first Paraguayan satellite not only implies acquiring knowledge in the design, development, and operation of its satellite but also incorporates other segments and activities that are necessary for the optimal use of space resources, which are the ground segment, the space education and outreach activities.

The country's first satellite marked a historical moment in the scientific and technological development in Paraguay; 2,9 million people followed the three-hour satellite deployment tv program in a country with a population of 7 million. With the launch of the GuaraniSat-1, space development was installed at public opinion, mobilizing the national pride and outreaching the space benefits. The impact was significant in every level of the country, inspiring, motivating and being an instrument of hope where Paraguayan people can dream of a brighter future.

CONCLUSION

BIRDS-4 is a constellation of three satellites including the first satellite of Paraguay. The CubeSats were deployed in orbit on 13th of March 2021 from the International Space Station. This paper presented the summary about each subsystem and mission design, as well as the preliminary on-orbit result of BIRDS-4 satellites. The first results show that Maya-2 and GuaraniSat-1 are experiencing an imbalance between power generation and consumption.

The satellites were able to take images of BIRDS member countries. Minimum success level was achieved for APRS, PSC, TMCR, HNT, and GLUE missions. SFWARD mission execution is on-going; tests are being performed to verify successful uplink. The ADCS mission, where the actuators will be activated, will be executed later in the satellite's operation and the results will be reported along with the full results of all missions. The CubeSats will be operated, and all missions will be executed until their end of life (EOL).

To improve the reliability of future projects, the lessons learned by the team before the satellites' delivery and after the initial operation were discussed showing the importance of carrying out exhaustive tests for different operating scenarios in order to mitigate possible failures that may occur.

Acknowledgments

This project was supported in part by JSPS Core to Core program, B. Asia-Africa Science Platforms.

The authors would like to express gratitude to the BIRDS-4 engineering team members in particular: Anibal Antonio Mendoza Ruiz, Daisuke Nakayama, Hari Ram Shrestha, Hiroki Hisatsugu, Hoda Awny Elmegharbel, Mark Angelo Cabrera Purio, Marloun Pelayo Sejera, Timothy Ivan Leong, Tomoaki Murase, Yasir Abbas, Yigit Cay, Yuma Nozaki.

The authors would like to acknowledge the support shown by stakeholders University of Philippines - Diliman (UPD) and Paraguayan Space Agency (AEP) of Maya-2 and GuaraniSat-1 respectively, Prof. Joseph Chang and Dr. Shu Wei of Nanyang Technological University (NTU) for providing the LDAP payload, and all the parties and individuals who assisted the project, including the members of BIRDS ground station network, the amateur radio community, and JAXA.

References

1. Turtogtokh Tumenjargal, JGMNB Project Members, JGMNB Project Members, JGMNB Partners and Mengu Cho, Development Status of Joint Global Multi-Nation BIRDS CubeSat Constellation Project; The 60th Space Sciences and Technology Conference, Hakodate, Japan , September 2016.
2. BIRDS-2, https://birds2.birds-project.com/
3. BIRDS-3, https://birds3.birds-project.com/
4. Apiwat Jirawattanaphol, Mengu Cho, Naomi Kurahara, BIRDS CubeSats Constellation Operations using ground station network, UKAREN, 2018