Development of KITSUNE: A 6U CubeSat for 5-m Class Imaging, C-band Radio Service, Ionospheric Research and IoT

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(Received January 5th, 2021)

KITSUNE (Fox in Japanese language) is a 6-unit (6U) CubeSat with multiple missions such as Earth observation with 5-m class resolution color images, demonstration of C-band communication service, development of 2-unit main bus system (2UMB), measurements of total electron content in the ionosphere, LORA on-orbit demonstration for Internet of things (IoT), and store-and-forward mission from the ground sensor terminals of the developing countries. KITSUNE satellite has been developed as a dual-satellite system that is composed of the section controlled by the amateur frequencies, which includes the 2UMB and 3U-sized camera payload, and the section controlled by the non-amateur frequencies that is called SPATIUM-II. While SPATIUM-II only receives battery power from the 2UMB section, it is controlled by an independent ground station to perform store-and-forward mission and ionospheric research. On the other hand, the 2UMB system executes the Earth observation mission and C-band amateur radio service. Even though the camera payload has been developed to capture 5-m class color images for entertainment purposes, it will be used to demonstrate wild-fire detection by a CubeSat platform as well. Finally, the flight model of the satellite has been successfully completed, and KITSUNE is expected to launch in early 2022.

Key Words: 6-unit CubeSat, Earth observation, lean satellite, Internet-of-Things, total electron content measurements

Abbreviations

2UMB	:	2-unit main bus
ACCIMT	:	Arthur C. Clarke Institute for Modern Technologies
ADCS	:	attitude determination and control
BIRDS	:	joint global multi nation Birds satellite project
CMOS	:	complementary metal–oxide–semiconductor
COTS	:	commercial off-the-shelf
CSAC	:	chip-scale atomic clock
CW	:	continuous wave
EO	:	Earth observation
EPS	:	electrical power system
GPS	:	global positioning system
GS	:	ground station
ICD	:	interface control document
IoT	:	Internet-of-Things
ISS	:	International Space Station
JPEG	:	joint photographic experts group
Kyutech	:	Kyushu Institute of Technology
LEO	:	low Earth orbit
Li-Ion	:	lithium ion
LoRa	:	long range
MLI	:	multi-layer insulation
NTU	:	Nanyang Technological University
OBC	:	onboard computer
PIC	:	peripheral interface controller
PNG	:	portable network graphic
PPS	:	pulse per second
RF	:	radio frequency
RGB	:	red green blue
Rx	:	reception, uplink
S&F	:	store-and-forward
SDR	:	software-defined radio
SPATIUM	:	space precision atomic-clock timing utility mission
SS	:	spread spectrum
TEC	:	total electron content
Tx	:	transmission, downlink
UART	:	universal asynchronous receiver-transmitter
UHF	:	ultra-high frequency

1. Introduction

Small satellites, which are also called SmallSats and

CubeSats, are improving continuously while being aligned with the technological development and increasing interest of the international space community. As the CubeSat bus systems and payloads become more capable and complex, their mission objectives are evolving to be more competitive and sophisticated as well. While the performance/cost ratio is increasing for these platforms, a compelling interest has been exhibited towards CubeSats for various missions in previous years.[1-3] Furthermore, 1-10 kg class of spacecraft have demonstrated the greatest growth rate comparing to the other small satellite platforms. [3]

Fig. 1. KITSUNE configuration.

KITSUNE satellite in Fig. 1 has been developed as a collaboration between international academic institutions and private sector in Japan while Kyushu Institute of Technology (Kyutech), which is the main satellite developer and integrator, acted as the middle ground to establish communication and collaboration between all entities. Kyutech team collaborated with Addnics Corp. and Harada Seiki Co. Ltd. in Japan for C-band communication and optical payload development while the team cooperated with Nanyang Technological University (NTU) in Singapore on CSAC (chip-scale atomic clock) payload and Arthur C. Clarke Institute for Modern Technologies (ACCIMT) in Sri Lanka on store-and-forward (S&F) mission payload. In addition, KITSUNE is the first multi-layer insulation equipped CubeSat to be deployed from International Space Station (ISS).

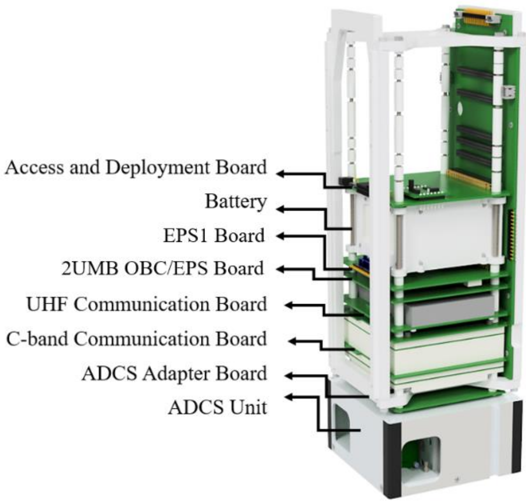

Fig. 2. 2UMB configuration.

KITSUNE has been developed as a dual-satellite system, and it has multiple frequencies for communication due to the divergent mission requirements. First, amateur frequencies have been selected for the 2-unit main bus (2UMB) in Fig. 2 and 3-unit camera payload with the following objectives:

- Earth observation with 5-m class resolution color images.
- Demonstration of C-band communication from the main and mobile ground stations.
- Development and demonstration of Kyutech standard bus system as 2UMB for future missions.
- Downlink of low-resolution images from a secondary camera by C-band uplink commands and amateur radio service.

Second, SPATIUM-II (space precision atomic-clock timing utility mission) in Fig. 3 is controlled by non-amateur frequency communication, and the objectives can be listed as below:

- Total electron content (TEC) measurements of the ionosphere.
- On-orbit demonstration of LoRa communication board.
- S&F mission from the ground sensor terminals of BIRDS countries.
- Monitoring chip-scale atomic clock (CSAC) board on-orbit performance (resuming one of the SPATIUM-I objectives[4,5]).
- Development of mobile and fixed ground sensor terminals (GSTs).

Fig. 3. SPATIUM-II configuration.

Finally, multiple countries in BIRDS project[6,7] will be deploying several GSTs that are based on the design by Kyutech to participate in the S&F mission. Section 2 describes the satellite development, and section 3 represents the mission descriptions. Finally, the satellite system is explained section 4, and the satellite project is concluded in section 5.

2. Satellite Development

Reference 8) highlighted the importance of the multi-disciplinary team in a small satellite project considering system engineering, communication, control, navigation and other subsystems. In addition, Reference 9) listed the fundamental elements for a successful small satellite project as a list of 10 items such as short timescale, adequate team communications, well-informed usage of available volume and state-of-the-art components and so on. Even though most of the items could be counted as relevant for the KITSUNE satellite development, some of the items were not applicable considering the Covid-19 pandemic. Furthermore, Reference 9) mentioned that having a small team composed of approximately 25 members with decent communication working in close proximity is significantly essential, and many traditional aerospace institutions have failed because of the rigidity of management structure and point of view. During 15 months of the KITSUNE satellite development, the team had to be moderately flexible while the project management announced and updated risk management and work rules considering constantly changing pandemic situation such as:

- A laboratory work guideline was distributed with 10 rules to all members including social distancing, tool sharing, contact avoidance and tracking of body temperatures.
- Laboratory work was distributed to five separate tables/work areas for 2UMB, SPATIUM-II, 3U camera payload, soldering station and integration.
- A time table was distributed with 3-hour intervals in order to avoid group work.
- Regular online meetings were arranged, and supporting members were available through remote access for the small number of team members in the facilities.

3. Missions

3.1. 5-m class Earth observation mission

KITSUNE satellite utilizes a 3-unit size optical payload with 5-m class imaging capability in low Earth orbit. The payload is a combination of a 31.4 million pixels CMOS sensor, customized optics, and a camera controller board. In addition, the optics are composed of a lens with a focal length of 300-mm and an active temperature control system for the light-transmitting components.

The main mission is 5-m class Earth imaging in order to capture man-made patterns on the ground by a group of people as providing entertainment during a social event, and these patterns are planned to be within 100 m x 100 m square. In addition, it will demonstrate machine learning capabilities on orbit as a secondary mission, and the camera controller board will utilize a pre-trained convolution network in order to identify wild-fires, which have become a critical natural disaster around the world, by image classification.[10,11)]

The payload requirements are determined from the perspective of mission and CubeSat limitations as below:

- The ground resolution should be approximately 5 m per pixel.
- The payload should be able to capture 6 images in sequence approximately with 1 frames per second.
- The ground swath should be approximately 20 km.
- The camera controller board should be able to take images and transfer over C-band communication board in real-time mode or store images in C-band flash memory for downlink when it is requested.
- The camera sensor should be able to capture RGB images with JPEG compression (>90%) with no false colors.
- The mission end-to-end power consumption should be less than 10.0 Wh per orbit, and the in-rush current should be less than overcurrent protection settings of 2UMB EPS.
- The mission should be able to perform by the uplink commands both from UHF GS and C-band mobile GS. In addition, overall images and telemetry should be downlinked to UHF GS and C-band main GS.
- ADCS subsystem should be able to point the camera and C-band Tx antenna with approximately 0.25° accuracy either in target or nadir pointing modes.
- The lens diameter should be less than 90.0 mm, and the overall payload should be shorter than 327.5 mm.
- The camera controller board should survive total ionization dose of approximately 200.0 Gy (20.0 krad), and the camera sensor and the controller board should be able to operate within the temperature range of -20.0°C to +55.0°C. In addition, the range of temperature difference for the lens components should be between -5.0°C and +5.0°C while capturing the images.
- The CMOS sensor should have pixel size larger than 3.0 μm, global shutter and the shutter speed less than 1/3200 s.

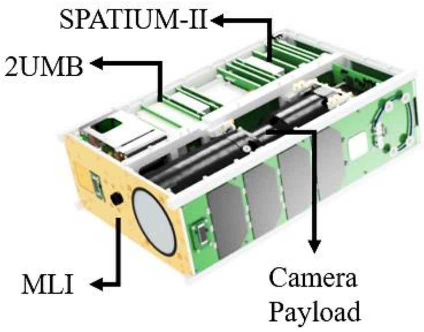

Fig. 4. KITSUNE configuration with 2UMB, SPATIUM-II and 3U camera payload in addition to the MLI on nadir pointing side.

The image size is detected as approximately 3 MB for compressed images in JPEG format while PNG images have a size of approximately 90 MB. In addition, the main mission will be executed end-to-end as the following:

- Step 1: sending uplink commands to the satellite over UHF or C-band communication.
- Step 2: taking 6 images in PNG format, compression to JPEG format, and the collection of ADCS data at high sampling mode.
- Step 3: downlink of thumbnails, ADCS telemetry and JPEG files.
- Step 4: downlink of the selected images in PNG format.

In addition to the described operation, the mission could be executed as the image taking in the same orbit of the uplink command and downlink over C-band communication in the next ground pass in JPEG format when a quick imaging operation is required. Finally, the main payload properties are given in Table 1 below.

Table 1. The payload properties.

Item	Information
Sensor	
Number of pixels	31.4 million pixels
Sensor type	CMOS
Shutter method	Global shutter
Shutter speed	30 μs to 10.0 s
Interface	Ethernet
Data transmission speed	10 Mbps
Power supply	+12 V
Camera controller board	
Model	Customized board with Raspberry Pi compute module 3+
Operating system	GNU/Linux Ubuntu distribution version 18.04
CPU	ARMv8, 1.2GHz
Memory	32 GB (Flash), 1 GB (RAM)
Image capturing speed	1.2 frames per second
Interface	Ethernet, USB, UART
Optics	
Focal length	300 mm
Temperature control	Active control and multi-layer insulator

3.2. C-band communication demonstration mission

The C-band communication board is added to the 2UMB system by collaboration with Addnics Corporation in Japan. This subsystem has functionality of CW (continuous wave) beacon, high-speed downlink, multiple speeds of uplink, combinational mode of uplink and downlink, and supporting amateur radio users.

Amateur radio users could send an uplink command to receive 2MP images of the ground in real-time after Kyutech announces the time and region when the mission is active.

The antenna system of C-band communication consists of one Tx antenna on –Z panel, and two Rx antennas on +/-X panels. The patch antenna and the configuration on the satellite are shown in Fig. 5 and 6.

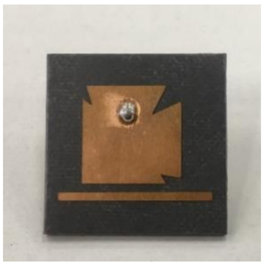

Fig. 5. 5.8 GHz C-band patch antenna.

C-band board is able to communicate with the 3U size camera payload and the onboard computer (OBC). First, the camera controller board can transmit images in real-time to C-band board for downlink to the GS, or it can store the captured images in the flash memory of the C-band board. Second, the C-band board can receive data from the communication PIC on the OBC for the downlink, or it can transfer the uplink data to the communication PIC. Third, it can recognize an uplink command for capturing images with the small camera system as seen in Fig 6 and transmit to the uplink command sender.

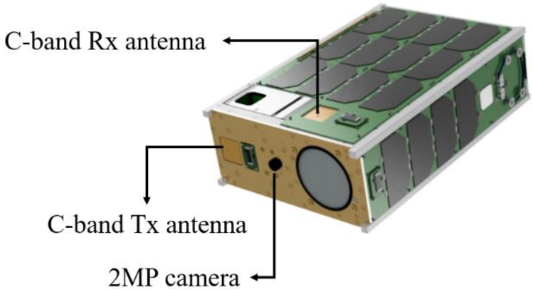

Fig. 6. C-band antennas and 2MP camera.

The subsystem has a capability of receiving uplink at 250 bps/1 kbps/4 kbps, the downlink to the GS at 100 kbps – 20 Mbps, and the CW beacon emission at 9.6 wps – 24 wps. It operates over the unregulated voltage bus of approximately 7.4 V with the operational range of 5.0 V to 9.6 V. In addition, the antenna system requirements were selected as below:

- Having the return loss less than -20 dB for each antenna.
- Achieving maximum gain of 6 dBi.
- Having the beam width (3 dB) of approximately 80°.

These requirements were selected in order to downlink to a GS with 2.4 m dish up to 20 Mbps speed and achieving 1Mbps downlink to a mobile GS with 0.6 m dish. Even though the C-band board could receive data at higher rates, the limitation for real-time data transmission speed is a result of the Raspberry Pi compute module 3+ UART speed at 1Mbps. Finally, a mobile GS is being developed in Kyutech with the capability of satellite tracking and uplink/downlink to the KITSUNE satellite (Fig. 7).

Fig. 7. C-band Mobile GS prototype.

3.3. TEC mission

SPATIUM project has been developed by Kyutech and NTU with a goal of global 3D ionosphere mapping mission via constellation of CubeSats equipped with atomic clocks.[12] TEC mission is a part of the second phase in this objective.

SPATIUM-I satellite was released from ISS on October 2018, and SPATIUM-II will be deployed from ISS in early 2022 as an integrated system in KITSUNE satellite. TEC mission payload consists of the following items onboard the satellite:

- CSAC board
- RF switch
- Software defined radio (SDR)
- Raspberry Pi compute module 3+
- GPS receiver

The ground system requires a spread spectrum (SS) transmitter, CSAC board as the clock source, SDR, Raspberry Pi compute module 3+, GPS receiver in addition to the non-amateur UHF GS to operate SPATIUM-II.

For this mission, the SS ranging signal with the gold code sequence generation is transmitted from the GS to SPATIUM-II. Two receivers on the ground and the satellite record the reception time of the starting bits of the gold code sequences. Since the reception time does not include the time delay due to the ionosphere on the ground, the ionosphere delay is calculated by comparison between these two reception times after subtracting the delays due to the distance between the satellite and the GS transmitter, the atmosphere and the troposphere.

The time stamp is retrieved from the GPS 1-PPS output in both receivers on the ground and the satellite. 1-PPS output turns off the RF switch for 800 µs periodically; therefore, it can be used as time and position reference with the GPS data for the starting bits of the gold sequences received on the satellite side. For this reason, a code is developed for RF switch detection within 1-second intervals (Fig. 8).

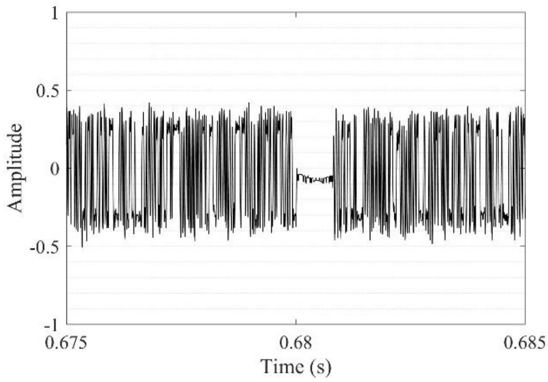

Fig. 8. RF switch detection onboard during the ground tests at 0.68 s.

Since the SS uplink has 250 bps data rate, the gold code sequences are transmitted every 4 ms. As a result, the ground receiver should be able to detect the difference between the starting bits every 4000 samples when the sampling rate of receiver is set as 1 MHz. The ground testing on SPATIUM-II showed that it could be achieved when the transmitted signal is sufficiently strong.

In order to detect the starting bits of the gold code sequences, a code is developed to cross-correlate between the received signal after demodulation and the pre-recorded gold code sequence on SPATIUM-II, the peaks of the cross-correlation within 4ms intervals indicate the results as in Fig. 9. Since the transmitter and the receiver are on the same location, no delay was detected.

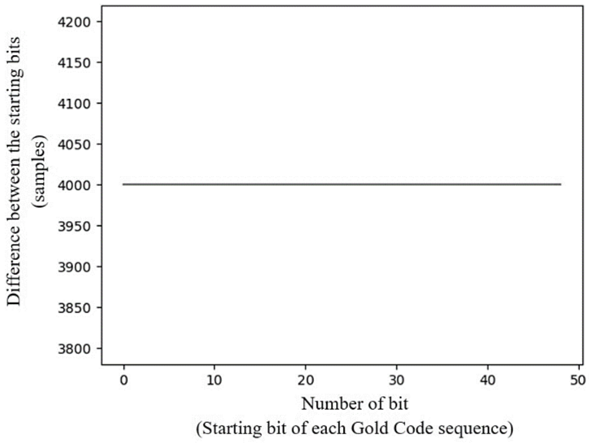

Fig. 9: Cross correlation results showing the difference between the gold code sequence starts.

SPATIUM-II uses two antennas for the TEC mission. First, a monopole antenna with approximately 2.1 dBi maximum gain is used for communication with non-amateur UHF GS. Second, a dipole antenna with a maximum gain of approximately 3.7 dBi is used for SS signal reception with the SDR.

SPATIUM-II will demonstrate on-board processing of SS-signal reception, signal demodulation and time-delay calculations.[13)] For SPATIUM-I, the transmitter was on the satellite side and the processing was performed on the GS instead. In addition, SPATIUM-II will also monitor the CSAC performance as resuming one of the objectives of SPATIUM-I mission in the late stages of SPATIUM-II operation.

3.4. S&F mission

The second mission of SPATIUM-II could be described as the collection of sensory data from the ground sensor terminals (GSTs) in multiple countries and distribute the downlinked data from the database on Kyutech non-amateur GS.

The S&F mission objectives could be listed by considering the satellite payload and the ground segment as below:

- Utilizing a S&F mission with a CubeSat for achieving IoT service and remote data collection.
- Developing low-cost and lower power GSTs, which could be fixed or mobile stations that could collect a wide range of sensory data.
- Distributing the GST design from Kyutech to developing countries in order to deploy the GSTs in various locations around the world.
- Supporting the developing countries to employ the most suitable sensor configurations on their GSTs by considering the needs of each country.
- Encouraging the students from various developing countries by contributing to a space mission on ground segment and having hands-on experience.

The onboard LoRa payload has eight LoRa receivers, which could be configured differently and receive sensory data from at least eight GSTs simultaneously. A description of the satellite payload is given in Ref. 14.

Table 2. The LoRa payload properties.[12)]

Parameters	Values
Dimensions	90 mm x 86 mm
Power consumption	240 mA at 3.5V
Frequency range	400 MHz – 440 MHz
Receiving data rate	11 bps – 9.3 kbps
Reconfigurable spreading factor	6 – 12
Bandwidth	7.8 kHz – 125 kHz
Coding Rate	4/5 – 4/8
Number of receivers	8
Antenna type	Monopole
Maximum gain	0.3 – 0.4 dBi
Antenna return loss	-15.4 – -14.9 dB

The GST design can support a wide range of sensor types with multiple interfaces. Since one of the objectives is developing low-cost ground segment, the overall development cost was estimated below $150. The developed GST is shown in Fig. 10.

Fig. 10: The fixed GST in Kyutech campus.

In addition to the sensory data collection and low-cost, another design requirement was to operate the GST, which relies on the solar panels, for approximately 24 hours during rainy season. During the demonstration, the GST achieved this requirement multiple times.

Multiple BIRDS countries have joint the GST development by participating the workshops by Kyutech considering educational and research activities. These countries can be listed as Bhutan, Philippines, Malaysia, Paraguay, Costa Rica, Sri Lanka, Nepal, Taiwan, Mongolia, Zimbabwe and Uganda.[14)] Finally, a database is currently being developed for the Kyutech GS in order to distribute the sensory data collected from the listed countries. After the data is received and processed, the users will be able to access the data online with a respective ID and password. Since all GSTs have unique IDs implemented in the received data, the users will be able to identify the data source and type conveniently.

4. Satellite System

KITSUNE satellite has been developed as dual-satellite system with amateur radio and non-amateur radio frequency controlled parts. As a result, it contains two OBC, two EPS and two UHF communication subsystems. After determining the preliminary requirements for volume, mass and power, the development started in three segments as:

- 2UMB
- SPATIUM-II
- 3U camera payload

2UMB system has been developed with an objective of building a standardized Kyutech bus system to be used in future missions as well. This system strongly used heritage from BIRDS satellite bus explained in Ref. 15). First, the EPS power requirement is increased due to changing from 1U to 6U form factor. Even though, BIRDS bus system showed flexibility to support most of the requirements, some changes are applied due to increased number of the solar cells, improved battery capacity, higher current consumption and different supply voltage requirements of payloads. For instance, KITSUNE satellite has 36 solar cells in total (Table 3), which is significantly higher than 1U CubeSat. The overall summary of KITSUNE satellite is given in Table 4.

Table 3. Number of solar cells on KITSUNE satellite.

Side	Number of Cells	Maximum Voltage/Current
+X panel	12	10 V/1.5 A
-X panel	12	10 V/1.5 A
+Y Panel	4	10 V/0.5 A
-Y Panel	4	10 V/0.5 A
+Z panel	4	10 V/0.5 A

Second, the battery design was changed from nickel/metal hydride to lithium ion (Li-ion) batteries in a configuration of two in series and 3 in parallel. As a result, the maximum capacity of the battery is 74.5 Wh with 7.2 V nominal voltage.

Third change from the BIRDS bus is the ADCS subsystem. Since KITSUNE C-band communication and the camera payload requires to be pointed, ADCS subsystem was developed based on Adcole Space MAI-401 and an adapter board to interface with the bus system. During the ground testing, detumbling duration is measured as approximately 100 minutes from 30 degree per second rotation. In addition, sun-pointing and nadir pointing maneuvers are performed within 4 minutes to achieve the target attitude, and the desaturation of the reaction wheels from maximum speed was observed within 45 minutes. The hardware is composed of the following items:

- MAI-401 ADCS unit including a control unit, three reaction wheels, three magneto-torquers, 3-axis gyroscope and two Earth sensors.

- ADCS adapter board.
- External sensors such as 3-axis magnetometer, six sun sensors, a GPS unit.

Table 4. KITSUNE satellite specifications.

Specification	Information
Mechanical Properties	
Dimensions	340.5 x 226.3 x 100 mm
Total weight	7544 g
Power Storage	
Battery Type	Li-ion
Cell connectivity	2S3P (2 in series, 3 in parallel)
Battery nominal voltage	7.2 V
Battery capacity	74.5 Wh
Power Generation per Orbit	
Sun tracking mode	7.5 Wh – 10.0 Wh
Nadir pointing mode	5.7 Wh – 7.4 Wh
Detumbling mode	5.2 Wh – 7.3 Wh
EPS Bus Voltage	
2UMB	(3x) Unregulated line (2x) +3.3 V line (1x) +5.0 V line (1x) +12.0 V line
SPATIUM-II system	(2x) Unregulated line (1x) +3.5 V line (1x) +4.5 V line (1x) +5.0 V line
Nominal Power Consumption	
2UMB	6.0 Wh
SPATIUM-II	1.5 Wh
ADCS Modes	
Nominal mode	Sun-tracking
EO mission mode	Nadir pointing
SPATIUM-II mission mode	No requirement
Deployment mode	De-tumbling
Antenna System	
2UMB	(1x) C-band Tx patch antenna (2x) C-band Rx patch antenna (1x) UHF dipole antenna
SPATIUM-II	(1x) UHF dipole antenna (2x) UHF monopole antenna
Communication System	
2UMB (Amateur Frequencies)	
C-band Tx/Rx speed	100 kbps – 20 Mbps 250 bps – 4 kbps
C-band Tx/Rx frequency	5.65 – 5.67 GHz 5.83 – 5.85 GHz
UHF Tx/Rx speed	4.8 kbps/4.8 kbps
UHF Tx/Rx frequency	435 MHz/437 MHz
SPATIUM-II (Non-amateur Frequencies)	
UHF Tx/Rx speed	4.8 kbps/4.8 kbps
UHF Tx/Rx frequency	401 MHz/450 MHz
LORA Rx speed	488 bps – 855 bps
LORA Rx frequency	400 MHz and 433 MHz
SS Rx speed	250 bps
SS Rx frequency	449 MHz

SPATIUM-II and 2UMB segments are connected through a backplane board similar to BIRDS bus design. The backplane board size is increased for 6U CubeSat design, and each system employed a complex programmable logic device between the subsystems to increase flexibility during the development phase. In addition, some of the 2UMB subsystems started to use 58-pin connectors compared to the 50-pin connector standard used in the BIRDS bus system due to increased requirement for number of the pins. Furthermore, SPATIUM-II system receives raw power from the battery of 2UMB system through the backplane board, and there is no control function is shared between the two parts. Therefore, SPATIUM-II EPS on OBC/EPS board in Fig. 3 is responsible only for regulating the voltage levels for its subsystems and control, and it does not have a separate battery. The 2UMB EPS also contains battery charger regulators between the solar panels and the battery, which is different than SPATIUM-II EPS subsystem. These functions are maintained by OBC/EPS board and EPS1 board in Fig 2. Finally, the 3U camera payload is developed with a COTS camera sensor while the camera controller board, the optics, lens temperature control system and software are designed, tested and integrated.

5. Conclusion

In this paper, a 6U CubeSat mission called KITSUNE is described. KITSUNE was developed as a dual-satellite system from the beginning by considering separate control with amateur and non-amateur frequencies. The bus system is developed by considering the future missions while using heritage of the BIRDS bus system. The 2UMB capabilities will be tested on-orbit through the support of the systems such as the 3U camera payload and SPATIUM-II. While the 2UMB system demonstrates 5-m class imaging mission, C-band communication, amateur radio service, wild-fire detection and onboard CNN training on a CubeSat, SPATIUM-II will be performing TEC measurements and S&F mission.

Acknowledgments

The authors would like to thank the KISTUNE development members not listed in the authors. Without their contribution, the satellite could never be built. In addition, the authors would like to acknowledge the support provided by Prof. Mohammad Tariqul Islam on C-band patch antennas. The part of KITSUNE development work, especially 2UMB, C-band and camera payload was supported by Ministry of Economy, Trade and Industry. The part of SPATIUM-II TEC mission development was supported by MEXT Coordination Funds for Promoting AeroSpace Utilization; Grant Number JP000959.

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