Technology Demonstration CubeSat KOSEN-1 for Jupiter Radio Observations

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Our CubeSat project organized by 10 colleges of the National Institute of Technology in Japan was selected as a CubeSat candidate for JAXA's Innovative Satellite Technology Demonstration-2. This 2U-CubeSat, named KOSEN-1, was launched by a JAXA Epsilon-5 Launch Vehicle on November 9th, 2021. KOSEN-1 will demonstrate three new spaceborne technologies for the CubeSat system: (1) a performance of the dual reaction wheel, (2) a usage of the Raspberry Pi CM1 based OBC, and (3) an expansion of a 6.6-m long dipole antenna. Furthermore, KOSEN-1 will observe Jupiter's decametric radio emissions to investigate the beaming characteristics.

Key Words: CubeSat, Technology Demonstration, Innovative Satellite, Jupiter Radio Science

1. Introduction

KOSEN-1, a 2U-CubeSat Jupiter Radio Observation Technology Demonstration Satellite, is developed by 10 colleges of the national institute of technology (Kochi College, Gunma College, Tokuyama College, Gifu College, Kagawa College, Yonago College, Niihama College, Akashi College, Kagoshima College, and Tomakomai College) led by Kochi College and Gunma College. KOSEN-1 was selected by JAXA as one of the themes for the Innovative Satellite Technology Demonstration-2, and was launched by JAXA's Epsilon-5 Launch Vehicle on November 9th, 2021. In this paper, the outline of KOSEN-1 satellite and the latest development of the system onboard KOSEN-1 is introduced.

2. Overview of KOSEN-1 satellite

Figure 1 shows the latest computer graphics of KOSEN-1. The size of the satellite is a 2U-CubeSat (dimensions: 10cm x 10cm x 23cm, weight: 2.6kg).

Figure 2 is a CG of the flight image of the Epsilon-5 Launch Vehicle, which is launched with nine satellites including the KOSEN-1 satellite, and Figure 3 is a CG of ARICA (1U-CubeSat of Aoyama Gakuin University) and KOSEN-1 (2U-CubeSat), which is simultaneously released from the E-SSOD installed at the Post Boost Stage (PBS), which can hold 3U.

The goal of KOSEN-1 satellite is to demonstrate new space technology in CubeSat as follows:

(1) Space demonstration of ultra-high precision attitude control by dual reaction wheel

(2) Space demonstration of OBC based on ultra-compact Linux microcontroller board Raspberry Pi CM1 based OBC

(3) Space demonstration of 6.6m long dipole antenna deployment technology for Jupiter radio observation

The mission also aims to investigate the beam characteristics of Jupiter's radio waves, which are natural radio emissions in the decameter band (shortwave band). It is planned to conduct simultaneous satellite and ground-based observations of Jupiter's radio waves together with large ground-based low-frequency radio telescopes such as the LWA (Long Wavelength Array) operated in the United States.

Fig. 1. CG of KOSEN-1, 2U-CubeSat. (Courtesy: JAXA)

Fig. 2. CG of the Epsilon-5 Launch Vehicle carrying the KOSEN-1 satellite. (Courtesy: JAXA)

Fig. 3. CG of the KOSEN-1 satellite being ejected from the Post Boost Stage (PBS). (Courtesy: JAXA)

Figure 4 describes the internal structure of the KOSEN-1 satellite, showing the arrangement of the main components: one third of the 2U-CubeSat is for the electronic board, the next third is for the dual reaction wheel, and the next third is for the antenna deployment for Jupiter radio observation.

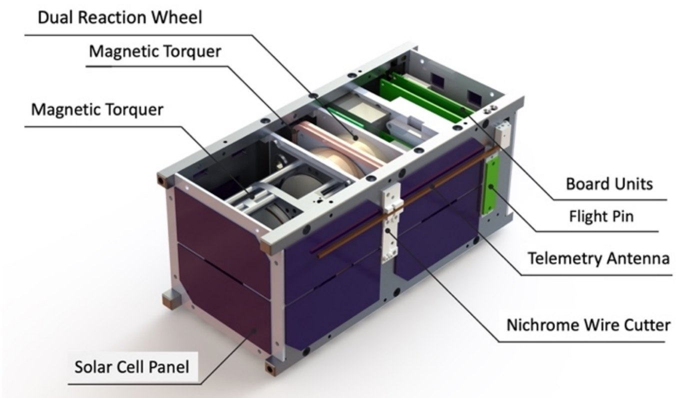

Fig. 4. Location of the main parts of the KOSEN-1 satellite components.

3. Three new satellite technology demonstrations

The first technology demonstration, the dual reaction wheel, is a mechanism to control the attitude by obtaining the differential torque by rotating two reaction wheels in opposite directions with a time difference from when they are stopped. This is the first satellite to be equipped with a dual reaction wheel. As shown in Figure 5, this dual reaction wheel is built into the center of the satellite, and the development of a new thin motor has made it possible to mount it on the CubeSat.

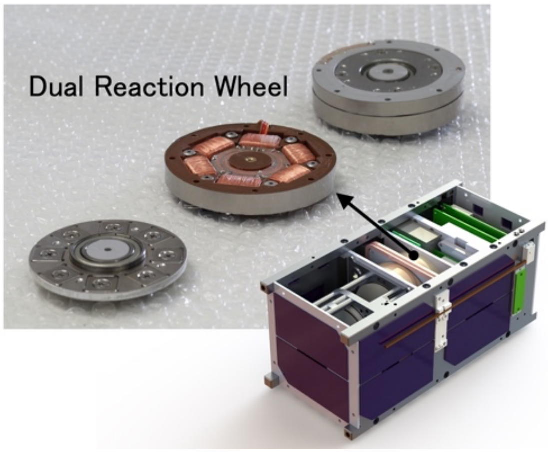

Fig. 5. Dual reaction wheel consisting of two planar motors.

The second technology demonstration, the OBC (CubePi-Board), uses a Raspberry Pi Compute Module 1 (CM1) similar to the Raspberry Pi Zero, which is an ultra-compact, low-power Linux microcontroller board that can use the vast resources of the Linux operating system. Figure 6 shows a photo of an actual OBC board in use. By using a commercially available CM1 board, it is also possible to simulate the hardware of the OBC. In the software development of the OBC, the CM1 board was used to share the OS image and GitLab was used to develop the software for each mission. This method enabled us to develop a new distributed OBC software with the participation of many college students.

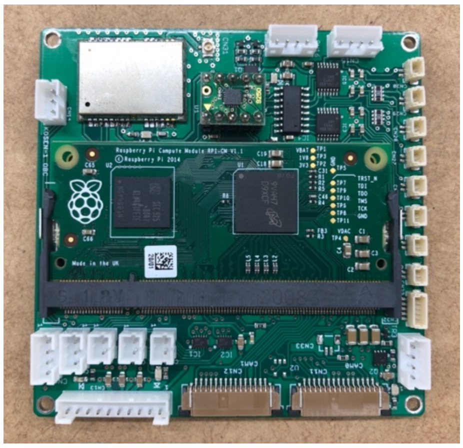

Fig. 6. Photo of the OBC board used in the KOSEN-1 satellite.

The third technology demonstration is the deployment of a half-wavelength dipole antenna with a center frequency of 20.5 MHz (3.3 m at one end and 6.6 m at both ends) for Jupiter radio observation. Figure 7 shows the deployed antenna for Jupiter radio observation. This is the first technology demonstration of such a long antenna on CubeSat. For this Jupiter radio antenna, we developed a new mechanism to secure the electrical contact of the feed points during deployment.

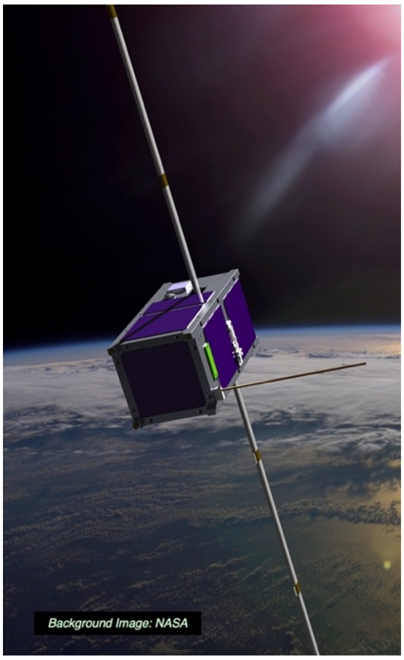

Fig. 7. Deployed antenna for Jupiter radio observation.

4. System configuration of KOSEN-1 satellite

Figure 8 shows an overview of the system configuration of KOSEN-1 satellite. The radio unit used is a new model TXE-430MFMCW-302A-RU (430MHz band) from Nishi Radio Laboratory, which contains the transmitter and receiver in the same case. For the communication control, a special board called CubeCom is used, and independent PIC microcomputers are used for transmitter and receiver.

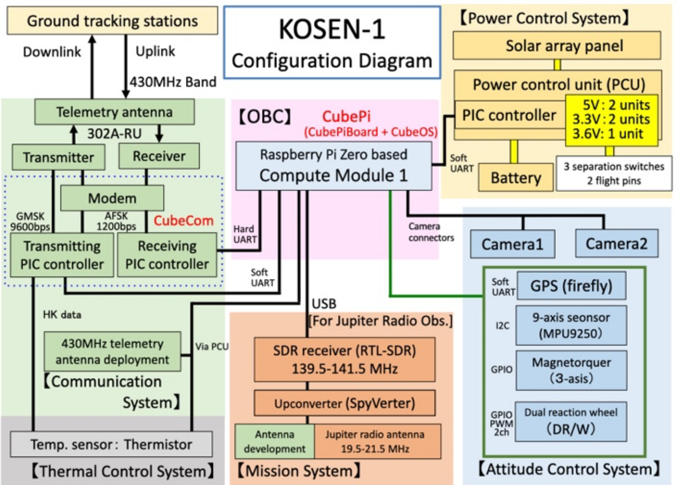

Fig. 8. System configuration of KOSEN-1 satellite.

For the reception of Jupiter's radio waves, we used a USB dongle type SDR (RTL-SDR) to receive the I/Q signals in the 2 MHz band from 19.5 MHz to 21.5 MHz, and the SDR receives the signals from 139.5 MHz to 141.5 MHz after adding 120 MHz frequency by an up-converter (SpyVerter).

The OBC (CubePiBoard) uses the Computer Module (CM1) of the Raspberry Pi to ensure software compatibility with the Raspberry Pi Zero, and the motherboard of the CM1 is developed independently. The CubePiBoard is connected to an SDR, two wide-angle cameras, a space GPS module (Firefly), a 9-axis sensor (MPU-9250), a magnetic torque control unit, and a dual reaction wheel control unit. The Raspberry Pi CM1 is equipped with Linux. In addition, the Lite version of Raspberry Pi OS, the Linux OS for Raspberry Pi, is used so that the system can be operated with minimum file size, and customized to save power by stopping unneeded processes. This customized OS is called CubeOS, and together with the CubePiBoard, we aim to create a power-saving and highly reliable Raspberry Pi for CubeSats, and call the whole system CubePi.

The serial communication (UART) of the OBC uses both hardware serial and software serial. This is due to the fact that the CM1 has only two channels of hardware serial, so we use software serial with multiple channels up to 9600 bps using a Python library called pigpio. The antennas of the GPS module are placed on both sides of the satellite structure to receive GPS signals in all directions.

5. Jupiter radio observation

Jupiter produces auroral radio emissions at frequencies below 40 MHz from both north and south polar regions of the planet. The highest frequency radio component is called decametric (DAM) radiation covering in a broad frequency range of a few through 40 MHz. Additionally, Jovian DAM radiation is partially controlled by the Jovian moon Io, thereby being called Io-related DAM (Io-DAM) emissions. The Io-DAM emissions, including millisecond-varying bursts called short-bursts or S-bursts, can be shown at narrow Io phases around 90º and 240º in Figure 9. The Io phase is an orbital angle between the observer and Io from superior conjunction.

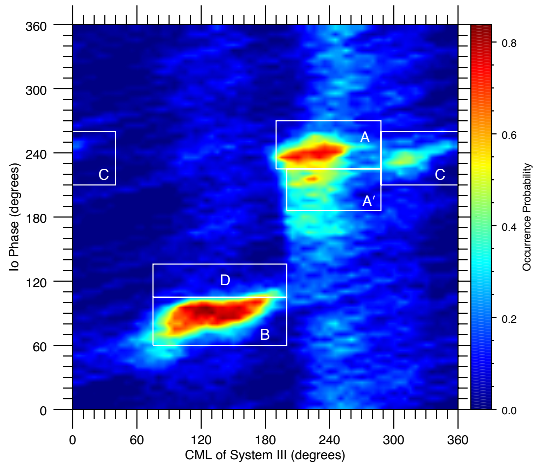

Fig. 9. Occurrence probability map based on 13 years of observation from NDA (Leblanc et al., 1993, and references therein).

Because the ground-based radio reception is sensitive down to 10 MHz, there are several long-baseline interferometer studies for Jovian S-bursts in understanding the radio beaming structures with thickness of beaming.

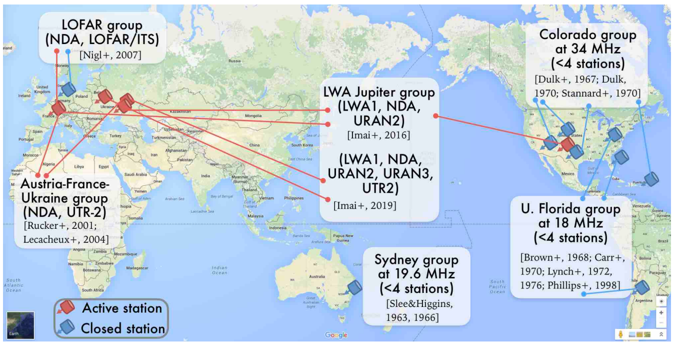

Fig. 10. Global studies on the coordinated Jovian S-bursts with multiple radio stations.

According to the previous studies summarized in Figure 10, the minimum thickness of the S-burst is estimated at least larger than a 2.75” east-west size (Imai et al., 2016, 2019) and a 1.8” north-south size (Lynch et al., 1976) using several radio telescopes. However, the length of the baseline in a usable pair on the ground is physically limited and the U-V coverage is biased due to a sparce low-frequency radio telescope network. In estimating the lower limit of the S-burst thickness, we propose to use KOSEN-1 satellite to coordinate with the ground-based radio telescopes, including LWA1. This approach would be beneficial to expand the length of the baseline up to the dimension of Earth and the wide range of U-V coverage at a short time.

KOSEN-1 satellite is equipped with a software-defined radio (SDR) receiver that can monitor the electric fields of the waves around 20 MHz by means of a 6.6-m long dipole antenna. The SDR receiver can provide both waveforms and spectra in a 2-MHz bandwidth, while the timing of the records is synchronized with the GPS 1 Pulse-Per-Second. The typical observation modes are summarized in Table 1. Depending upon the available telemetry, the operation modes are selected.

Table 1. KOSEN-1 SDR receiver operations for Jovian S-bursts.

Spectrum	Temporal resolution (ms)	Spectral resolution (kHz)	Observation Duration (ms)
Minimum mode	1000	8	1000
Normal mode	5	128	500
Waveform	I/Q signals	Sample rate	
Normal mode	Yes	2.048 MSPS	10

We plan to observe Io-DAM S-burst events with KOSEN-1 and ground-based radio telescopes. As following by Imai et al. (2016, 2019), our approach to estimate the thickness of the S-bursts is, at first, to make the dynamic spectra of the concurrent Jovian S-bursts from KOSEN-1 and the ground-radio telescope, respectively. Next, we calculate the time difference of the S-burst arrivals between KOSEN-1 and the ground-based radio telescope. This time difference includes the useful information to determine whether Jovian S-burst forms as (1) flashlight-like or (2) beacon-like beaming illustrated in Figure 11.

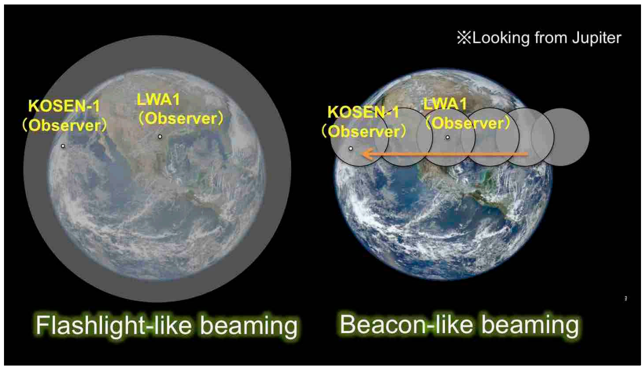

Fig. 11. Candidates of Jovian radio beaming models (adapted from Imai et al., 2016).

Because the S-bursts appear only in a specific configuration of Jupiter and Io (Figure 9), we assume that the radio sources are concentrated along a magnetic field line in a narrow region. Model 1 offers that the radio source emits over large solid angles (larger than the dimension of Earth), while Model 2 provides that the radio source emanates over small solid angles being enough to travel from the edge of the planet to another edge. Also, the rotation of the beaming is synchronized with Jupiter and Io. We can describe the time difference of the arrivals from Model 1 (τ_1) and Model 2 (τ_2) as follows:

$$\tau_1 = \tau_{prop} + C, \quad (1)$$

$$\tau_2 = \tau_{prop} + \tau_{rot} + C, \quad (2)$$

where C is the offset of the constant time, τ_{prop} is the propagation differential time between two observers, and τ_{rot} is the rotation lag time related to the motion of Jupiter and Io.

If the observation fits with Model 1, the baseline between two observers provides the minimum thickness of the S-burst. For a pair of KOSEN-1 satellite and the ground-based radio telescope, this baseline tends to vary from 9,000 through 13,000 km, which corresponds to the angular resolution of about 3-4”. If Model 2 is more favorable than Model 1 for the observation, the above angular resolution is the upper limit of the thickness of the S-burst.

6. Ground stations

The earth stations of the KOSEN-1 satellite consist of six stations. This is because setting up earth stations over a wide area in terms of longitude and latitude allows for the completion of received data and flexible operation of control commands. Figures 12, 13, and 14 show an example of the earth station at the Nankoku Manufacturing Support Center in Nankoku City, Kochi Prefecture, which is capable of controlling the KOSEN-1 satellite that passes over the city four times a day. Beacon radio waves and downlink data from the KOSEN-1 satellite are automatically received, including antenna tracking, and can be scheduled for unattended operation.

Fig. 12. The building where the earth station of the KOSEN-1 satellite is located.

Fig. 13. Antenna system for tracking the KOSEN-1 satellite.

Fig. 14. Radio system receiving the radio signals from KOSEN-1 satellite and sending control commands.

7. Toward the initial operation

We have succeeded in receiving the beacon signal from the KOSEN-1 satellite on the first pass after its launch. Figure 15 shows the decoded Morse code from the satellite that was first received at the earth station in Nankoku City, Kochi Prefecture, 24 minutes after the satellite was released.

Currently, various tests are being conducted to prepare the satellite for initial operation. In particular, the satellite is being checked to see if it can accept control commands from the earth station, and what kind of attitude it has. Figure 16 shows the first successful downlink of a medium resolution color image taken by one of the two cameras on board the KOSEN-1 satellite at 09:55 JST on January 2, 2022.

Fig. 15. The first Morse code of the beacon signal from the KOSEN-1 satellite.

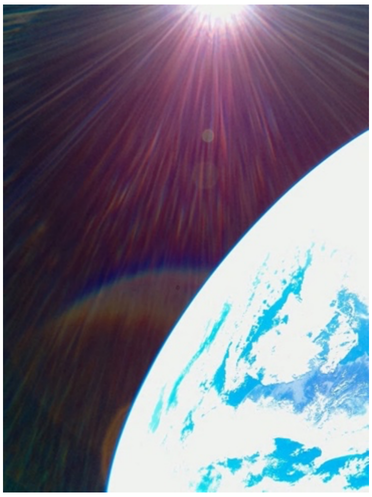

Fig. 16. The first color image taken by the KOSEN-1 satellite.

8. Conclusion

KOSEN-1 satellite includes the development of many innovative elemental technologies required for the next generation of CubeSats. In addition, as a development method, KOSEN-1 took a new distributed development approach in which many organizations participate, fully using the Internet. The technology will be inherited by KOSEN-2, which has been selected as the satellite for JAXA's Innovative Satellite Technology Demonstration-3 Program. And also, we would like to open our technology so that it can be used by many organizations.

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