Development and testing methods of the Attitude Determination and Control System for the astronomical 6U CubeSat VERTECS

Jose Rodrigo Cordova-Alarcon, Akihiro Ikeda, Wenceslao Bejarano-Torres, Kei Sano
Kyushu Institute of Technology
Kitakyushu City, Japan
cordova.rodrigo207@mail.kyutech.jp

Takao Nakagawa, Hayato Tanaka
JAXA Institute of Space and Astronautical Science
Sagamihara City, Japan
nakagawa@ir.isas.jaxa.jp

Satoshi Ikari
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan
ikari@space.t.u-tokyo.ac.jp

Ichiro Jikuya
Kanazawa University
Kanazawa City, Japan
jikuya@se.kanazawa-u.ac.jp

Keiichi Hirako
Japan Aerospace Exploration Agency JAXA
Tokyo, Japan
hirako.keiichi@jaxa.jp

Yoichi Yatsu
Tokyo Institute of Technology
Tokyo, Japan
yatsu@hp.phys.titech.ac.jp

ABSTRACT

VERTECS (Visible Extragalactic background RadiaTion Exploration by CubeSat) is a 6U CubeSat conceived to elucidate the star-formation history along the evolution of the universe by conducting several observations of the visible extragalactic background light (EBL) using a 3U size telescope mounted on the CubeSat. The observation strategy is done by capturing four images of the extragalactic background with a 60-second exposure time, shifting the observed field four times by 3° increments to cover a 6°×6° field of view, and stacking the acquired images afterward to perform photometry in the four bands in the ground. The satellite is designed to operate the telescope payload in a sun-synchronous orbit at an altitude of 500 km and 8:00 ~10:00hrs local time of descending node to observe the EBL on the eclipse phase to avoid stray light from the Sun and Earth. Such an observation strategy requires a pointing stability of 10 arcsec (1 sigma) over 1 minute and alignment of the deployable solar panels to the Sun during nominal operations to optimize the power generation capacity. To meet these pointing requirements, the attitude determination and control system (ADCS) includes a set of 3 reaction wheels and a star tracker for precise pointing maneuvers. This work describes the development and testing strategies to verify the pointing requirements of the VERTECS ADCS and the observation strategy. The stability and mission feasibility analysis are conducted through numerical and processor-in-the-loop simulations, where the observation method and sun-tracking mode are simulated along one orbit. Through our table-sat setup and ground station equipment, we verify the nominal and observation modes by operating the ADCS in in-orbit operation conditions. Our target is to verify the pointing maneuvers through hardware-in-the-loop simulation methods in a simulated space environment on the ground with our EM and FM models. The FM model will be completed by the end of the fiscal year in 2024 and launched by FY 2025.

INTRODUCTION

Traditionally, Earth observation missions have relied on satellites with heavy, expensive, and complex payloads. However, the miniaturization of electronics, advancements in electric power systems, availability of off-the-shelf components, and reduced launch costs have made CubeSats increasingly popular. These small satellites are now widely used not only for Earth observation but also for various Earth and interplanetary missions[1,2]. CubeSats feature a standardized size of 100x100x100mm and a weight of 1.33kg, known as a 1U CubeSat unit. Developed by California Polytechnic State University and Stanford University, the CubeSat standard supports the development of missions in various form factors based on the 1U size, such as 2U, 3U, 6U, and 12U. This standardization offers significant advantages in terms of cost and development time. CubeSats are far more affordable to build and launch compared to traditional satellites, making them accessible to universities, research institutions, and small companies. The use of off-the-shelf components and a modular design reduces both the complexity and duration of the development process[3].

With the growing popularity of CubeSat missions to perform a wide variety of tasks, there has been an increasing demand for high accuracy pointing capabilities. As a result, attitude control systems (ACS) have become essential for meeting mission objectives[4]. To ensure the successful implementation of an attitude determination and control system (ADCS), both numerical simulations and experimental tests are critical components of the CubeSat development process[5]. Laboratory simulation of a spacecraft's attitude dynamics and kinematics has led to the creation of various testbeds, including air-bearings, robotic manipulators, piñata rigs, gimbals, and sub-orbital systems. Among these, air-bearing platforms are particularly popular and cost-effective, making them accessible to academic institutions[5,6].

The objective of this paper is to describe the design, system architecture, assembly and test plan of the ADCS of VERTECS, a 6U CubeSat developed in Kyushu Institute of Technology in collaboration with JAXA Institute of Space and Astronautical Science, Japan. VERTECS will carry out a series of observations of the extragalactic background with a 60-second exposure time, shifting the observed field four times by 3° increments to cover a 6°×6° field of view, and stacking the acquired images afterward to perform photometry in the four bands in the ground[7]. Such observation campaigns shall be done by keeping an attitude stability of 10” (1σ)/min. To meet this attitude requirement, a high precision ADCS unit shall be used and integrated in the 3U satellite BUS.

To ensure the attitude stability of VERTECS during in-orbit operations and meet pointing requirements for observation missions, several test methods are proposed. These include software-in-the-loop simulations to validate the ADCS for attitude maneuvers, processor-in-the-loop tests to validate the ADCS control software, and hardware-in-the-loop tests to verify ADCS performance for detumbling and Sun tracking maneuvers. This paper describes these testing facilities and discusses the preliminary results of the testing campaigns.

This paper is structured as follows: Section 2 provides an overview of the VERTECS satellite. Section 3 details the technical specifications of the VERTECS Attitude Determination and Control System (ADCS). Section 4 describes the testing methods for the ADCS, with preliminary results presented in Section 5. The paper concludes with final remarks in the Conclusions section.

OVERVIEW OF VERTECS SATELLITE

VERTECS consists of a 6U CubeSat platform with dimensions of 100mm x 226mm x 340.5mm and a weight of 8kg. It is integrated in 2 sections: a 3U-size high-resolution telescope payload and the 3U-size BUS system (Fig. 1). The telescope payload is developed to enable the scientific objectives of the VERTECS mission. It consists of a custom-built telescope and camera module, which incorporates a Sony IMX533 monochrome imaging sensor. Communication for transmitting commands to and receiving data from the camera module is facilitated through a gigabit Ethernet connection[8]. The 3U BUS system possess flight heritage from previous satellite projects developed in Kyutech[9] and consists of the following subsystems: a camera controller board (CCB) which operates the telescope payload and facilitate the high-speed downlink operations; a X-band transmitter and S-band transceiver; a high precision ADCS unit; an ADCS adapter board that serves as an interface between the ADCS unit and the BUS; an on-board computer and electric power system. VERTECS is also equipped with deployable solar panels to support power demanding operations of VERTECS such as the observation missions and downlink.

Fig. 1. The VERTECS satellite.

ATTITUDE DETERMINATION AND CONTROL SYSTEM OF VERTECS SATELLITE

The ADCS of VERTECS consists of the following hardware:

- The ADCS adapter board
- The ADCS unit + GPS module
- External sensors

The ADCS adapter board design is based on KITSUNE satellite ADCS[10] and serves as an interface with the satellite BUS and the ADCS unit (Fig. 2). The ADCS adapter board is designed to utilize the hardware resources of the OBC to efficiently control the ADCS unit and retrieve its telemetry data stored in the dedicated Flash memory.

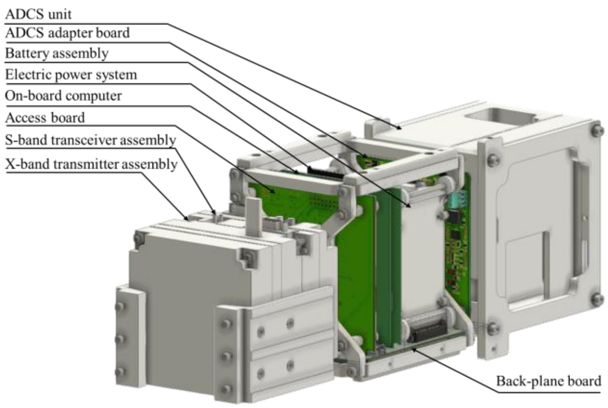

Fig. 2. The VERTECS BUS.

The ADCS unit

The ADCS unit of VERTECS is the Blue Canyon XACT-15[11], a compact and precise attitude control system tailored for small satellites. It provides three-axis stabilization and high-performance pointing accuracy, incorporating integrated star tracker, reaction wheels, magnetic torquers, and a control board. Renowned for its reliability and efficiency, the XACT-15 is well-suited to meet the demanding requirements of VERTECS. Table 1 shows the specifications of the XACT-15.

Table 1: Specifications of the XACT-15

Item	XACT-15 (BCT) + GPS slice
Size, mm	100x100x75
Mass, kg	1.25
Accuracy, deg (1σ)	0.003 (10 arcsec)
Random noise of gyro sensor, rad/s/ (1σ)	1.24e-4
Accuracy of STT cross boresight, deg	0.00167
Accuracy of STT about boresight, deg	0.011
Max output of MTQs, Am^2	0.1
Max torque of RWs, mNm	4
Max momentum of RWs, mNms	15
GPS Receiver	Included
Sun sensor + magnetometer assembly	External x4

The ADCS adapter board

The ADCS adapter board operates the XACT-15 and stores its telemetry in dedicated flash memory (Fig. 3). The board's MCU, a PIC18F67J94, receives commands from the OBC to perform the following tasks:

- Retrieve telemetry from the ADCS MCU and the XACT-15
- Power on/off the XACT-15
- Set the operating modes of the XACT-15
- Calibrate the attitude sensors and actuators via uplink commands
- Retrieve the GPS time and calibrate the main bus time

The ADCS adapter board provides continuous electric power to the XACT-15 though an unregulated power line, regardless of any reset event of the ADCS MCU. Once the ADCS MCU is turned on, the ADCS XACT-15 can be turned on/off by the ADCS MCU through GPIO lines. The telemetry of the ADCS XACT-15 can be saved at every 60 seconds by the ADCS MCU, and a 5Hz sampling rate can be requested via an uplink command.

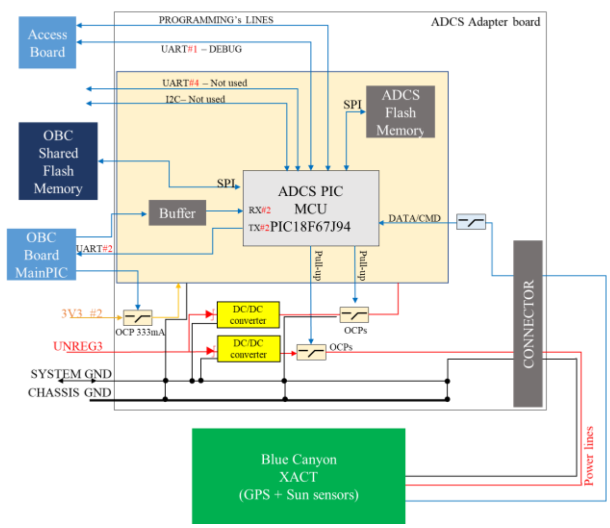

Fig. 3. The VERTECS ADCS system diagram.

The ADCS modes of operation

The VERTECS ADCS requires the following modes of operation to accomplish the mission objectives:

- Detumble
- Sun tracking
- Nadir/target pointing
- Inertial pointing

The detumble mode allows the satellite to reduce its angular rate. It uses the magnetorquers and the magnetometer. It is used when the satellite is released from the launcher and upon request via uplink command.

The Sun tracking mode is the nominal mode of the VERTECS ADCS (Fig. 4), and it allows the satellite to align the deployable solar panels of the satellite towards the Sun for optimal energy generation. As back-up plan, the Sun tracking mode will be set to align the large body mounted panel towards Sun. It will be useful when the deployable panels are not deployed or to warm up the satellite body.

The nadir and target pointing mode are set when the satellite carries out downlink. Those modes of operation are scheduled via uplink at the specified time and duration. As for the target pointing, the geographical coordinates of the location of the ground station are also set. The reference coordinate system can be also set to allow the nadir pointing maneuver while the satellite deployable panels are aligned towards the Sun for optimal power generation.

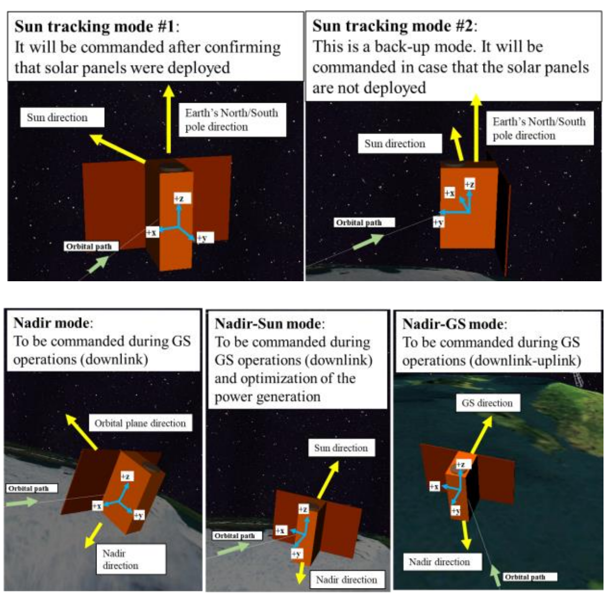

Fig. 4. ADCS modes: Sun tracking and Nadir

The inertial pointing mode is shown in Fig. 5. Similar as Sun-tracking mode, the satellite will conduct 4 small maneuvers during eclipse of 3deg. Each observation lasts 1 minute and attitude stability requirement is 10 arcsec (1σ). After this ADCS mode of operation, the ADCS mode will be set back to Sun-tracking.

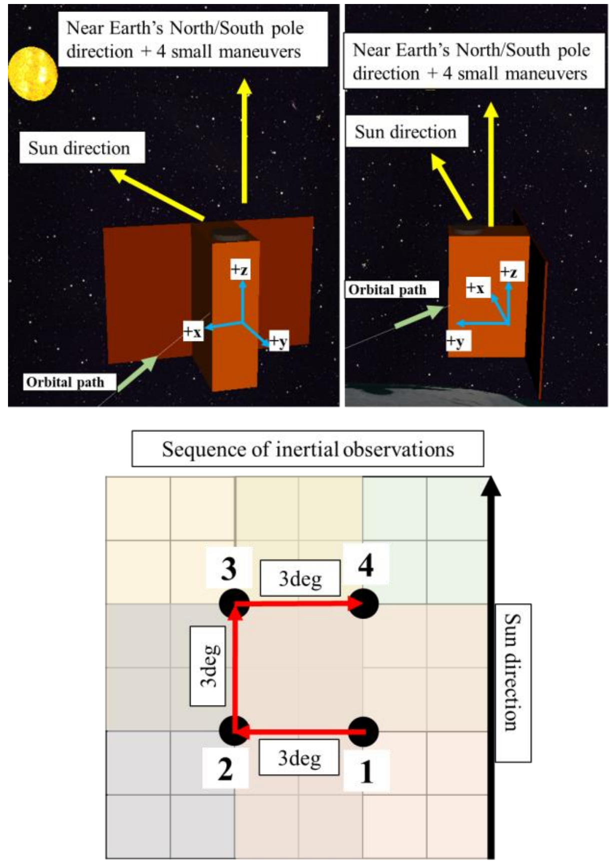

Fig. 5. ADCS modes: Inertial mode and observation strategy

TEST PLAN OF VERTECS ADCS

The testing methods implemented to verify the performance of the ADCS are described in this section to ensure the success of the mission objectives of VERTECS during in-orbit operations.

Software-in-the-loop testbed

Developed by Blue Canyon Technologies, this testbed simulates the attitude and orbit of the VERTECS satellite. It helps to understand the capabilities and limitations of the ADCS XACT-15 during attitude pointing maneuvers, considering VERTECS' physical properties such as mass, moment of inertia, sensor and actuator features, orbital parameters, and attitude control modes. The testbed also allows for estimating the duration of each pointing mode, especially for the observation operations. Developed to be run in MATLAB, it includes the following modules:

- Satellite dynamics
- Orbital dynamics
- Attitude dynamics and kinematics

- Environmental attitude disturbances: atmospheric drag, Earth's gravitational disturbance, and residual magnetic field
- XACT-15 ADCS software

Figure 6 shows the configuration of the software-in-the-loop testbed.

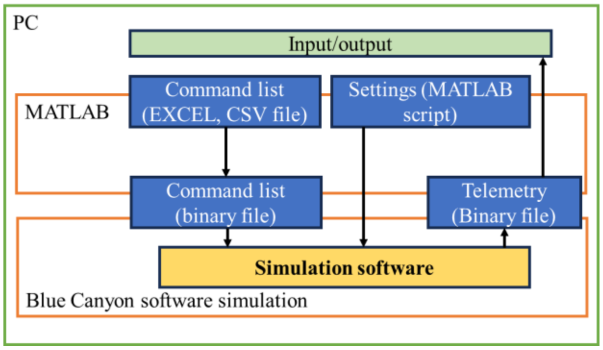

Fig. 6. Software-in-the-loop simulation

Processor-in-the-loop testbed

This testbed is developed to evaluate the performance of the XACT-15 attitude control algorithms and its interface with the satellite BUS when commanding it to conduct the requested pointing maneuvers. It consists of the following elements:

- ADCS unit (XACT-15)
- Real-time dynamics processor (RDP) provided by Blue Canyon Technologies[11]
- ADCS adapter board
- PC (operation and debug of the ADCS adapter board and XACT)

Figure 7 illustrates the block diagram of the processor-in-the-loop testbed configuration. The Real Time Dynamics Processor (RDP) provided by Blue Canyon Technologies features a real-time attitude and orbit dynamics simulator, enabling comprehensive testing of the XACT in realistic mission scenarios. This setup allows for the accurate simulation of various mission conditions, which is crucial for validating the performance and reliability of the ADCS. By integrating the ADCS adapter board and the On-Board Computer (OBC), the testbed can effectively evaluate the software responsible for command and data handling routines. This integration facilitates thorough testing of the communication and control protocols necessary for operating the XACT.

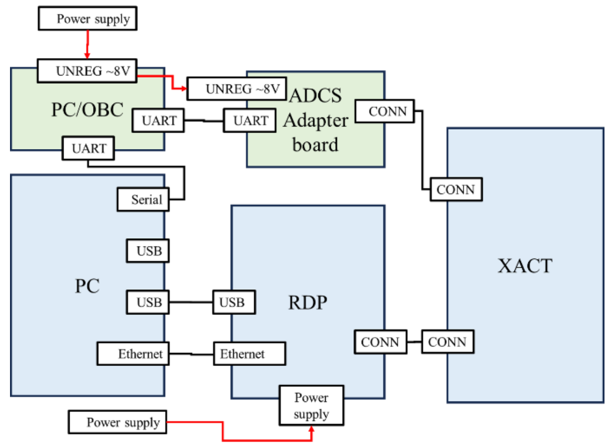

Fig. 7. Processor-in-the-loop simulation

Hardware-in-the-loop testbed

The satellite VERTECS is placed on an air-bearing table which simulates the friction-free condition in space while the satellite is orbiting the Earth. This testbed is useful to verify the direction of attitude control commands and axis definition of sensors and actuators. It consists of the following elements:

- Satellite (EM/FM)
- Air bearing testbed:
  - Air bearing + air compressor
  - Balancing mechanism
  - Control board + IMU
- Helmholtz cage + PC
- Sun simulator

Figure 8 shows the hardware-in-the-loop testbed setup. The air bearing uses a PIglide Hemisphere A-65 from Physik Instruments, with airflow controlled by a Bronkhorst MV-302 regulator and filtered by a Physik Instruments A-801 filter. An in-house designed Helmholtz cage generates a magnetic flux density of +/- 100 uT, controlled by an external power supply and a PC that calculates the necessary current. The platform's center of mass is fine adjusted using an in-house auto-balancing mechanism, which includes four CFRP rods with moving weights driven by stepping motors. This mechanism is controlled by a board with an STM32F446RE microcontroller, which balances the platform based on data from the onboard IMU. The test campaigns using this facility require the setup of the ground station to operate the XACT-15 through the satellite BUS by uplink commands via S-band communications.

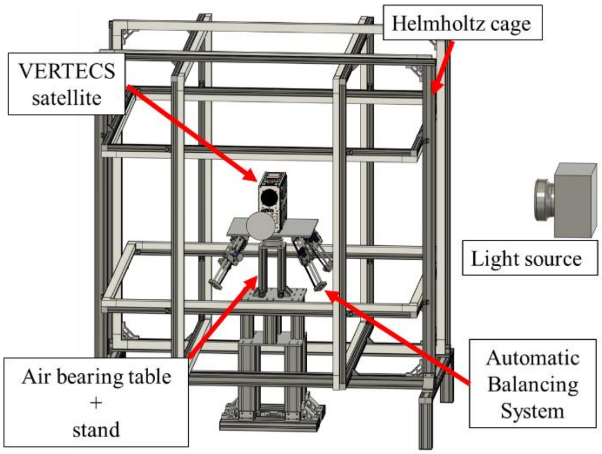

Fig. 8. Processor-in-the-loop simulation

PRELIMINARY RESULTS OF THE ADCS TESTING USING SILS

Figures 9 and 10 shows the simulation results of the ADCS using the software-in-the-loop testbed (Fig. 6). The observation mode was tested by scheduling the ADCS targets as shown in Fig. 5. The command sequence was sent to the ADCS control software as follows: Run simulations by sending a sequence of cmds → Sun tracking → Inertial pointing → 4 small maneuvers → Sun tracking. It is noted that the satellite spins at a constant rate of 1deg/s when the satellite is in eclipse phase and waiting for the Sun vector acquisition. The Nadir mode was tested by sending scheduled command sequence as follows: Sun tracking → Nadir pointing → Sun tracking.

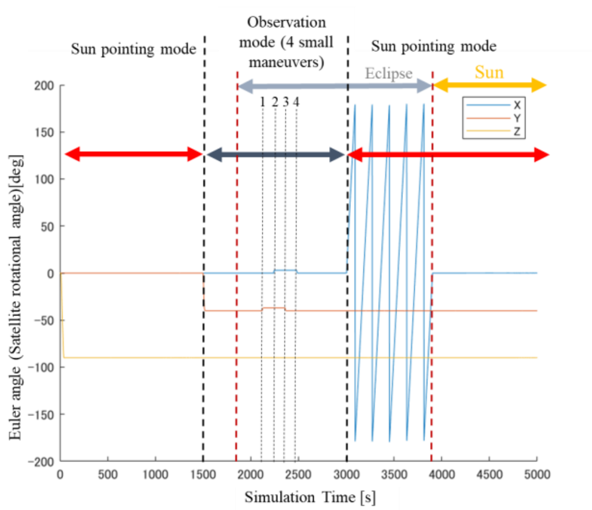

Fig. 9. Simulation of the transition between Sun-tracking and observation mode

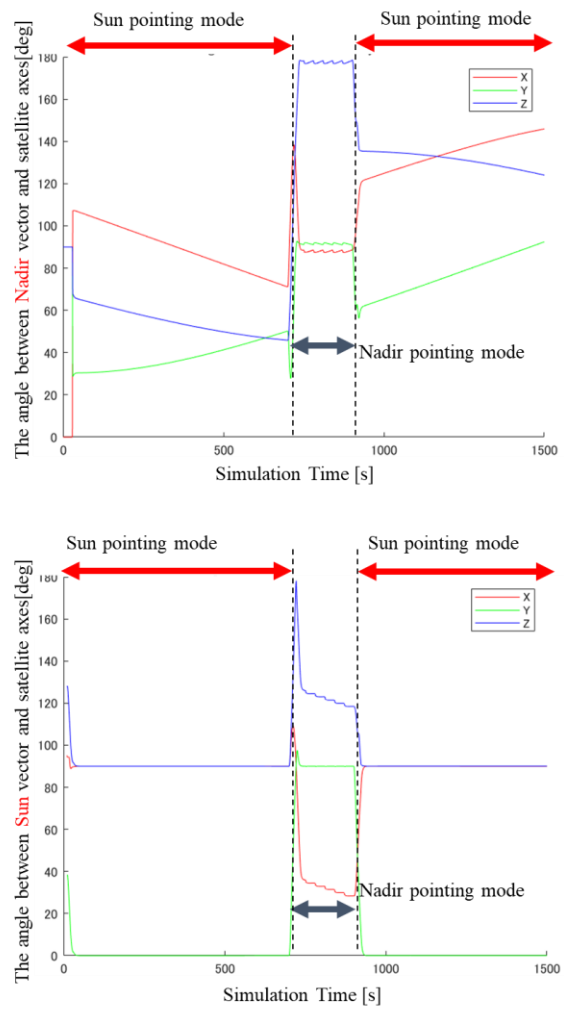

Fig. 10. Simulation of the transition between Sun-tracking and Nadir mode

From these simulation results, we validated the command format and sequence for the XACT-15 to execute pointing maneuvers at the desired times. We also estimated that the satellite can stabilize at the target within 15-30 seconds. This confirms that the XACT-15 is suitable as the ADCS unit for VERTECS and can handle the observation sequence effectively. To ensure the performance of the VERTECS ADCS, comprehensive test campaigns using both processor-in-the-loop and hardware-in-the-loop testbeds are essential. As the development of VERTECS progresses, we will continue to test the electrical interfaces between the XACT-15 and the satellite bus, ensuring seamless integration and operation.

CONCLUSIONS

This paper outlines the test plan for the VERTECS ADCS, involving software-in-the-loop, processor-in-the-loop, and hardware-in-the-loop testing. The software-in-the-loop testbed validates the attitude control maneuvers of VERTECS and estimates their duration, providing a reference for mission operation planning and ADCS XACT-15 control gains adjustment.

The processor-in-the-loop testbed verifies the ADCS XACT-15 control software under simulated attitude and orbital parameters. It also tests the ADCS adapter board's functionality in gathering and processing telemetry and receiving commands from the OBC or a PC via uplink.

As VERTECS prepares for in-orbit operations, these testing platforms will guide mission planning, emergency operations, and the calibration of sensors and actuators via uplink commands. Future work will focus on refining these test procedures, further integrating hardware components, and enhancing the accuracy of the simulations to ensure optimal performance during actual space missions.

References

1. Aragon, B., Ziliani, M.G., Houborg, R. et al.: CubeSats deliver new insights into agricultural water use at daily and 3 m resolutions. Sci Rep 11, 12131, 2021. DOI: https://doi.org/10.1038/s41598-021-91646-w
2. Alandihallaj, M. A., Emami, M. R.: Multiple-payload fractionated spacecraft for earth observation, Acta Astronautica 191 (2022) pp. 451–471. DOI: https://doi.org/10.1016/j.actaastro.2021.11.026
3. Nugent, R., Munakata, R., Chin A., Coelho R., Puig-Suari J., The CubeSat: The Picosatellite Standard for Research and Education, AIAA SPACE 2008. DOI: https://doi.org/10.2514/6.2008-7734
4. King, J. T., Kolbeck, J., Kang, J. S., Sanders, M., Keidar, M.: Performance analysis of nano-sat scale μCAT electric propulsion for 3U CubeSat attitude control, Acta Astronautica, 178 (2021), pp. 722–732. DOI: https://doi.org/10.1016/j.actaastro.2020.10.006
5. Farissi, M. S., Carletta., S., Nascetti, A. and Teofilatto, P.: Implementation and Hardware-In-The-Loop Simulation of a Magnetic Detumbling and Pointing Control Based on Three-Axis Magnetometer Data, Aerospace, 6, 133 (2019). DOI: https://doi.org/10.3390/aerospace6120133
6. Wilde M., Clarka, C. and Romano, M.: Historical survey of kinematic and dynamic spacecraft simulators for laboratory experimentation of on-orbit proximity maneuvers, Progress in Aerospace Sciences, 110, 100552, 2019. DOI: https://doi.org/10.1016/j.paerosci.2019.100552
7. Sano K., et al., Astronomical 6U CubeSat mission VERTECS: Scientific objective and project status, SPIE Astronomical Telescopes + Instrumentation, Yokohama, Japan, 2024.
8. Fielding E., Schulz V. H., Chatara K. A. A., Sano K., Hanazawa A., VERTECS: A COTS-based payload interface board to enable next generation astronomical imaging payloads, SPIE Astronomical Telescopes + Instrumentation, Yokohama, Japan, 2024.
9. Orger, N.C.; Cordova-Alarcon, J.R.; Schulz, V.H.; Dayarathna, T.; Cho, M.; Yamauchi, T.; Masui, H.; Ampadu, O.J.; Kim, S.; Lepcha, P.; et al. KITSUNE: A 6U CubeSat for 5-m Class Imaging, C-Band Radio. In Proceedings of the 33rd International Symposium on Space Technology and Science, Oita (Virtual), Japan, 28 February–4 March 2022.
10. Cordova-Alarcon, J.R.; Jara-Cespedes, A.J.; Withanage, D.C.; Schulz, H.; Orger, N.C.; Kim, S.; Cho, M. Attitude Determination and Control System for the 6U CubeSat KITSUNE. In Proceedings of the 33rd International Symposium on Space Technology and Science, Oita (Virtual), Japan, 28 February–4 March 2022
11. Blue Canyon Technologies, product catalog, https://www.bluecanyontech.com/static/datasheet/BCT-Product-Catalog.pdf [accessed in June 2024]