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Development of a Compact Wide-Field Telescope to be Mounted on VERTECS

Kohji Takimoto, Takao Nakagawa, Aoi Takahashi
Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA)
Sagamihara, Kanagawa 252-5210 Japan
takimoto@ir.isas.jaxa.jp

Kei Sano, Yuto Tome, Hisataka Kawasaki, Shunsuke Nakagawa, Rin Sato
Department of Space Systems Engineering, School of Engineering, Kyushu Institute of Technology
Tobata, Kitakyushu, Fukuoka, 804-0015, Japan
sano.kei288@mail.kyutech.jp

Shuji Matsuura, Yuki Hirose, Akimasa Ojika, Akane Tsumoto, Taiko Iwaki
Department of Physics and Astronomy, School of Science, Kwansei Gakuin University
Sanda, Hyogo, 669-1337, Japan
matsuura.shuji@kwansei.ac.jp

Kohji Tsumura
Department of Natural Sciences, Faculty of Science and Engineering, Tokyo City University
Setagaya, Tokyo, 158-8557, Japan
ktsumura@tcu.ac.jp

ABSTRACT

In recent years, CubeSat projects have initiated plans to conduct astronomical observations by deploying mission payloads. CubeSats present a promising solution for swiftly addressing critical challenges in astrophysics with flexibility. Within CubeSats, where both the bus system and mission payload occupy about half of the volume, there is a necessity to miniaturize mission equipment. The critical factor in astronomical observations, light-gathering ability, is determined not only by the aperture size but, more importantly for diffuse emission, by the optical throughput, i.e., the product of the aperture area and the observing solid angle. Consequently, even with a compact optical system, specializing in wide-field observations enables achieving light-gathering ability equivalent to that of a large-diameter telescope. Therefore, we propose equipping CubeSats with small, wide-field telescopes specialized for observing essential quantities in understanding the cosmic history of star formation, such as extragalactic background Light (EBL), and foreground components like zodiacal light and diffuse galactic light. Radiation from first-generation celestial bodies, which is challenging to detect due to their darkness in the distant universe, is included in the EBL in the visible to near-infrared wavelengths. Hence, wide-field survey observations in the visible and near-infrared play a crucial role in unraveling when, where, and how the first-generation stars were born in the early universe. However, current technology has not enabled the development of CubeSats with mechanisms capable of cooling infrared detectors to temperatures below a few tens of Kelvin. Therefore, we have designed an optical system focusing on the visible EBL. In the astronomical W6U CubeSat mission VERTECS (Visible Extragalactic background RadiaTion Exploration by CubeSat), we are developing a 3U mission payload, comprised of 1U-sized lens optics, camera modules, and baffles each. The lens optical system achieves a high throughput ($> 10^{-6}$ m^2 sr) by covering the entire field of view with 6 degrees by 6 degrees and each pixel with a field of view of 11 arcseconds by 11 arcseconds. The camera module uses a CMOS sensor with high quantum efficiency in visible light, featuring sufficiently low dark current noise (approximately 0.01 electrons per second at 269 K) and readout noise (approximately 2.6 electrons at 24 dB analog gain), compared to the photocurrent generated by the EBL and foreground photon noise. The baffle is designed to attenuate stray light from the Sun and Earth to negligible levels compared to the EBL signal. Additionally, a set of color filters divides the wavelength range of 400 to 800 nm into four bands. In our observation strategy, we capture 60-second exposure images by shifting the field of view by 3 degrees and perform photometry on the stacked images in the four bands. VERTECS project was selected in JAXA-Small Satellite Rush Program

in 2022 and is currently advancing in satellite development, with a scheduled launch in FY2025. Thus far, a significant portion of the mission payload design meets the required specifications, and progress is underway towards the fabrication of the engineering model. In this presentation, we will report on the progress of our optical telescope development, our strategy for visible EBL observations, and our future plans.

INTRODUCTION

Understanding the origins and evolution of the universe requires extensive astronomical observations. To unravel the history of star formation, it is essential to detect faint light from distant celestial objects. CubeSats, with their compact size and flexibility, are gaining attention as a means to conduct space observation missions quickly and economically. The use of CubeSats holds significant potential, especially for wide-field observations. Wide-field observations enable the survey of numerous celestial objects per unit time, providing critical data for studying star formation history and galaxy evolution. Despite their small size, CubeSats can efficiently house mission payloads and bus systems, accommodating the necessary observational instruments. However, achieving miniaturization and high performance within the constraints of limited space and weight is technically challenging, and there have been few examples of CubeSats being used as astronomical satellites.

Recent advancements in CubeSat technology have made it possible to deploy compact, high-performance astronomical observation instruments in space, opening new avenues in the field of astronomy. Notably, the development of precise attitude and orbit control subsystems (AOCS), capable of accurate pointing and orientation control even within a small 1U size, has been pivotal. Additionally, there have been significant advancements in communication systems capable of high-rate data uplinks and downlinks, as well as power systems that ensure continuous power supply. These developments have significantly enhanced the potential for astronomical observation missions using CubeSats. ASTERIA, a 6U CubeSat launched in 2017 by NASA JPL and MIT, demonstrated precise pointing for astrophysical observations.[1] CUTE, launched in 2021 by the University of Colorado Boulder, studies exoplanet atmospheres in the UV spectrum.[2] ZODIAC, a future mission, aims to map interplanetary dust by observing zodiacal light.[3] These missions showcase the advanced capabilities of CubeSats in conducting sophisticated space research.

In astronomical observations, the light-gathering ability is a crucial factor determining the performance of an observational instrument. The light-gathering ability depends on the product of the telescope's aperture size and the observed solid angle. Therefore, even with a compact optical system, specializing in wide-field observations can provide light-gathering capabilities comparable to those of larger telescopes. Wide-field observations are particularly significant for observing extragalactic background light (EBL) and several foreground light sources. EBL offers vital information for probing the star formation activities in the early universe. In the visible to near-infrared wavelength range, EBL includes radiation from the first generation of celestial bodies, making it possible to shed light on the processes of star formation in the early universe. However, current technology has not yet enabled the development of CubeSats with mechanisms capable of cooling infrared detectors to temperatures below a few tens of Kelvin. Therefore, our project focuses on observing visible EBL.

In this study, we aim to observe visible EBL through the W6U CubeSat mission "VERTECS" (Visible Extragalactic background RadiaTion Exploration by CubeSat).[4] This mission involves developing a 3U mission payload equipped with a 1U-sized lens optical system, camera modules, and baffles to achieve wide-field and high-throughput observations.[5] This paper details the design concept of the VERTECS mission, the specifics of the optical system, and the observation strategy. Additionally, we report on the current progress of the development and future prospects of the mission.

VERTECS MISSION DESCRIPTION

Scientific Objectives

The VERTECS mission is driven by several scientific objectives aimed at advancing our understanding of the universe through the study of EBL and other celestial phenomena. These objectives are focused on measuring the intensity and characteristics of EBL, investigating foreground components, and exploring the early universe's star formation history. The primary scientific goal of VERTECS is to accurately measure the intensity of EBL across different wavelengths within the visible spectrum. EBL encompasses all the accumulated light from extragalactic sources over cosmic history, providing crucial information about the formation and evolution of stars and galaxies. By quantifying the EBL intensity, VERTECS aims to:

- Quantify Cosmic Star Formation: Determine the contributions of various astrophysical sources, including stars and galaxies, to the EBL, thus tracing the history of star formation in the universe.
- Investigate Galaxy Evolution: Analyze the integrated light from different epochs, shedding light on how galaxies evolve and how their luminosity changes over time.
- Constrain Dark Matter and Energy Models: EBL measurements can also provide constraints on models of dark matter and dark energy by revealing the distribution and amount of light from the early universe.

In addition to EBL, VERTECS aims to study and account for various foreground components that can affect the accuracy of EBL measurements. These components include:

- Zodiacal Light (ZL): The diffuse light from interplanetary dust scattered by sunlight, which is a significant foreground source in visible observations. Understanding its intensity and distribution helps in accurately isolating the EBL signal.
- Diffuse Galactic Light (DGL): Light scattered by interstellar dust within the Milky Way. Characterizing DGL aids in differentiating between galactic and extragalactic light, ensuring precise EBL measurements.

One of the most intriguing scientific objectives of VERTECS is to explore the cosmic history of star formation by detecting radiation from the first generation of stars (Population III stars) and other early-universe objects. These stars are thought to have formed shortly after the Big Bang and are challenging to detect due to their faintness and the vast distances involved. VERTECS focuses on:

- First-Generation Star Detection: By observing EBL in the visible, VERTECS aims to identify the faint radiation from these primordial stars, providing insights into their properties and the conditions under which they formed.
- Reionization Epoch: Understanding the contribution of early stars and galaxies to the reionization of the universe, a key phase in cosmic history when the first light sources ionized the intergalactic medium.

The VERTECS mission also aims to refine the techniques and methodologies for EBL measurement using CubeSats. This includes developing advanced image processing and data analysis methods to improve the accuracy and reliability of EBL observations. By pioneering these techniques, VERTECS sets a precedent for future missions, contributing to the overall advancement of astrophysical research using small satellite platforms.

Technological Innovations and Design

The VERTECS mission incorporates several technological innovations designed to maximize the capabilities of the CubeSat platform and achieve high-precision astronomical observations despite the constraints of limited size and resources. This mission is implemented using a 6U CubeSat platform, with 3U dedicated to the mission payload and 3U allocated for the bus system, including power, communication, and control subsystems. The payload consists of the following key components:

- Lens Optics: This system is designed to achieve high throughput and wide-field coverage. It consists of high-quality lenses arranged to focus light onto the CMOS sensors.
- Camera Module: Camera module includes a CMOS sensor and associated electronics for image capture and data processing. The module is designed to operate at low temperatures to minimize noise.
- Baffle: The baffle is strategically placed to block stray light and protect the optical system from direct sunlight and reflections from the Earth and the Moon.
- Color Filters: The filters are placed in front of the camera modules to divide the incoming light into four spectral bands, facilitating detailed analysis of the EBL and foreground components.

Figure 1 shows the schematic view of the VERTECS. The Lens optics of VERTECS is meticulously designed to fit within the 1U size constraint while maintaining high efficiency. This system covers a field of view of 6 degrees by 6 degrees and provides a high throughput exceeding 10^{-6} m^2 sr. Achieving such a wide field of view while maintaining high resolution involves the use of high-quality lenses, precisely arranged to focus the incoming light onto the CMOS sensors efficiently. The design focuses on optimizing light-gathering efficiency and

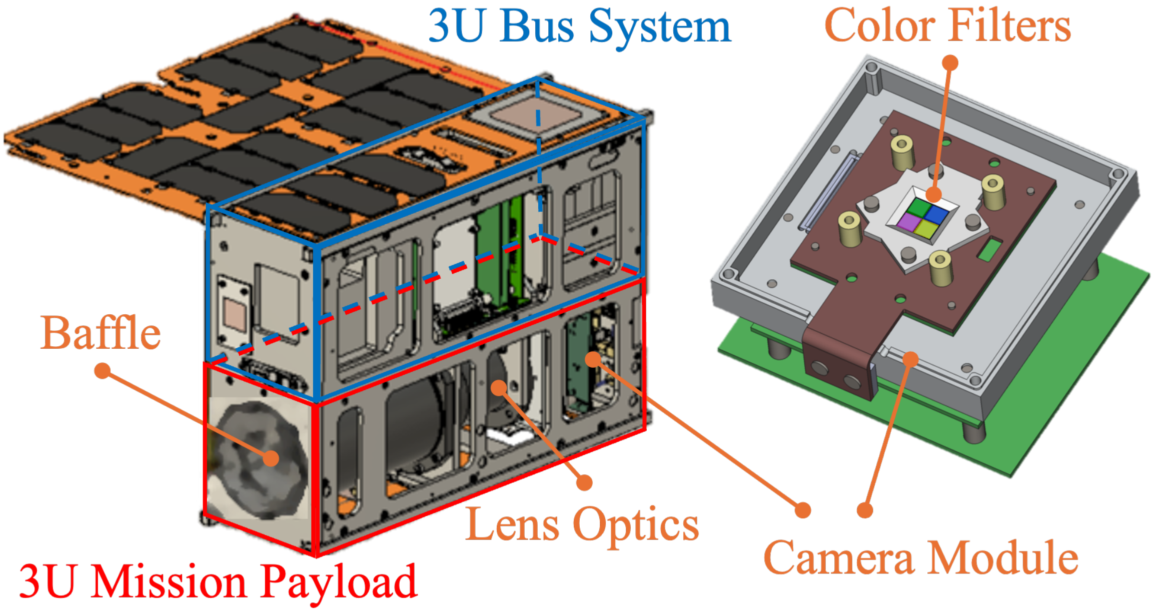

Figure 1: Schematic view of the VERTECS. The internal structure of the baffle is mosaicked due to confidential information.

maintaining image quality across the entire field of view. The camera module utilizes CMOS sensor with high quantum efficiency in the visible spectrum. This sensor is optimized to operate in low-temperature environments, reducing dark current noise to approximately 0.01 electrons per second at 269 K and readout noise to about 2.6 electrons at 24 dB analog gain. These specifications are crucial for accurately measuring the faint signals of EBL. Additionally, the sensor employs passive cooling techniques to minimize thermal noise, ensuring high sensitivity and precision in capturing weak cosmic signals. The VERTECS mission employs an advanced baffle system designed to effectively block stray light from the Sun and Earth, which could otherwise interfere with EBL observations. Stray light can introduce significant noise into the data, making it essential to minimize its impact. The baffle system is engineered to block light entering from specific angles, thereby reducing direct and reflected light contamination. The design of the baffles is informed by optical simulations to determine the optimal shape and placement for maximum efficacy. VERTECS employs a set of color filters to divide the wavelength range of 400 to 800 nm into four distinct bands. This allows for detailed spectral analysis of the EBL across multiple wavelengths. The color filters are positioned in front of the camera modules, directing light corresponding to each filter band to the respective sensors. This arrangement enables the simultaneous collection and analysis of data across different spectral regions, providing comprehensive information about the EBL and other sources.

OBSERVATION STRATEGY

The observation strategy for VERTECS involves capturing 60-second exposure images while shifting the field of view by 3 degrees between each exposure. This approach allows for comprehensive coverage of the target area and enhances the signal-to-noise ratio through image stacking. The key steps in the observation strategy are:

1. Field Selection: Choosing regions of the sky with minimal contamination from bright stars and other known sources.
2. Exposure and Shifting: Capturing a series of 60-second exposures while shifting the field of view by 3 degrees after each exposure. This strategy ensures that any given point in the target area is observed multiple times, improving data quality.
3. Image Stacking and Analysis: Stacking the captured images to enhance the EBL signal

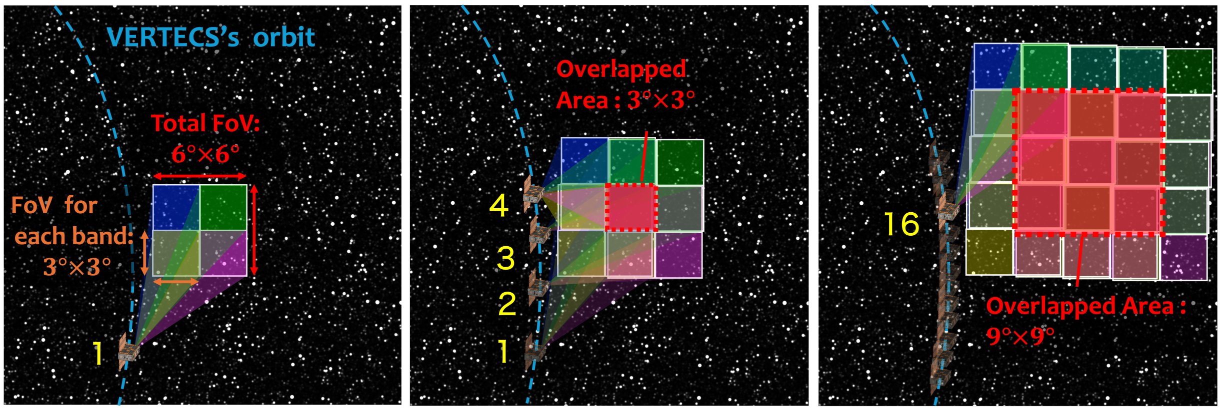

Figure 2: The process of creating the EBL intensity map: (Left) Single imaging observation. (Middle) Four imaging observations during one orbit. (Right) Sixteen imaging observations during four orbits.

and reduce noise. The stacked images are then analyzed in the four spectral bands to extract information about the EBL and other sources.

VERTECS is designed to operate on a sun-synchronous orbit, conducting observations on the nighttime side of Earth. Currently, VERTECS's observation plan involves obtaining wide-field imaging data of $9° \times 9°$ for each observation region. For this plan, a total of 16 imaging observations (four orbit cycles) are necessary (Figure 2).

DEVELOPMENT AND TESTING

The development of the VERTECS mission involves several critical phases. It begins with the design and prototyping stage, where detailed designs of the optical system, camera modules, baffles, and filters are created. During this phase, individual components are prototyped and tested to ensure they meet the required specifications. To develop the telescope for the satellite that we will launch, we need to create a bread board model to finalize component selection and structural design, and an engineering model designed equivalent to the flight model for conducting environmental tests on the ground. We have advanced the design of the telescope to meet the requirements shown in Table 1.

Following this, the integration and testing phase involves assembling the components into the CubeSat platform and conducting comprehensive tests to verify functionality and performance, including thermal vacuum tests, vibration tests, and optical alignment tests. The principal test flow to be carried out by VERTECS is shown in Figure 3.

Table 1: General requirements for the telescope

Lens Optics	**Requirements**
FoV	$6° \times 6°$ ($\phi 8.4°$)
Wavelength	0.4-0.8 μm in quadrants
Total length	$\leq$ 110 mm
PSF	$\phi_{\mathrm{EE90\%}} \leq 10$ μm
Transmittance	$\geq$ 80% at all wavelength bands
Distortion	Less than $\pm 3\%$
Vignetting	At least 90% of the center of FoV in the sensor diagonal.
Lens material	Use radiation-resistant materials and radiation shield glass

Camera Module	**Requirements**
Pixel FoV	< 20"
Wavelength	0.4-0.8 μm
Readout noise	~ 2.6 e$^-$
Dark current	< 0.1 e$^-$/s
Total length	$\leq$ 80 mm

Baffle	**Requirements**
Total length	$\leq$ 120 mm
Baffle aperture diameter	$\leq \phi 100$ mm
Black treatment	Black paint or black plating
Rejection performance	• $G(\theta_{Earth}) \leq 1 \times 10^{-6}$ • $G(\theta_{Moon}) \leq 1 \times 10^{-5}$

Color Filters	**Requirements**
Wavelength	0.4-0.8 μm in quadrants
AOI	$< 15°$ for F/2 optics
Size	~ 6 mm $\times$ 6 mm $\times$ 1 mm
Transmittance	• In-Band: $T > 98\%$ • Out-Band: $T < 0.1\%$

Calibration is the next crucial step, where the optical system and camera modules are calibrated to ensure accurate measurements. This process includes characterizing the response of the sensors to known light sources and adjusting the system to correct any discrepancies. Finally, the launch and deployment phase prepares the CubeSat for launch, coordinating with the launch provider, and ensuring

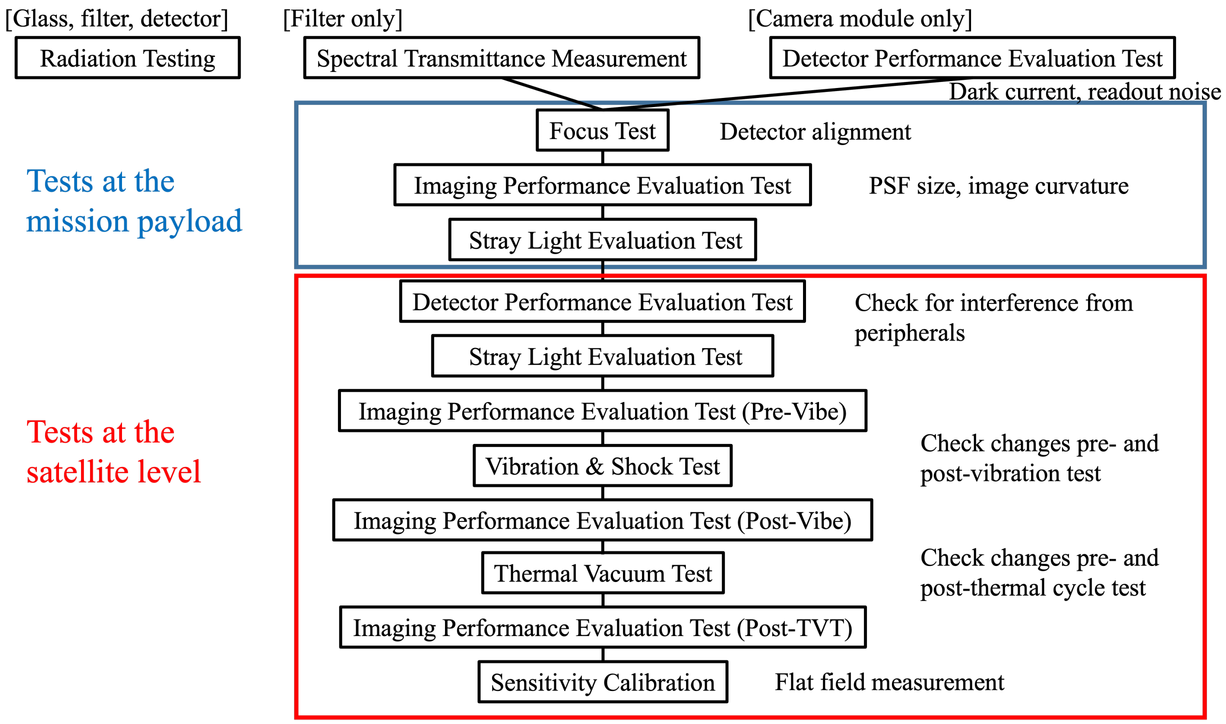

Figure 3: Test flow chart for VERTECS.

the satellite is correctly deployed into its designated orbit.

CURRENT STATUS & FUTURE PLANS

VERTECS project was selected in JAXA-Small Satellite Rush Program in 2022 and is currently advancing in satellite development, with a scheduled launch in early 2025. As of now, the VERTECS mission is in the advanced stages of development. The key achievements include:

- Design Validation: Successfully validating the designs of the optical system, camera modules, and baffles through extensive testing and simulations.
- Prototype Testing: Completing the testing of bread board model components, demonstrating that they meet or exceed the required performance specifications.
- Engineering Model Fabrication: Progressing towards the fabrication of the engineering model, which will be used for final integration and testing before the flight model is built.

Looking ahead, the following milestones are planned:

- Final Integration: Completing the integration of all components into the CubeSat platform and conducting final system-level tests.
- Launch Preparation: Coordinating with the launch provider to prepare for the satellite's deployment, including finalizing the launch schedule and ensuring all logistical arrangements are in place.
- In-Orbit Operations: Once launched, the CubeSat will be monitored and controlled from a ground station. The mission operations will involve executing the observation strategy, collecting data, and transmitting it back to Earth for analysis.
- Data Analysis and Publication: Analyzing the collected data to achieve the scientific objectives of the mission. The results will be published in peer-reviewed journals and shared with the broader scientific community.

CONCLUSION

The VERTECS mission is expected to make significant contributions to our understanding of the universe. By providing precise measurements of the EBL in the visible spectrum, it will shed light on the star formation history and the evolution of cosmic structures. Additionally, the mission's innovative use of CubeSat technology will demonstrate the feasibility of conducting advanced astronomical observations with small satellites, potentially paving the way for future missions with similar objectives.

The VERTECS mission represents a pioneering effort to explore the visible EBL using CubeSat technology. Through a combination of advanced optical systems, high-performance camera modules, and innovative observation strategies, VERTECS aims to achieve groundbreaking results in the field of astrophysics. The mission's development is progressing well, with significant milestones already achieved and future plans firmly in place. As the launch date approaches, the VERTECS team remains committed to ensuring the success of this ambitious and scientifically valuable mission.

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