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METUCUBE: A 3U CUBESAT FOR DISASTER MONITORING AND EARLY WARNING SYSTEMS

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ABSTRACT

This paper presents the design methodology and development experience of METUCube, a 3U CubeSat mission that integrates multispectral and thermal imaging payloads within strict volume and power constraints. The satellite is designed for post-disaster monitoring and early warning applications, with additional capabilities for environmental observation of agricultural areas and water resources. Key challenges include payload integration, power management, thermal regulation, and pointing stability, which were addressed through trade-off analyses and in-house component design. METUCube is planned to operate in a sun-synchronous orbit at approximately 500 km altitude with a mission lifetime of about three years, and the Engineering Model is scheduled for completion by early 2026. The lessons learned from this effort provide valuable guidance for future CubeSat missions requiring compact, multi-payload configurations.

Keywords: METUCube; CubeSat; remote sensing; disaster monitoring; early warning systems

INTRODUCTION

Climate change impacts have amplified the occurrence of extreme weather events, creating unprecedented challenges for disaster response organizations and affected communities [Stephens et al., 2024]. The increasing frequency and severity of natural disasters worldwide necessitate improved monitoring and early warning capabilities. Satellite-based Earth observation systems provide unique advantages for disaster management, offering wide-area coverage and real-time data acquisition capabilities that are unaffected by ground-based infrastructure damage before, during, and after catastrophic events [Le Cozannet et al., 2020].

Traditional satellite systems for these purposes often require significant investment and long development cycles, limiting their accessibility for rapid development and cost-effective disaster response applications. METUCube addresses this need through a dedicated small satellite mission. The satellite is designed to monitor post-disaster situations and investigate near real-time disaster detection using cost-effective CubeSat

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technology. Dual multispectral and thermal infrared imaging systems have proven effective for disaster assessment and environmental monitoring applications, providing critical data for disaster and resource management [Lee et al., 2015; Cruz Ulloa et al., 2024].

The integration of a dual imaging payload within the constrained 3U CubeSat form factor presents an engineering challenge across multiple coupled resources. These include limitations in volume and optical path length, trade-offs between power generation and peak consumption, thermal management constraints, and the need to maintain pointing stability for image quality [Song et al., 2018]. The primary objectives include damage assessment for floods, earthquakes, and wildfires, as well as continuous environmental monitoring of agricultural areas and water bodies to prevent food crises and manage resources efficiently.

The purpose of this study is to present the comprehensive design experience and methodology employed in METUCube development, documenting the approaches and lessons learned that may inform future small satellite development projects with similar technical requirements and constraints.

METHODOLOGY AND DESIGN APPROACH

The development of METUCube follows a systems engineering approach based on Asia-Pacific Space Cooperation Organization (APSCO) standards under the APSCO CubeSat Competition (ACC) project framework. The methodology encompasses design phases, trade-off analyses, and integrated subsystem development aimed at achieving mission objectives within the 3U CubeSat form factor constraints. The approach addresses the engineering challenge of integrating dual imaging payloads (multispectral and thermal infrared imaging systems) within the volume, power, thermal, and pointing stability limitations inherent in small satellite platforms.

The integration of dual imaging capabilities within a 3U CubeSat presents multiple challenges. As mentioned in the Introduction Section, these challenges are extensively studied through the component placement studies, power budget evaluations, thermal modeling, and attitude control assessments that relate system performance to mission requirements.

This methodology section presents the design experience and approach employed in METUCube development, documenting the technical solutions and observations that may be relevant to future small satellite development projects with similar payload configurations and operational requirements. The methodology reflects the educational objectives and capacity-building aspects of the project while maintaining alignment with technical requirements for space mission development.

Project Lifecycle and Development Phases

The METUCube project follows the development sequence defined by APSCO-ACC and it establishes the design maturity through defined review phases. This approach provides structured oversight and ensures requirement traceability from mission objectives through subsystem implementation. The development phases completed to date include four key milestones that address design evolution and requirement verification. The project lifecycle encompasses the following phases performed so far:

Mission Proposal (MP): This initial phase established METUCube's mission objectives through comprehensive stakeholder analysis and feasibility assessment. The proposal defined disaster monitoring as the primary objective, with secondary objectives focusing on early warning system investigation. Key performance requirements were established, including spatial resolution targets of better than 25 meters, swath width exceeding 30 kilometers, and maximum temporal resolution of three days. The phase included mission concept development, operational procedures definition, and preliminary cost estimation to demonstrate feasibility within the allocated budget constraints.

Preliminary Design Review (PDR): The PDR phase evaluated subsystem architectures through trade-off studies and preliminary analyses. Key accomplishments included establishing the dual-band communication architecture (S-band for payload data, UHF for telemetry), selecting the COTS ISIS Onboard Computer with the back up processing unit Raspberry Pi 5, and developing preliminary interface specifications. This review validated technical feasibility and requirement coverage across all subsystems, establishing the foundation for detailed design development.

Critical Design Review (CDR):

The CDR phase validated that all subsystem designs meet requirements and are ready for production. This phase confirmed system integration feasibility and demonstrated readiness for engineering model development. Key accomplishments included finalizing dual imaging payload integration within the 3U form factor. The multispectral and thermal imaging systems were confirmed to operate within design constraints. ADCS design was validated through simulation, confirming adequate pointing accuracy for mission requirements. Communication system verification confirmed the dual-band architecture performance. Power analysis validated energy balance during critical operational periods. Structural analysis demonstrated compliance with launch environment requirements through modeling that confirmed adequate structural margins. CDR established manufacturing readiness through detailed specifications, vendor qualification, and interface documentation. This verification process confirmed technical readiness for engineering model development scheduled for October 2025 completion.

Detailed Design Report (DDR): The DDR phase completed the evolution of preliminary design concepts and detailed implementation plans. This phase emphasized interface control and management following systematic engineering principles, with interface specifications developed to define physical, electrical, mechanical, and data characteristics across all subsystem boundaries. Key accomplishments included finalizing detailed system and subsystem level specifications that define exact functionality, performance parameters, and operational constraints for each component, while completing interface specifications for subsystem interactions to ensure coherent functionality and seamless integration between all system elements. The DDR validated the distributed onboard data handling architecture comprising three processing units: the ISIS On-Board Computer (OBC) serving as primary flight computer, and Raspberry Pi 5 functioning as the primary payload computer for image processing algorithms. Communication subsystem architecture finalized around the Cubecom STXG2 transmitter and Gauss UHF Radio. The ADCS subsystem specification was completed with CubeADCS Gen1 module selection.

Current Phase: METUCube now established foundation for engineering model development scheduled for completion by no later than first quarter of 2026, and the changes in the project between the CDR expressed in the Section Design Philosophy and Component Selection Strategy.

Design Philosophy and Component Selection Strategy

The design strategy for METUCube emphasizes the development and integration of self-developed subsystems wherever feasible. While commercial off-the-shelf (COTS) components are widely adopted in CubeSat missions due to their shorter development timelines and reduced costs [Di Roberto et al., 2023], reliance on COTS solutions limited METUCube's design flexibility and system-level customization. In contrast, METUCube project pursues the maximum the use of custom-developed hardware and software, and using open-source projects and university-driven developments to increase transparency, adaptability, and create educational value for future missions. Therefore, this mission contributes institutional know-how and builds local capacity for sustainable satellite development. Many students across multiple engineering disciplines gain hands-on experience in a space project and satellite subsystem design, integration, and testing.

The custom-development based approach encompasses several critical subsystems. The Electrical Power System (EPS) is being developed internally to meet specified mission requirements and provide hands-on learning opportunities for the engineering student team. Similarly, the Onboard Computer (OBC) utilizes a custom-developed solution based on the Raspberry Pi CM5 module integrated with NASA's Core Flight System (cFS) framework, providing both cost-effectiveness and educational value. The communication subsystem leverages the open-source LibreSpace SatNOGS COMMS board, aligning with the mission's commitment to open-source solutions. Additionally, the UHF antenna and solar panel assembly are designed and manufactured in-house, with only solar cells being purchased.

However, risk mitigation strategies are implemented for critical subsystems where mission success could be compromised. For the Attitude Determination and Control System (ADCS), a hybrid approach is adopted. The primary design is based on a custom-developed solution that includes in-house development of the sun sensor, magnetorquer, and ADCS computer, while critical components such as magnetometer, GNSS receiver, gyroscope, and reaction wheels are procured as COTS components. A backup COTS ADCS subsystem from

TensorTech has been identified as a contingency option to ensure mission success if the primary custom solution fails to meet performance requirements. For the S-band antenna, a COTS solution from Clyde Space is selected to ensure reliable high-data-rate communications. This balanced approach between in-house innovation and selective COTS adoption ensures that METUCube remains both educationally valuable and technically achievable within the mission timeline, while maintaining acceptable risk levels for mission-critical functions.

Orbital Analysis and Trade-offs

Comprehensive orbital analysis was conducted to compare a mid-inclination orbit (45°) with a Sun-Synchronous Orbit (SSO). The trade study considered both ground coverage performance and power-generation efficiency. Results of the coverage analysis is as follows, total coverage time on points of interest of the 45° inclined orbit for 30 days is around 10421.5 minutes, 625300 seconds. Whereas the total coverage time on points of interest of the SSO for 30 days is around 5352 minutes, 321000 seconds. The result of the coverage analysis dictates that the total coverage time of the SSO is almost half of the 45° inclination orbit.

Ultimately, a 500 km SSO was selected as the baseline orbit. The choice was influenced by the power budget, since the SSO configuration maintains a consistently favorable solar incidence angle, allowing the solar arrays to operate at greater than 85% of their maximum capacity, whereas in a 45° inclined orbit, seasonal and geometric variations could reduce efficiency to below 40% under worst-case conditions. This stability in power availability is critical for supporting continuous imaging operations and ensuring sufficient battery recharging margins.

In Figure 1, the ground track of METUCube is shown. The pink line represents the first day of the orbital projection, while the yellow lines represent the subsequent two days. The blue region covering Türkiye and the surrounding areas indicates the region where METUCube can communicate with the ground station located in Ankara. And Figure 2 shows the coverage pattern of METUCube's multispectral camera over a 1-day orbital projection.

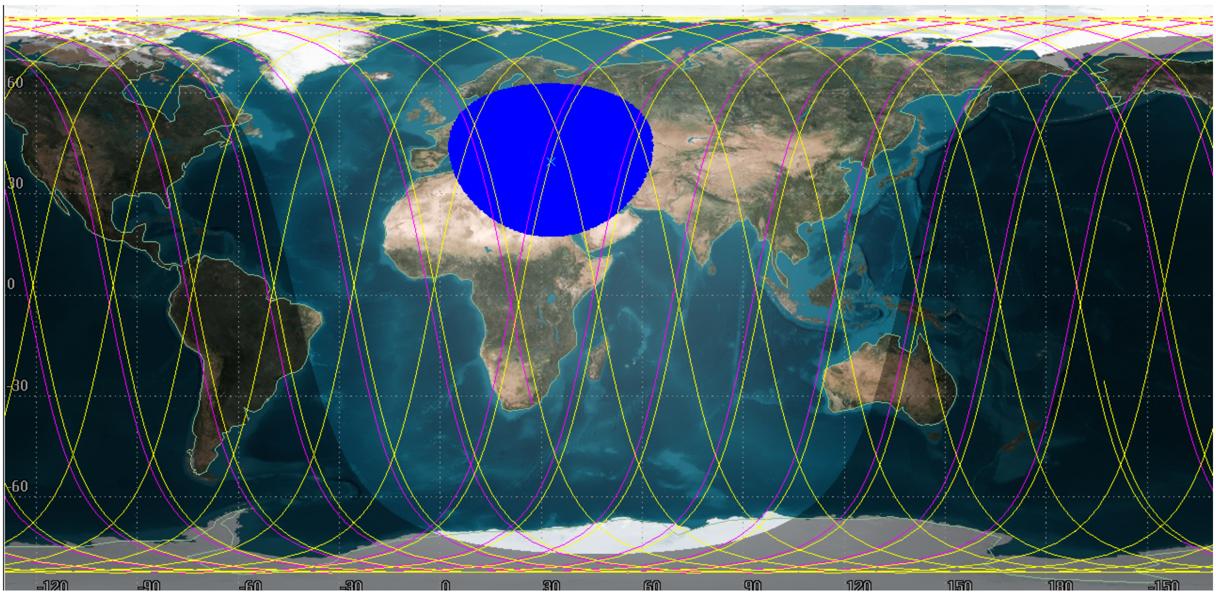

Figure 1: Ground track of METUCube over 3 days. The pink line represents the first day of orbital passes, yellow line indicates the subsequent two days.

Integrated Subsystem Design

Every subsystem went through phases of thorough design and analysis. To confirm adherence to launch loads and frequency specifications, Finite Element Method (FEM) is used in structural analysis with ANSYS software. Thermal analysis validated the sufficiency of passive thermal control using both ESATAN software and MATLAB-based 6-node modeling. Detailed orbital modeling was incorporated into the power system design to ensure energy balance throughout all operational modes.

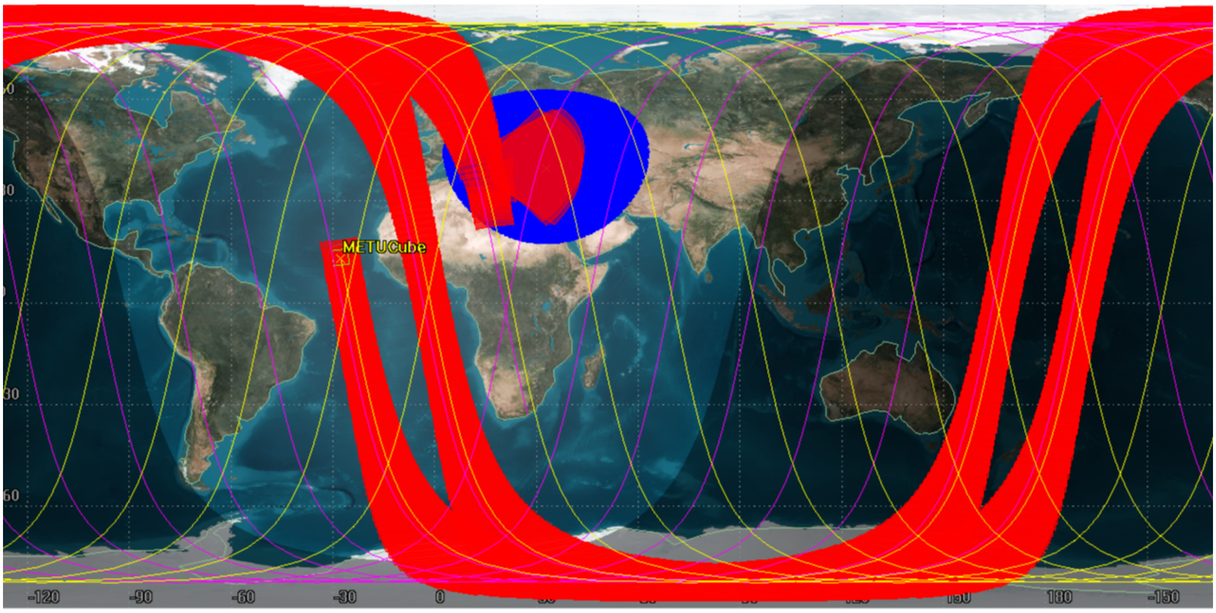

Figure 2: Multispectral camera's coverage map of METUCube indicated with the color red over approximately 1 day.

PRELIMINARY RESULTS

The CDR phase has yielded comprehensive design solutions across all subsystems, demonstrating technical feasibility within CubeSat constraints. The design verification process and validation results demonstrate the effectiveness of the employed methodology and reveal insights applicable to similar development efforts.

System Architecture and Integration Design

The METUCube system architecture demonstrates successful integration of multispectral and thermal imaging payloads within the restrictive 3U CubeSat form factor constraints. The overall system design employs a modular approach where the multispectral imager and thermal infrared camera are strategically positioned to maximize structural efficiency and maintaining thermal management. The platform architecture consists of seven primary subsystems: the onboard computer serving as the central processing unit, the attitude determination and control system providing three-axis stabilization, dual-band communication systems utilizing both S-band and UHF links for high-rate payload data transmission and telemetry operations, the electrical power system featuring deployable solar panels and lithium-polymer battery storage, the structural framework manufactured from aluminum 6061. Integration of these subsystems has been achieved through careful component placement optimization and standardized PC104 interfaces, enabling efficient data flow between payload computer and subsystems. The architecture of METUCube addresses the primary design challenge of accommodating two distinct imaging payloads and ensuring adequate power generation through the implementation of deployable solar panel mechanisms that extend the photovoltaic surface area beyond the 3U surface.

Mass and Power Budget Validation

The internal view of the METUCube is shown in Figure 3. The integrated system design hass a mass of approximately 2.5 kg. The power system design incorporates 19 solar cells (5 body-mounted, 14 on deployable panels) and a 47.5 Wh lithium-polymer battery, ensuring continuous operation throughout eclipse periods with a conservative depth of discharge of approximately 8%. In nominal mode, in which the satellite maintains its attitude as Earth pointing and transmits telemetry to the ground at regular intervals, approximately 150 W-min more energy is generated per orbit than is consumed. In addition, approximately 140 W-min of excess energy is generated per orbit during imaging, and about 110 W-min per orbit during image downlink. Table 1 shows the operating percentages of the equipment in different modes.

For illustrative purposes, a one-day test was conducted. In the test, an image is captured during the 5th orbit

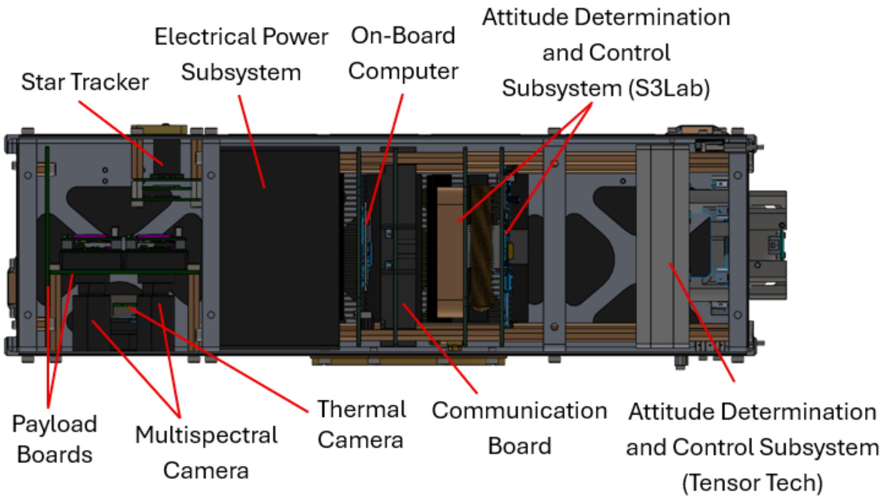

Figure 3: METUCube 3U CubeSat internal component layout and subsystem integration.

Table 1: Subsystem power consumption in different modes

	Nominal	Camera	Communication
OBC	100	100	100
MS Camera	0	1.6	0
Thermal Camera	0	1.6	0
ADCS	100	100	100
S-Band Transmitter	0	0	15
UHF Transmitter	10	10	10
UHF Receiver	100	100	100
EPS	100	100	100

and downlink-ed during the 7th orbit. The corresponding power graphs are as follows. Figure 4 illustrates the power generated by the satellite (resetting at the start of each orbit for clarity) and the battery status over a 24-hour period. Figure 5 depicts the power consumed by the equipment that is active at the corresponding times. Figure 6 shows the instantaneous total consumption and generated power.

Payload Performance Verification

Payload has progressed through a structured design and selection process. Figure 7 shows a four-camera configuration was adopted to cover distinct spectral bands, with focal length calculated from the resolution requirement and suitable lenses chosen accordingly. Spectral filters were selected for the required wavelengths based on the mission's disaster-monitoring objectives, while camera selection was guided by noise characteristics, exposure time, and quantum efficiency analyses. The identified cameras, lenses, and filters are now being procured. In parallel, image-processing algorithms are being developed to merge data from the four spectral bands and extract meaningful information, ensuring that the payload can deliver the targeted spatial, spectral, and temporal performance.

Sun Sensor Design

The proposed sun sensor system integrates five photo-diodes, a precision temperature sensor, and a low-power analog-to-digital converter (ADC) to achieve accurate light intensity measurement with temperature compensation, as shown in Figure 8.

Experimental Setup and Results: The sun sensor was tested using a controlled indoor setup with a halogen lamp as the light source to simulate solar illumination. The sensor was mounted on a protractor to enable precise adjustment of the incident light angle, with output signals acquired using an Arduino board for data logging.

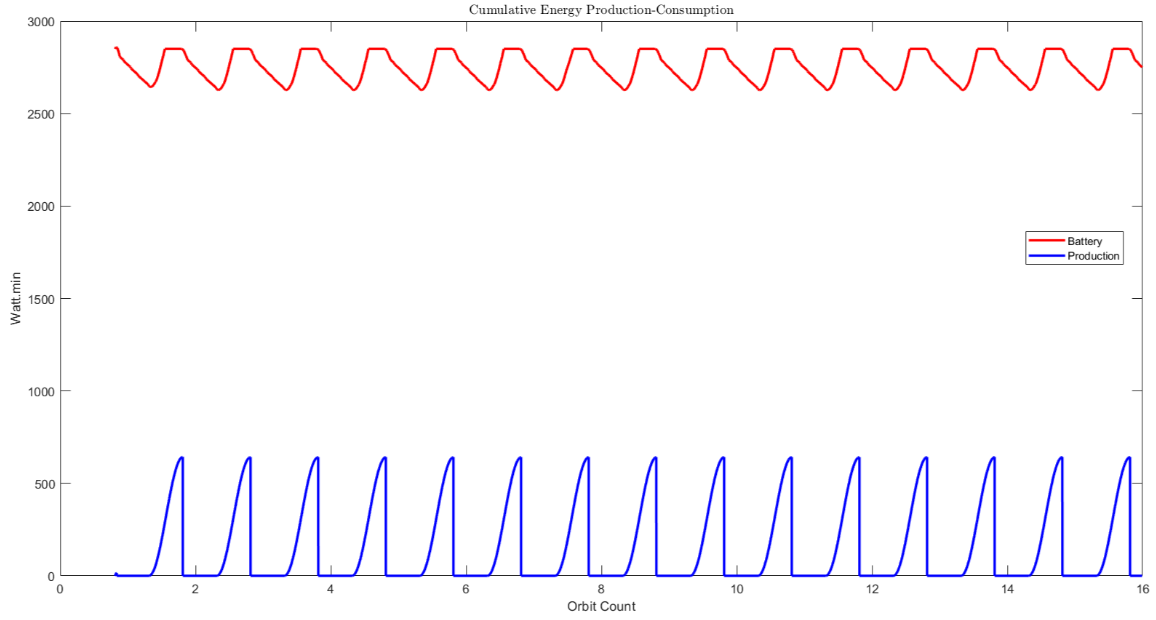

Figure 4: Cumulative energy production-consumption of METUCube

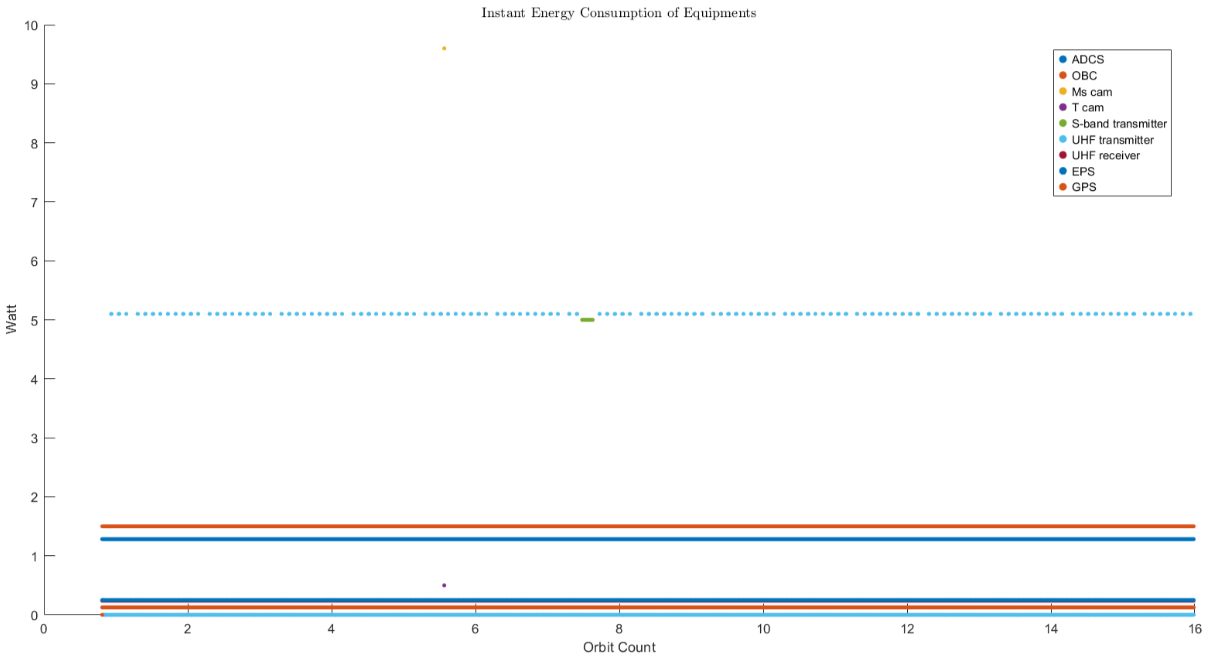

Figure 5: Instant energy consumption of equipment in the METUCube.

In the first experiment, the sensor was rotated in the YZ plane from -120° to 120° in 15° increments. The voltage values from photodiode channels CH1–CH5 were recorded at each angle. Results showed a distribution consistent with the physical orientation of the photodiodes, with the centrally positioned photodiode (CH5) reaching maximum voltage at 0°, confirming proper sensor geometry operation.

In the second experiment, photodiode outputs were processed by an algorithm to calculate unit vectors and derive angle values. The setup was rotated from -120° to $+120^\circ$ in 30° increments, with calculated angles compared to true values. The experiment was repeated at three distances (35 cm, 65 cm, and 90 cm) to examine measurement consistency and errors.

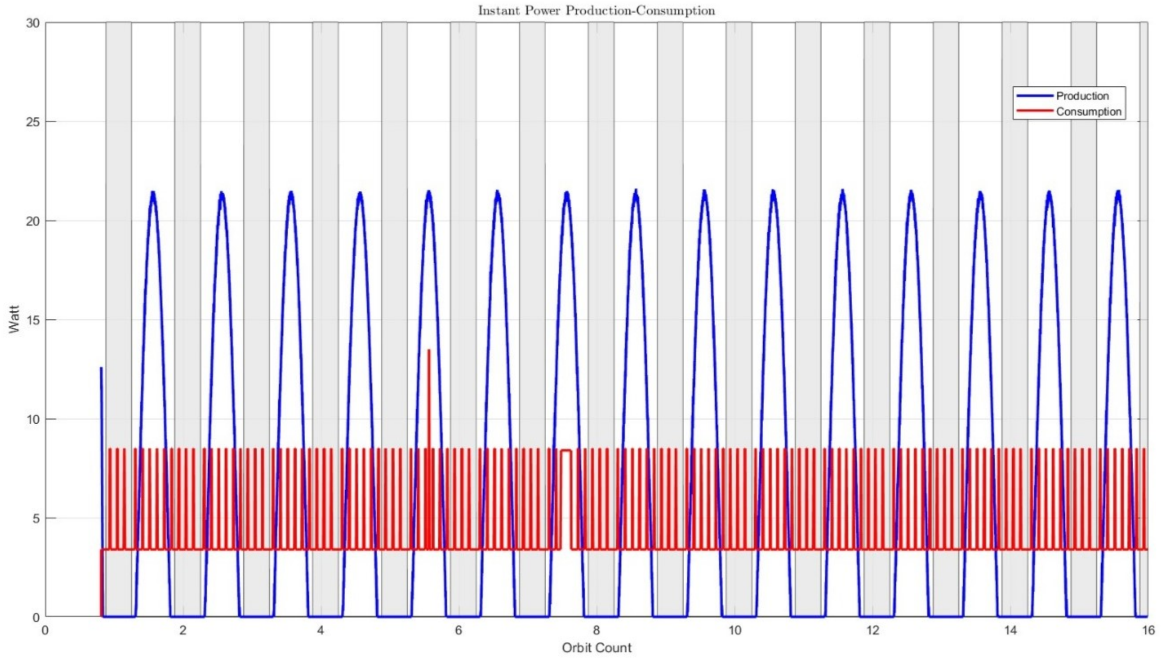

Figure 6: Instant power production and consumption of METUCube over orbit counts.

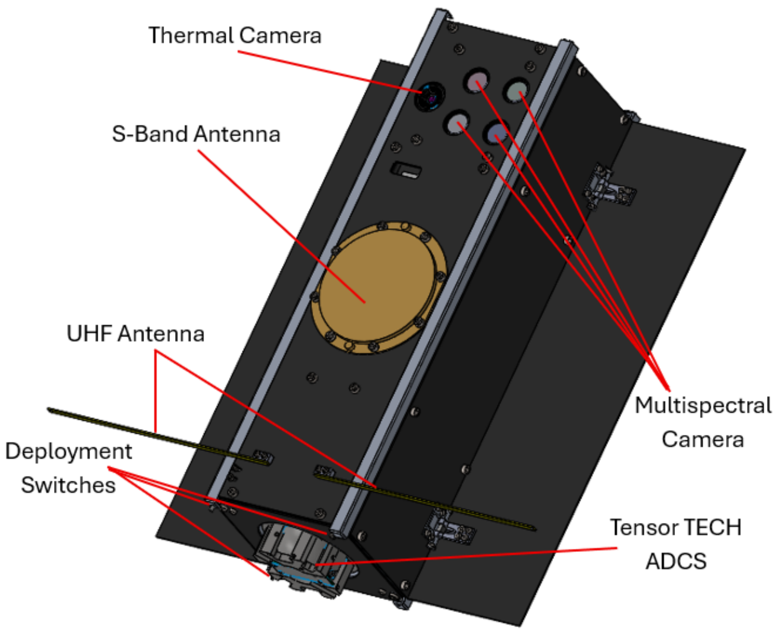

Figure 7: METUCube 3D CAD view showing external component arrangement

Magnetorquer Design

Two magnetorquer configurations have been designed and analyzed for the METUCube ADCS subsystem: an air-core and two iron-core design. Both configurations serve as primary actuators for attitude control and momentum unloading operations. The air-core magnetorquer features a rectangular shaped coil with 450 windings wound around the U-shaped frame. At 100 mA operating current, this design generates approximately 0.19 $A{\cdot}m^2$ magnetic dipole moment with 0.62 W power consumption. Each iron-core magnetorquer utilizes a stainless steel ferromagnetic core with 1050 turns. Operating at 100 mA, this configuration produces approximately 0.19 $A{\cdot}m^2$ magnetic dipole moment while consuming only 0.16 W of power.

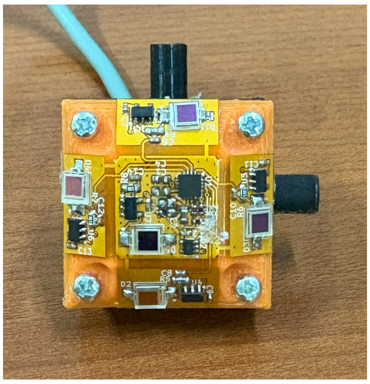

Figure 8: Developed Sun Sensor

Design calculations have been performed to validate the theoretical magnetic dipole moment generation capability of both configurations. The analysis provides baseline performance characteristics for the magnetorquer subsystem, which will be validated against the complete ADCS torque requirements during subsystem-level integration. The calculated dipole moment values are expected to be sufficient for the 3U CubeSat platform, as similar magnetic dipole moments are available in commercial space-heritaged magnetorquer boards designed for detumbling operations as large as 12U CubeSats. Currently, detailed analysis of the torque generation in the specified orbital environment is being conducted to verify the performance requirements.

Prototypes of both magnetorquer designs have been manufactured to conduct future experimental validation. Further testing and performance characterization will be performed to evaluate thermal behavior, and power characteristics to support the final design selection for the engineering model.

On-Board Computer Design

The OBC is built upon a Raspberry Pi Compute Module 5 which features a BCM2712, quad-core Cortex-A76 (ARMv8) 64-bit System-on-Chip (SoC). A highly functional board is developed in-house for the CM5, for the means of compiling with the PC104 standards for structural integrity purposes. The board also has a power unit, a Type-C interface, an ethernet port, a port for CAN, and for RS485. This strong card has a 2.4 GHz clock speed, which is a lot more than what is needed for a CubeSat. However, the reliability and accesibility of this card makes it a good candidate for plug-and-play OBC solution.

The card also has a 2GB of Synchronous Dynamic RAM, and 16 GB of eMMC. The eMMC is much more reliable than a SD Card, which makes the CM5 a better candidate than all other Raspberry Pi products, which are built upon the SD Card storage. The card is used via Raspberry Pi OS Lite 64-bit, and with undervoltage settings to the processor in order to lower the power consumption. The clock cycle is also limited to a lower cap than the original CM5 design, however since the software is not demanding that many cycles, the power consumption does not change significantly.

As a software solution, the NASA cFS framework is established. It runs on a linux kernel, and provides most of the necessary tools in order to build a well-designed compact OBC software. The ease of creating HK applications, file savings and task scheduling with a little overhead is precious for space applications. In addition to the ease of app developing, the cFS also offers Operating System Abstraction Layer (OSAL) and Platform Support Package (PSP) APIs, which allows developers to run the software in many different hardware and software system, which includes Linux, RTEMS, and VXWORKS systems with x86 / x86_64, ARM, PPC and LEON hardwares.

With this hardware and software solutions, the development of the OBC is more informative for the developing team. In addition to that, since the specified hardware outperforms any off-the-shelf OBC product - both in terms of money and price -, the need for this solution urged. Thus, the solution were developed in house, with the developed OBC board, a software that runs on NASA cFS, and with off-the-shelf Raspberry Pi CM5. This solution also provides an easily accessible OBC, since Raspberry Pi products are publicly accessible around the world, and 20x cheaper then the other OBC branded hardware.

Structural and Thermal Performance Verification

Finite Element Method (FEM) analyses were performed in ANSYS 2025 R2 to verify the structural integrity of the CubeSat frame under launch conditions. Static structural analysis with a 5g acceleration in the z–direction and rail-mounted constraints showed maximum von Mises stress of 2.37×10^5 Pa, which is well below the yield strength of Al 6061–T6 (276 MPa). This corresponds to a safety factor of approximately 1.17. Stress concentrations were observed at fillet regions, indicating that larger radii would further reduce peak stresses.

Modal analysis confirmed compliance with launcher requirements. The first natural frequency was 952.75 Hz, far exceeding the minimum thresholds of 50 Hz lateral and 100 Hz longitudinal, signifying a well-stiffened structure. High modal frequencies enhance structural robustness, though excessive stiffness and mass penalties should be checked in future iterations.

Random vibration analysis was conducted using Power Spectral Density (PSD) inputs across launch frequency bands. The CubeSat experienced maximum directional displacements of 0.55 μm (z–axis), 25.5 μm (y–axis), and 24.1 μm (x–axis), while average displacements remained below 1 μm. The maximum equivalent stress was 40.4 MPa, yielding a safety factor of 6.8. Although stresses are within allowable limits, localized stress concentrations were observed around screw interfaces, suggesting potential fatigue risk under repeated loading.

Overall, FEM analyses verified that the CubeSat frame meets launch requirements with adequate safety margins. Minor design refinements, particularly at stress concentration zones, are recommended to further enhance long-term structural reliability.

Thermal analysis using both 6-node MATLAB modeling and ESATAN validation confirms that passive thermal control maintains all components within operational temperature ranges (-10°C to 50°C) throughout orbital variations.

Communication System Design

Link budget calculations demonstrate robust communication capabilities with positive margins: 9.1 dB for UHF telemetry, 4.7 dB for S-band downlink data transmission, and 14 dB for UHF command uplink. The dual-band approach enables 9600 bps telemetry rates and up to 1 Mbps payload data transmission, meeting mission requirements for timely disaster response communications.

Cost Analysis and Schedule Performance

Preliminary cost estimation indicates total mission costs of \$112,000, including approximated estimated cost \$30,000 for the space segment, \$80,000 for launch services, and \$2,000 for ground segment development. This represents a significant achievement under the \$100,000 constraint for the spacecraft alone. The engineering model development timeline targets completion by early 2026, maintaining schedule compliance with project milestones.

Risk Assessment Outcomes

Risk assessment identifies procurement timeline challenges as a primary concern, particularly for high-precision ADCS components as well as other in-house developed components which may have extended lead times. Cost management represents an additional risk factor given the budget constraints and precision component requirements. Early vendor engagement has been identified as a critical mitigation strategy to prevent schedule delays.

CONCLUSIONS

The METUCube project has completed the Critical Design Review phase, demonstrating technical readiness for engineering model development and establishing a clear pathway toward flight model implementation. The engineering model development is scheduled for completion by early 2026, representing the next phase in the project timeline. Flight model feasibility has been established through subsystem trade-off analyses and vendor component availability assessment. Total mission costs are estimated at \$112,000, including space segment, launch, and ground segment elements.

The design approach addresses the technical challenges of implementing dual imaging payload configuration of multispectral and thermal infrared sensing capabilities within standard 3U form factor limitations, providing a reference for projects that have similar constraints and objectives. Communication system design provides data transmission rates suitable for Earth observation applications, with link budget margins confirming operational viability.

Future work includes engineering model production, integrated system testing, and performance validation prior to potential flight model development. The project provides design reference data for CubeSat missions requiring imaging payloads and high-data-rate communication systems. Operational mission results will be evaluated following successful engineering model testing and potential flight implementation.

Acknowledgments

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