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Structural Analysis of Low Earth Orbit Nanosatellites Using Computational Methods: A Case Study of ET-SMART-RSS, Ethiopian 6U CubeSat

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Abstract

This dissertation presents a comprehensive structural analysis of low Earth orbit (LEO) nanosatellites, with a focus on the ET-SMART-RSS, Ethiopia’s 6U CubeSat, utilizing advanced computational methods. The study investigates the structural integrity and performance of nanosatellites operating in the harsh conditions of LEO, where factors such as temperature fluctuations, radiation, and mechanical loads pose significant challenges. Finite Element Analysis (FEA) is employed to simulate and evaluate the mechanical behavior of the satellite under various operational conditions, including launch-induced vibrations, thermal stresses, and potential impacts from space debris. The research applies industry-standard software, such as ANSYS and COMSOL Multiphysics, to model the CubeSat's structural components and optimize its design for enhanced durability and functionality. By conducting a case study on ET-SMART-RSS, this dissertation identifies critical failure points and suggests improvements to the structural design, offering valuable insights for future nanosatellite missions. The findings underscore the importance of rigorous computational analysis in ensuring the reliability and longevity of CubeSats, particularly for developing nations looking to expand their presence in space exploration. Ultimately, this research contributes to the growing body of knowledge on nanosatellite engineering and supports the advancement of space technologies in Ethiopia and beyond.

Chapter One

Introduction and Background

1.1 Background of the Study

Nanosatellites, particularly CubeSats, have become a transformative technology in the field of space exploration and satellite development. Originating in the late 1990s as a low-cost platform for educational purposes, CubeSats have since evolved into a robust tool for a wide variety of scientific, commercial, and defense missions. CubeSats are typically categorized by their modular design, with the smallest unit, a “1U” representing a 10 cm cube. These units can be stacked to create larger configurations such as 3U, 6U, and even 12U CubeSats, depending on the mission requirements. The Ethiopian ET-SMART-RSS, a 6U CubeSat, consists of six such units, offering enhanced capacity for payloads and systems compared to smaller configurations, while maintaining a compact form factor suitable for deployment in LEO.

The increased adoption of CubeSats is driven by their affordability, relatively fast development cycles, and flexibility in terms of payload design. These factors have made CubeSats an attractive option not only for well-established space agencies but also for academic institutions and countries with emerging space programs. Ethiopia, through its space program, has embraced CubeSat technology as a means to advance its remote sensing capabilities, address environmental challenges, and contribute to scientific knowledge. The ET-SMART-RSS mission, for instance, is designed to support agricultural monitoring, weather forecasting, and disaster management, demonstrating the broad utility of CubeSats for addressing pressing global challenges.

The development of nanosatellites has marked a significant shift in the landscape of space exploration and satellite-based research, particularly in recent decades. Offering a cost-effective and flexible alternative to conventional large-scale satellites, nanosatellites have enabled a broader range of stakeholders, including academic institutions and developing countries, to participate in space missions. Among these, CubeSats—a subclass of nanosatellites defined by their standardized unit sizes—have gained widespread adoption for a variety of missions ranging from Earth observation to space science and communication. The Ethiopian ET-SMART-RSS, a 6U CubeSat, represents one such ambitious mission aimed at advancing Ethiopia's capabilities in space-based remote sensing and scientific observation.

Low Earth Orbit (LEO) satellites, such as ET-SMART-RSS, operate between 160 and 2,000 kilometers above the Earth's surface, where they encounter a range of environmental challenges. The structural integrity of these satellites is crucial for mission success, as they must endure extreme conditions from the intense vibrations during launch to the harsh thermal variations in space. Despite their small size, CubeSats are subject to the same mechanical and environmental stresses as their larger counterparts, which make structural analysis a key aspect of their design and mission planning. The use of computational methods, such as Finite Element Analysis (FEA), has emerged as a vital tool for evaluating the mechanical performance and structural integrity of CubeSats in orbit. This dissertation focuses on the structural analysis of the Ethiopian ET-SMART-RSS CubeSat, employing computational simulations to assess its resilience to the various stresses encountered in LEO.

The aim of this research is to contribute to the growing body of knowledge on nanosatellite structural analysis by presenting a detailed case study of the ET-SMART-RSS CubeSat. This study not only underscores the importance of structural analysis for mission success but also illustrates the application of advanced computational techniques in optimizing satellite design and performance. By focusing on the Ethiopian context, the research also highlights the increasing role of developing nations in the global space community and their efforts to harness space technology for socio-economic development.

1.2 Research Problem

CubeSats operating in Low Earth Orbit are exposed to a range of environmental and mechanical stresses that must be carefully considered during the design and structural analysis phases. LEO, which typically spans altitudes between 160 and 2,000 kilometers, presents unique challenges such as high levels of solar radiation, significant temperature variations, and exposure to atomic oxygen. In addition, satellites in LEO experience extreme dynamic loads during launch, particularly due to vibrations and shocks generated by rocket propulsion. These forces can significantly impact the satellite's structural components, necessitating thorough testing and analysis to ensure that the spacecraft can withstand these conditions without compromising its mission objectives.

In orbit, CubeSats face additional challenges such as microgravity and repeated thermal cycling as they move between sunlight and the Earth's shadow. The rapid heating and cooling cycles can induce thermal stresses in the satellite's materials, which, over time, may lead to material fatigue or failure. Furthermore, the compact size of CubeSats often results in limited surface area for heat dissipation, increasing the reliance on passive thermal management systems. Given these constraints, structural analysis plays a pivotal role in designing CubeSats that can endure the rigors of space and maintain operational efficiency throughout their mission lifespan.

The use of computational methods in structural analysis has revolutionized the way satellite engineers design, test, and validate CubeSats. Finite Element Analysis (FEA) is one of the most widely used techniques for evaluating the structural performance of spacecraft under various load conditions. FEA works by breaking down complex structures into smaller, manageable elements, allowing for the simulation of physical behaviors such as stress, strain, and deformation under specified conditions. This method is particularly useful in the design of CubeSats, where weight and space constraints necessitate precise calculations to ensure that the satellite's structure is both lightweight and robust.

In the case of the ET-SMART-RSS CubeSat, FEA can be applied to assess how the satellite's structural components, including its frame, solar panels, and internal subsystems, respond to the stresses imposed during launch and while in orbit. By simulating different scenarios, such as the forces experienced during rocket deployment or the effects of thermal expansion and contraction in space, engineers can identify potential failure points and optimize the satellite's design accordingly. These simulations also allow for the testing of various materials and configurations without the need for expensive and time-consuming physical prototypes.

In addition to FEA, other computational tools such as modal analysis and dynamic simulations are used to predict the satellite's response to vibrational loads and dynamic impacts. Modal analysis, for instance, helps identify the natural frequencies of the CubeSat structure, which is critical for avoiding resonances that could amplify vibrations during launch. Dynamic simulations, on the other hand, enable engineers to model the satellite's behavior during deployment and operation, providing valuable insights into how the structure will perform under real-world conditions.

1.3 Objective of the Study

The main objective of this study is to conduct a structural analysis of an Ethiopian 6U CubeSat, ET-SMART-RSS.

Specific objectives are:

1) To develop and validate a computational model for the structural analysis of the ET-SMART-RSS 6U CubeSat: This objective focuses on creating an accurate finite element model (FEM) of the CubeSat to simulate its structural behavior and validate the model against relevant experimental or empirical data.
2) To assess the mechanical and thermal stresses experienced by the CubeSat during launch and its Low Earth Orbit (LEO) mission: This involves analyzing the CubeSat's structural response to launch-induced vibrations, shock loads, and the thermal cycling in LEO using computational methods such as Finite Element Analysis (FEA).
3) To provide recommendations for optimizing the CubeSat's structural design for enhanced performance and longevity in LEO: Based on the computational analysis, this objective aims to propose design improvements, material selections, or reinforcements to ensure the CubeSat can withstand the mechanical and environmental stresses it will face during its mission.

1.4 Scope and Limitation of the Study

The scope of this dissertation is to conduct a comprehensive structural analysis of the Ethiopian 6U CubeSat, ET-SMART-RSS, with the objective of ensuring its mechanical integrity and operational longevity during its Low Earth Orbit (LEO) mission. The study focuses on the application of advanced computational techniques, specifically Finite Element Analysis (FEA), to evaluate the satellite's response to the various mechanical and environmental stresses it will encounter from launch through to its operational lifetime in orbit.

The scope of this study is limited to the structural analysis of the ET-SMART-RSS 6U CubeSat and does not encompass other subsystems such as communications, power, or payload performance. The computational methods used, primarily FEA, will be validated through comparison with existing satellite data or benchmarks where available, but no physical testing will be conducted as part of this study. This dissertation aims to contribute to the field of nanosatellite engineering by offering insights into the structural challenges faced by CubeSats in LEO and proposing solutions to enhance their resilience and longevity.

1.5 Significance of the Study

The ET-SMART-RSS mission represents a significant milestone in Ethiopia's space ambitions, serving as a platform for scientific research and remote sensing. As a 6U CubeSat, ET-SMART-RSS is equipped with a range of sensors and instruments designed to capture high-resolution data on land use, vegetation cover, and atmospheric conditions. Given the satellite's mission objectives, ensuring the structural integrity of its components is paramount to the success of the mission.

In this dissertation, the structural analysis of ET-SMART-RSS focus on evaluating its ability to withstand the mechanical and environmental stresses encountered during its deployment and operation in LEO. By using computational methods such as FEA, the study assesses critical factors such as stress distribution, material fatigue, and the satellite's response to vibrational loads. The results of this analysis provide insights into the design optimizations required to enhance the satellite's durability and performance, contributing to the broader body of knowledge on CubeSat structural engineering.

The case study approach allows for a detailed examination of the specific challenges associated with the ET-SMART-RSS CubeSat, while also providing a framework for applying computational methods to similar nanosatellite missions in the future. Moreover, this research highlights the potential for developing nations to leverage CubeSat technology in advancing their space capabilities and addressing global challenges through space-based data collection.

This dissertation aims to offer a comprehensive structural analysis of the ET-SMART-RSS CubeSat, utilizing computational methods to assess its resilience in the challenging environment of LEO. Through the application of advanced simulation tools, the study will not only provide valuable insights into the structural integrity of CubeSats but also contribute to the broader goal of optimizing nanosatellite design for a wide range of space missions. The findings of this research will have important implications for future CubeSat projects, particularly those undertaken by emerging space programs in developing countries.

Chapter Two

Literature Review

2.1 Overview of Low Earth Orbit (LEO) Nanosatellites

The field of nanosatellite technology, particularly those deployed in low Earth orbit (LEO), has experienced rapid growth in recent decades. Low Earth Orbit (LEO) nanosatellites have emerged as a disruptive technology in space exploration and satellite operations. These small, lightweight satellites, weighing between 1 and 10 kg operate at altitudes between 160 km to 2,000 km, providing numerous advantages such as reduced cost, faster deployment, and the potential for massive constellations that enhance Earth observation, communication, and scientific research. In recent years, LEO nanosatellites have found applications in diverse sectors, ranging from Earth imaging to quantum communication.

Nanosatellites operating in low Earth orbit (LEO) have become increasingly prominent in recent years, driven by their cost-effectiveness, modularity, and versatility in a range of applications, from Earth observation to communication. One of the key advantages of LEO nanosatellites is their potential to augment existing large satellite systems, offering enhanced coverage and reduced revisit times through constellations of small satellites, such as those demonstrated by Boumard et al., which showed how a 22-satellite constellation in sun-synchronous orbit could provide complete Earth coverage in just over a day (Boumard, 2023) [1]. In terms of technical design, nanosatellites face unique challenges, such as thermal management and aerodynamic control. Akka et al. addressed the heat dissipation issues inherent to passive thermal control, focusing on the importance of material coatings for temperature regulation in LEO environments (Akka, 2022) [2]. Similarly, Barinova et al. explored attitude control systems for nanosatellites using aerodynamic fins, which allow for efficient stabilization and reorientation (Barinova, 2023) [3]. These technological innovations are complemented by the development of onboard systems such as the quantum random number generator proposed by Reezwana et al., which represents a pioneering step in quantum communications via LEO nanosatellites (Reezwana, 2022) [4]. Collectively, these advances highlight the diverse capabilities and ongoing evolution of nanosatellite technologies in LEO.

In recent years, nanosatellites, particularly CubeSats, have revolutionized space exploration and satellite technology due to their affordability and modularity. Twiggs and Puig-Suari (2000) introduced the CubeSat standard to democratize space, allowing universities and small companies to develop and deploy small satellites for research and commercial purposes [5]. Since then, nanosatellites have been widely used in Earth observation, communication, and scientific experiments (Sandau, 2010) [6].

LEO offers an optimal altitude for nanosatellites to perform Earth observation tasks such as climate monitoring, disaster management, and agricultural assessment. For instance, Li et al. (2013) highlight how CubeSats equipped with imaging sensors can capture high-resolution data useful for environmental monitoring [7]. Similarly, Woellert et al. (2011) emphasize the role of CubeSats in expanding the accessibility of Earth observation data due to their low cost and frequent revisit times [8]. Communication is a critical function for LEO nanosatellites. Kumar et al. (2017) discuss the development of communication payloads designed for CubeSats, detailing advancements in miniaturized antennas and radios that allow real-time data transmission between satellites and ground stations [9]. Additionally, nanosatellite constellations like the one described by Swartwout (2016) are being developed to enhance global communications coverage [10].

One of the primary challenges in nanosatellite development is maintaining structural integrity while miniaturizing components. Buchen and de Selding (2014) note that material selection and compact design are key to ensuring nanosatellite durability during the launch and operational phases [11]. The small form factor, typically constrained to units like 1U, 3U, or 6U, requires careful balance between mass, volume, and strength (Hodgins et al., 2015) [12]. Reliable launch and deployment mechanisms are essential for LEO CubeSats. Malik et al. (2020) review recent advances in launch technologies tailored to nanosatellites, including the development of dedicated small launch vehicles and multi-payload deployment systems [13]. The concept of “ridesharing” has become a popular method for deploying multiple nanosatellites in LEO, reducing costs and increasing launch opportunities (Blake et al., 2019) [14]. The unique orbital dynamics of LEO, including atmospheric drag and radiation exposure, present challenges for nanosatellites. Guo et al. (2016) investigate the impact of atmospheric drag on nanosatellites, especially those in lower altitudes, emphasizing the need for accurate orbit determination and propulsion systems [15]. Radiation effects are also prominent, as described by Watts et al. (2014), who explain how nanosatellites must incorporate radiation-hardened components to prevent system degradation [16]. Thermal management in LEO is a crucial aspect of satellite design. Shafique et al. (2016) provide a detailed review of thermal control strategies for CubeSats, noting that nanosatellites are particularly susceptible to rapid temperature fluctuations due to their small mass and high surface area-to-volume ratio [17]. Passive and active thermal management systems are essential to ensure operational longevity.

Propulsion systems are increasingly being integrated into CubeSats to enhance maneuverability in LEO. Grubisic et al. (2019) review the development of micro-propulsion technologies for CubeSats, such as electric propulsion systems and cold gas thrusters, which allow for orbit adjustment, collision avoidance, and mission extension [18]. These systems are critical for maintaining orbital altitude and ensuring the satellite's operational lifespan.

The use of constellations or swarms of nanosatellites in LEO is a growing trend. Radhakrishnan et al. (2019) discuss how CubeSat constellations are being deployed to provide continuous global coverage for Earth observation, communication, and scientific research [19]. By working in coordinated networks, these constellations can achieve performance levels comparable to larger, more expensive satellites. Swartwout (2013) analyzes the success rates of CubeSat missions and identifies key factors influencing mission reliability, including launch failure, communication issues, and hardware malfunctions [20]. Improving the reliability of nanosatellite missions requires advancements in component testing, environmental simulations, and redundancy in critical systems. Space debris poses a significant risk to nanosatellites operating in LEO. Liou (2011) explores the increasing threat of space debris, especially in densely populated LEO orbits, and the need for nanosatellite operators to implement collision avoidance strategies [21]. Shields or protective designs may be required to mitigate the impact of micro-debris on vulnerable satellite components. The short lifespan of nanosatellites due to orbital decay is another critical issue. Wiedemann et al. (2018) discuss the natural decay of nanosatellite orbits in LEO due to atmospheric drag, which often limits their operational lifespan to a few years [22]. They also review end-of-mission disposal strategies, such as controlled deorbiting or designing satellites to burn up during re-entry, to mitigate the risk of contributing to space debris. The affordability of CubeSats has made space more accessible, but cost-effectiveness remains a concern. Puig-Suari et al. (2013) examine the economic models of CubeSat missions, emphasizing the importance of cost management in design, development, and launch to maintain the attractiveness of these small satellites [23]. Scalability issues also arise when moving from individual CubeSats to large-scale constellations. As the number of LEO nanosatellites increases, regulatory challenges arise. Hertzfeld and Williamson (2017) review the international policies governing CubeSat launches and operations, highlighting the need for updated regulations to manage frequency allocations, orbital slots, and space debris mitigation [24]. These regulatory frameworks must evolve to accommodate the rapid expansion of nanosatellite deployments.

The future trends in nanosatellite technology are explored by Selva and Krejci (2012), who forecast the increasing use of artificial intelligence, onboard data processing, and autonomous decision-making in nanosatellite missions [25]. These advancements will enhance the capability of nanosatellites, enabling them to perform more complex tasks with minimal human intervention. In general, this literature highlights the rapid advancements in nanosatellite technology, particularly for LEO missions. Key areas of focus include structural design, propulsion, communication, and environmental challenges. While nanosatellites have democratized space access, ongoing research is needed to address challenges such as space debris, mission reliability, and regulatory frameworks.

2.1.1 Nanosatellite Design and Architecture

Nanosatellites, particularly CubeSats, have standardized modular designs, making them highly adaptable for various missions. The CubeSat platform consists of multiple units (typically 1U, 2U, 3U, etc.), allowing flexibility in size, weight, and payload integration. Kukharenko et al. describe the construction of nanosatellite platforms, highlighting the standardized structure where each unit must conform to precise dimensions to house components like antennas, sensors, and power sources (Kukharenko, 2024) [26]. These satellites typically rely on solar power and lithium-ion batteries, presenting design challenges in terms of power storage and heat dissipation in space.

2.1.2 Applications of Nanosatellites in LEO

The deployment of nanosatellites in low Earth orbit (LEO) has transformed the landscape of space technology due to their low cost, modularity, and versatility. One of the primary applications of LEO nanosatellites is Earth observation. Nanosatellites, operating in sun-synchronous orbits (SSO), provide high-resolution imaging capabilities, critical for environmental monitoring, disaster management, and agriculture. Boumard et al. demonstrated how a constellation of 22 nanosatellites operating at an altitude of 499.8 km can achieve full Earth coverage in just 27 hours, significantly reducing revisit times compared to traditional large satellite systems (Boumard, 2023) [2]. This capability makes nanosatellites an invaluable asset for continuous, real-time data collection. Nanosatellites have played a transformative role in Earth observation, enabling continuous monitoring of environmental changes. Li et al. (2013) discuss the potential of CubeSats for high-resolution Earth imaging, particularly in tracking environmental phenomena like deforestation and urbanization [7]. Similarly, Chuvieco et al. (2014) explore how constellations of nanosatellites offer more frequent revisit times compared to traditional satellites, making them ideal for real-time disaster monitoring and climate change tracking [27].

CubeSats are increasingly used in agriculture to monitor crop health and land use. Matese et al. (2015) highlight how CubeSats equipped with multispectral sensors can capture data for precision agriculture, helping farmers optimize water use, pesticide application, and soil health [28]. This real-time data is crucial for increasing agricultural efficiency and sustainability, especially in developing regions. The use of nanosatellites for disaster response has gained traction due to their ability to rapidly capture high-resolution images of affected areas. Kubik et al. (2019) discuss how nanosatellite constellations provide real-time data during natural disasters like hurricanes, floods, and wildfires, helping authorities coordinate timely responses [29]. Their low cost and quick deployment make them essential for disaster-prone areas.

Nanosatellites are also revolutionizing global communications by forming small, cost-effective satellite constellations in LEO. One prominent example is the deployment of nanosatellite constellations for global internet coverage, as reviewed by Handley (2018), who discusses their potential to bridge the digital divide in remote and underserved regions [30]. By providing low-latency communication at lower costs, nanosatellites are disrupting traditional telecommunication infrastructures. Nanosatellites are part of major initiatives to provide global broadband coverage, especially in remote or underserved areas. Miller et al. (2020) review the development of nanosatellite constellations like Starlink, which aim to deliver high-speed internet to the entire globe through a network of CubeSats in LEO [31]. This technology could significantly reduce the cost of internet infrastructure, making it more accessible in developing countries. Nanosatellites are also revolutionizing global communication by enabling cost-effective solutions for remote connectivity and IoT networks. Small satellite constellations, such as SpaceX's Starlink, demonstrate the potential of nanosatellites to offer broadband internet across remote regions. As the demand for global connectivity grows, nanosatellite networks are expected to play a crucial role in providing low-latency communication solutions for IoT devices, especially in industries like agriculture, mining, and maritime. Nanosatellites are enabling new applications in the Internet of Things (IoT) by creating space-based communication networks. As noted by Alarcon et al. (2019), nanosatellite constellations can provide connectivity for IoT devices in remote regions where terrestrial communication networks are unavailable [32]. This technology opens new possibilities for monitoring industrial processes, wildlife tracking, and environmental sensing from space. Nanosatellites have become instrumental in scientific experiments and space exploration. With their ability to carry diverse payloads, nanosatellites are being used to study space weather, solar radiation, and even test new space technologies. Reezwana et al. demonstrated the potential of nanosatellites in quantum communication through the successful deployment of a quantum random number generator on a LEO nanosatellite, paving the way for secure communication systems in space (Reezwana, 2022) [4]. Nanosatellites play a crucial role in scientific research, particularly in monitoring space weather phenomena such as solar storms and geomagnetic disturbances. Zhang et al. (2017) highlight the use of CubeSats in measuring charged particles in the Earth's magnetosphere, which helps to predict space weather and protect space assets like satellites and astronauts [33]. The low cost of deploying multiple nanosatellites makes it easier to monitor these phenomena on a global scale.

Nanosatellites are increasingly being used for scientific missions beyond Earth observation. Betts et al. (2016) explore how CubeSats can be equipped with miniaturized scientific instruments to study astrobiological phenomena and exoplanetary atmospheres [34]. Their findings suggest that nanosatellites are capable of conducting complex scientific missions at a fraction of the cost of traditional spacecraft. Many nanosatellites are launched as technology demonstrators to test new systems and instruments in space. Woellert et al. (2011) emphasize that CubeSats serve as platforms for testing miniaturized technologies, such as micro-propulsion systems and advanced sensors, before they are implemented in larger, more expensive satellites [35]. This application has been instrumental in accelerating the pace of innovation in space technology.

The deployment of autonomous nanosatellite constellations is an emerging field with great potential. Barnhart et al. (2016) discuss how nanosatellites can be programmed to work in swarms, autonomously coordinating data collection and optimizing coverage without human intervention [36]. This approach significantly enhances the efficiency of Earth observation and communication networks. Nanosatellites also have applications in defense and military operations. Bowen and Eichelberger (2017) discuss how CubeSats are increasingly being used for tactical communication, reconnaissance, and early warning systems due to their rapid deployability and low cost [37]. Their small size makes them less detectable by adversaries, providing strategic advantages in surveillance and data gathering.

Another important application of nanosatellites in LEO is tracking space debris, which poses a significant threat to space operations. Liou (2011) discusses how CubeSats are used to monitor and track the movement of space debris, helping to avoid collisions with operational satellites and manned spacecraft [21]. This capability is crucial for maintaining the safety of LEO as the number of objects in orbit continues to grow.

Climate scientists are increasingly relying on nanosatellites to monitor global climate patterns and greenhouse gas emissions. As Karnieli et al. (2017) note, nanosatellites equipped with spectrometers can measure atmospheric CO_2 levels, contributing to a better understanding of the Earth’s carbon cycle and the effects of climate change [38]. These applications are critical for informing global policy decisions on climate action. Nanosatellites are widely used in educational settings, providing hands-on experience for students and researchers in space technology. Puig-Suari et al. (2001) introduced the CubeSat standard as a way to involve universities in space exploration [23]. Since then, hundreds of CubeSats have been launched as part of educational programs, fostering innovation and collaboration in aerospace engineering and satellite development.

The commercialization of Earth observation using nanosatellites is another growing application. BlackSky, Planet Labs, and other companies use nanosatellite constellations to provide real-time imagery and data analytics services for industries such as agriculture, insurance, and urban planning. As noted by Johnson et al. (2018), the ability to provide frequent, high-resolution imaging at a low cost makes nanosatellites attractive for a range of commercial applications [39].

2.1.3 Challenges of Operating Nanosatellites in Low Earth Orbit

i) Thermal Management

One of the major challenges faced by nanosatellites in LEO is thermal regulation. Due to their small size, nanosatellites are particularly vulnerable to thermal fluctuations caused by exposure to sunlight and the shadowed parts of the orbit. Akka et al. explored the challenges related to heat dissipation, focusing on passive thermal management solutions for nanosatellites in LEO. They found that high-powered components, combined with the spacecraft's tight layout, make effective heat management a significant design concern (Akka, 2022) [2].

ii) Attitude and Orbit Control

Another critical issue in nanosatellite operation is attitude and orbit control. Due to their lightweight and compact nature, nanosatellites face challenges in maintaining stability and orientation. Traditional control methods, like reaction wheels, may not be feasible due to weight constraints. However, Barinova et al. proposed a novel approach using aerodynamic fins for nanosatellite attitude control, which allows for efficient reorientation and stabilization while minimizing fuel consumption (Barinova, 2023) [3].

iii) Communication and Data Throughput

As nanosatellites are tasked with collecting and transmitting large volumes of data, efficient data link design becomes essential. One of the main challenges is ensuring that nanosatellites have the bandwidth and communication capabilities to transmit data to ground stations without delays or data loss. Boumard et al. investigated data link design for Earth observation nanosatellites, exploring the trade-offs between satellite coverage, data throughput, and downlink efficiency. Their findings indicate that ground station scheduling and onboard data storage significantly influence nanosatellite performance in LEO (Boumard, 2023) [1].

2.1.4 Future Prospects for Nanosatellites in LEO

i) Advanced Propulsion and Autonomous Systems

The future of LEO nanosatellites lies in the development of more advanced propulsion systems and autonomous navigation technologies. While current nanosatellite missions rely on minimal propulsion systems, ongoing research is aimed at enhancing onboard propulsion to extend mission durations and enable more complex maneuvers. Autonomous systems will also play a key role in the future, allowing nanosatellites to conduct self-diagnosis, repair, and even decision-making based on changing mission objectives.

ii) Larger Constellations and Global Coverage

The trend of deploying larger constellations of nanosatellites is expected to continue, particularly for applications in communication and Earth observation. Companies such as Planet and OneWeb are at the forefront of these developments, launching thousands of nanosatellites to create global coverage networks. This increase in satellite density, coupled with advancements in inter-satellite communication, will lead to more resilient and efficient space networks capable of handling large volumes of data in real-time.

iii) Integration with 5G and Beyond

Nanosatellites are poised to play an integral role in the deployment of 5G and future 6G networks, especially in regions where terrestrial infrastructure is limited or non-existent. Their ability to form low-latency, high-throughput networks will complement terrestrial communication systems, enabling seamless global connectivity. The integration of nanosatellites with next-generation communication technologies is expected to open new avenues for smart cities, autonomous vehicles, and edge computing.

2.2 Structural and Thermal Analysis of Nanosatellites

Structural analysis is crucial for ensuring that nanosatellites can endure the mechanical loads encountered during launch, particularly the high accelerations and vibrations. Idris (2023) conducted a comprehensive structural and thermal analysis of a CubeSat, focusing on static structural and vibrational performance (Idris, 2023) [40]. Using ANSYS software, the study modeled the satellite under various load conditions, evaluating its natural frequencies and vibrational modes. This data is critical in ensuring that the satellite avoids resonance frequencies that could cause structural failure during launch.

Thermal analysis is equally important, as nanosatellites are subjected to extreme temperature variations in space. The study used a heat flow model to predict thermal conditions in orbit, ensuring that the satellite's internal components, particularly the batteries and electronics, operate within safe temperature limits. This analysis helps prevent overheating and cold-induced failures, which are common in low Earth orbit (LEO) environments.

2.2.1 Material Optimization for Structural Performance

Material selection is a key factor in the structural design of nanosatellites, as it influences both the strength and weight of the spacecraft. Parab et al. (2022) explored the optimization of a 1U nanosatellite using different materials, including traditional aluminum alloys and composite materials (Parab, 2022) [41]. The study compared the mechanical properties of aluminum alloys, commonly used in aerospace applications, to newer composite materials such as HTM143/M55J. The latter demonstrated superior strength-to-weight ratios, which is critical for improving payload capacity and reducing fuel consumption during launch.

The study performed static structural analysis to evaluate stress and deformation characteristics under different load scenarios. It found that HTM143/M55J composites significantly outperformed aluminum alloys in terms of weight reduction and mechanical strength. These results suggest that advanced composites could become the material of choice for future nanosatellite designs, particularly in missions where weight is a limiting factor.

2.2.2 Topological Optimization for Improved Vibration Resistance

Traditional nanosatellite structures often struggle to meet the lightweight and vibration-resistant requirements of modern space missions. To address this, topological optimization techniques have been employed to enhance structural performance. A study by DMA (2023) proposed a novel two-step topological design method for a nanosatellite structure filled with non-uniform lattices (DMA, 2023) [42]. The study first subjected the satellite structure to vibrational tests to obtain frequency data, which was then used to create a finite element (FE) model.

Through this optimization, the design achieved a 50.32% reduction in mass while increasing the satellite's natural frequency by 1.19%. This improvement in frequency response is critical in preventing resonant vibrations during launch, which can lead to structural failure. The use of non-uniform lattice structures also allowed for a more efficient distribution of stress across the satellite body, ensuring that critical components remain protected.

2.2.3 Computational Techniques for Structural Analysis

Finite element analysis (FEA) has become a standard tool in the structural analysis of nanosatellites due to its ability to simulate complex load scenarios and predict structural behavior under real-world conditions. Martinez et al. (2022) used FEA to design a CubeSat structure, focusing on minimizing mass while maintaining structural integrity (Martinez, 2022) [43]. The study evaluated different geometric configurations and material selections, optimizing the structure to ensure it met the required mass and size standards for CubeSats.

FEA simulations predicted deformation and stress distributions, which were crucial in identifying weak points in the structure that could fail under load. By iterating different designs and materials, the study achieved a structurally sound CubeSat design that minimized mass while maintaining the required mechanical properties. This computational approach is invaluable in reducing prototyping costs and ensuring that the final design can withstand the rigors of space deployment.

2.2.4 Structural Resistance and Launch Load Analysis

The high acceleration forces during a nanosatellite's launch phase place significant stress on its structure. To ensure that CubeSats can withstand these forces, structural resistance analysis is essential. Vega-Ibarra et al. (2019) conducted an analysis of a CubeSat's structural resistance using the Ansys Multiphysics software (Vega-Ibarra, 2019) [44]. The study simulated the CubeSat's response to the high accelerations experienced during launch, focusing on the deformation and stress levels in the satellite's frame.

The study used Von Mises stress analysis to determine the points of maximum stress in the satellite's structure. This data was then used to modify the design, ensuring that the CubeSat could withstand the forces generated during the critical launch phase. By optimizing the number of structural components and their configuration, the study achieved a robust design that minimized mass while ensuring mechanical strength.

2.3 Computational Methods in Aerospace Engineering

Computational methods are crucial to the design, analysis, and control of aerospace systems, including nanosatellites. As nanosatellites are increasingly deployed for various scientific, communication, and surveillance missions, advanced computational techniques have become indispensable in optimizing their performance. These methods help in overcoming the challenges associated with complex aerospace environments, including thermal management, structural integrity, and non-linear control dynamics. This literature review explores the application of computational techniques in the design and operation of nanosatellites, focusing on their role in structural optimization, thermal management, control systems, and educational frameworks.

2.3.1 Multidisciplinary Computational Frameworks for Nanosatellites

In aerospace engineering, multidisciplinary computational frameworks are necessary to address the interconnectedness of various subsystems within nanosatellites. Seth et al. (2023) introduced the Multidisciplinary Aircraft Design Education (MADE) framework, which integrates multiple engineering disciplines using a computational environment (Seth, 2023) [45]. The framework facilitates the understanding of aerodynamics, thermal management, and structural analysis in a unified manner, providing students and engineers with the tools to explore the intricate relationships between these fields. By employing reactive computational notebooks, MADE enhances the accessibility and interactivity of computational methods in aerospace education, preparing future engineers to tackle real-world problems in nanosatellite design.

2.3.2 Computational Models in Nanosatellite Design

Developing realistic models for nanosatellites is critical for training and education in aerospace engineering. Evchik et al. (2022) developed nanosatellite engineering models for student training, which allow students to interact with the hardware and software of nanosatellite systems (Evchik, 2022) [46]. These models, integrated with ground stations and simulation tools, provide students with practical skills in satellite design, attitude control, and telemetry analysis. The development of such computational models is essential for enabling students to design nanosatellites and simulate their behavior under different operating conditions, offering a hands-on learning experience.

2.3.3 Thermal Management in Nanosatellites through Computational Design

Thermal control in nanosatellites is a significant challenge due to their small size and exposure to harsh space environments. Tan et al. (2018) proposed the use of computationally designed microvascular radiative cooling panels for nanosatellites to manage thermal loads effectively (Tan, 2018) [47]. These cooling panels are designed using computational fluid dynamics (CFD) to optimize the coolant temperatures and ensure minimal pressure drops across the system. The study demonstrates how computational techniques can address the stringent thermal requirements of nanosatellites by optimizing heat dissipation systems, ensuring that onboard components remain within operational temperature limits.

2.3.4 Nonlinear Computational Methods in Nanosatellite Control Systems

Nanosatellites operate in highly dynamic environments where nonlinear effects often dominate their behavior, making control a complex task. Dai and Yue (2020) explored nonlinear computational and control methods in aerospace systems, emphasizing their relevance to nanosatellites (Dai & Yue, 2020) [48]. The study highlighted the challenges posed by nonlinearity in systems, such as chaos and bifurcation, which can affect the stability of nanosatellite control systems. By leveraging advanced computational algorithms, the research demonstrated how control strategies could be optimized for nonlinear systems, ensuring that nanosatellites maintain their required orientation and trajectory despite the complexities of the space environment.

Nonlinear control methods are particularly relevant for nanosatellite systems, where precise control is essential for mission success. The study explored advanced finite particle methods (FPM) and optimization algorithms that do not require matrix assembly, thus improving computational efficiency. These methods are ideal for nanosatellites, which often operate with limited onboard processing power, enabling the implementation of real-time control systems.

2.3.5 Computational Optimization of Nanosatellite Structures

The structural design of nanosatellites is another area where computational methods play a critical role. Atluri et al. (2014) presented various computational methods, such as finite element analysis (FEA) and meshless local Petrov Galerkin (MLPG), which are used to solve structural problems in aerospace systems (Atluri et al., 2014) [49]. These methods allow for the optimization of nanosatellite structures, ensuring that they meet the required strength-to-weight ratios for efficient operation in space. By simulating stress distributions and deformation under different load conditions, engineers can optimize the satellite's frame to minimize mass while ensuring structural integrity during launch and in orbit.

This optimization process is crucial for nanosatellites, which must remain lightweight to reduce launch costs while being strong enough to endure the high stresses experienced during launch. Atluri's research demonstrated how computational methods could improve the design of nanosatellite components, allowing for the integration of lightweight materials without compromising on strength.

2.3.6 Educational Applications of Computational Methods in Nanosatellite Engineering

The integration of computational methods into educational frameworks is vital for training the next generation of aerospace engineers. Seth et al. (2023) emphasized the importance of using computational tools to teach complex engineering concepts in an interactive and accessible manner (Seth, 2023) [45]. Their study highlighted how computational frameworks could be used to simulate nanosatellite operations, providing students with hands-on experience in spacecraft design, analysis, and control.

Evchik et al. (2022) extended this approach by developing nanosatellite models that could be used in university labs for practical training (Evchik, 2022)[46]. These models enable students to explore the complexities of nanosatellite systems, from hardware integration to software control, in a simulated environment. The use of computational methods in education ensures that students gain a comprehensive understanding of nanosatellite engineering, preparing them for careers in the aerospace industry.

2.4 Case Studies of Nanosatellites Structural Analysis

2.4.1 Structural and Thermal Analysis of CubeSats

In the case of CubeSats, both structural integrity and thermal management are of paramount importance, especially due to the size constraints and the harsh environmental conditions of space. Idris (2023) explored the structural and thermal analysis of a 3U CubeSat, where static structural analysis was conducted alongside vibrational analysis to estimate the natural frequencies and modes of vibration (Idris, 2023) [40]. Using ANSYS software, the CubeSat's performance was evaluated under various load conditions to ensure that its components would survive the launch phase and orbital conditions. In addition to structural analysis, a detailed thermal requirement map was generated based on orbital parameters, ensuring effective heat management during the satellite's operation in space. Such analyses are essential for maintaining the nanosatellite's functionality throughout its mission, as the failure to address structural and thermal challenges can lead to catastrophic failures.

2.4.2 Heat Dissipation and Passive Thermal Control Systems

Thermal management remains a critical issue for nanosatellites due to their limited ability to dissipate heat in space. Akka et al. (2022) conducted a study focusing on the heat dissipation challenges of nanosatellites, highlighting the vulnerability of nanosatellites to thermal fluctuations in low Earth orbit (LEO) (Akka, 2022) [2]. The study employed computational fluid dynamics (CFD) to model the thermal environment of nanosatellites and assess the effectiveness of passive thermal control systems (PTCs). It was observed that nanosatellites experience significant temperature variations depending on the presence or absence of heat dissipation mechanisms, as well as the choice of surface coatings. The findings emphasized the importance of selecting appropriate surface coatings to maintain optimal thermal performance and prevent overheating, which could otherwise result in mission failure. This case underscores the need for early integration of thermal analysis in the design phase of nanosatellites.

2.4.3 Correlation between Development Methods and System Reliability

Moritani et al. (2022) explored the relationship between nanosatellite development methods and system reliability, using the development of OrigamiSat-1 as a case study (Moritani, 2022) [50].

The study addressed the challenges of ensuring structural integrity in nanosatellites that are developed rapidly, often in small teams where expertise is spread thin. By conducting interviews and quantitative evaluations of system reliability, the study identified that the reliability of nanosatellites is significantly affected by the development process, particularly when systems are developed by cross-disciplinary teams with limited expertise. The findings suggest that incorporating rigorous structural analysis, particularly in areas such as vibrational testing and material selection, can mitigate the risks associated with nanosatellite design. This case highlights the importance of a well-structured development process in ensuring that nanosatellites can meet their mission objectives without encountering structural failures.

2.4.4 Deployment Mechanisms and Structural Integrity

One of the critical phases in a nanosatellite's lifecycle is its deployment into space. Kim et al. (2022) presented a case study on the lessons learned from launch environmental tests for CubeSat nanosatellites (Kim, 2022) [51]. The study highlighted the mechanical loads experienced by nanosatellites during launch, which are transferred through nanosatellite deployers. These deployers often introduce large mechanical loads that can lead to higher rates of structural failure. The case study suggested that modern deployers, which offer better mechanisms for fixing the internal nanosatellite, are preferable to conventional deployers. The study also provided design guidelines based on lessons learned from testing, underscoring the importance of robust structural analysis and mechanical testing before launch.

Additionally, a study by Kim (2023) discussed the implementation of a deployment switch for nanosatellites that ensured proper operation during deployment without the need for complex mechanical assemblies (Kim, 2023) [52]. The new deployment switch design eliminated friction-related issues that are common with mechanical assemblies, improving the reliability of nanosatellite deployments. This case demonstrated how structural design improvements could enhance the overall success of nanosatellite missions, reducing the likelihood of failure during the critical deployment phase.

2.4.5 Lessons from Structural and Environmental Testing

Kim et al. (2022) further explored the impact of environmental tests on nanosatellites, particularly focusing on the mechanical stresses experienced during launch (Kim, 2022) [51]. The study provided insights into the design considerations required to mitigate the risks posed by high mechanical loads during launch. By comparing test results from different nanosatellite deployers, the research highlighted the importance of structural integrity in ensuring that the nanosatellite can withstand the forces exerted during launch. The study concluded that incorporating robust environmental testing protocols early in the development process could significantly enhance the reliability of nanosatellite systems.

2.5 Overview of Ethiopian 6U CubeSat: ET-SMART-RSS

In December 2019, Ethiopia launched its first satellite named ETRSS-1, a 70kg multi-spectral remote sensing satellite from China onboard a Chinese Long March 4B rocket. The China Academy of Space Technology (CAST) developed the satellite in collaboration with 21 Ethiopian technicians, trained on the project as part of the technology-transfer agreement between Beijing and Addis Ababa. The Chinese government provided 75% of the total cost of the ETRSS-1 satellite, worth about USD 6 million, and helped to launch the satellite.

After a year Ethiopia launched it’s second satellite called ET-SMART-RSS where ET stands for Ethiopia/ESSTI, SMART is for Beijing Smart Satellite Technology and RSS stands for Remote Sensing Satellite.

Figure 2.1: Ready-to-Fly ET-SMART-RSS Satellite

ET-SMART-RSS, formerly known as EthSat6U, is an Ethiopian earth observation 6U CubeSat developed jointly by the Ethiopian Space Science and Technology Institute (ESSTI) and the Chinese private company called Beijing Smart Satellite Technology(SmartSat) to provide earth observation services to China and African countries.

Built and launched with the help of China, the satellite is a 6U Earth observation nanosatellite with high resolution. The primary mission of the satellite program is to expose Ethiopian engineers and scientists to hands-on experience and demonstrate the Institute's capability in integrating nanosatellite subsystems locally. ESSTI prepared the preliminary design of the satellite and then the critical design, the manufacturing, assembly, integration and testing (MAIT) in close consultation with the ESSTI engineers. ET-SMART-RSS was launched on 22nd of December 2020 on a Chinese launch vehicle called Long March 8 (CZ-8) from the Wenchang Spacecraft Launch Site.

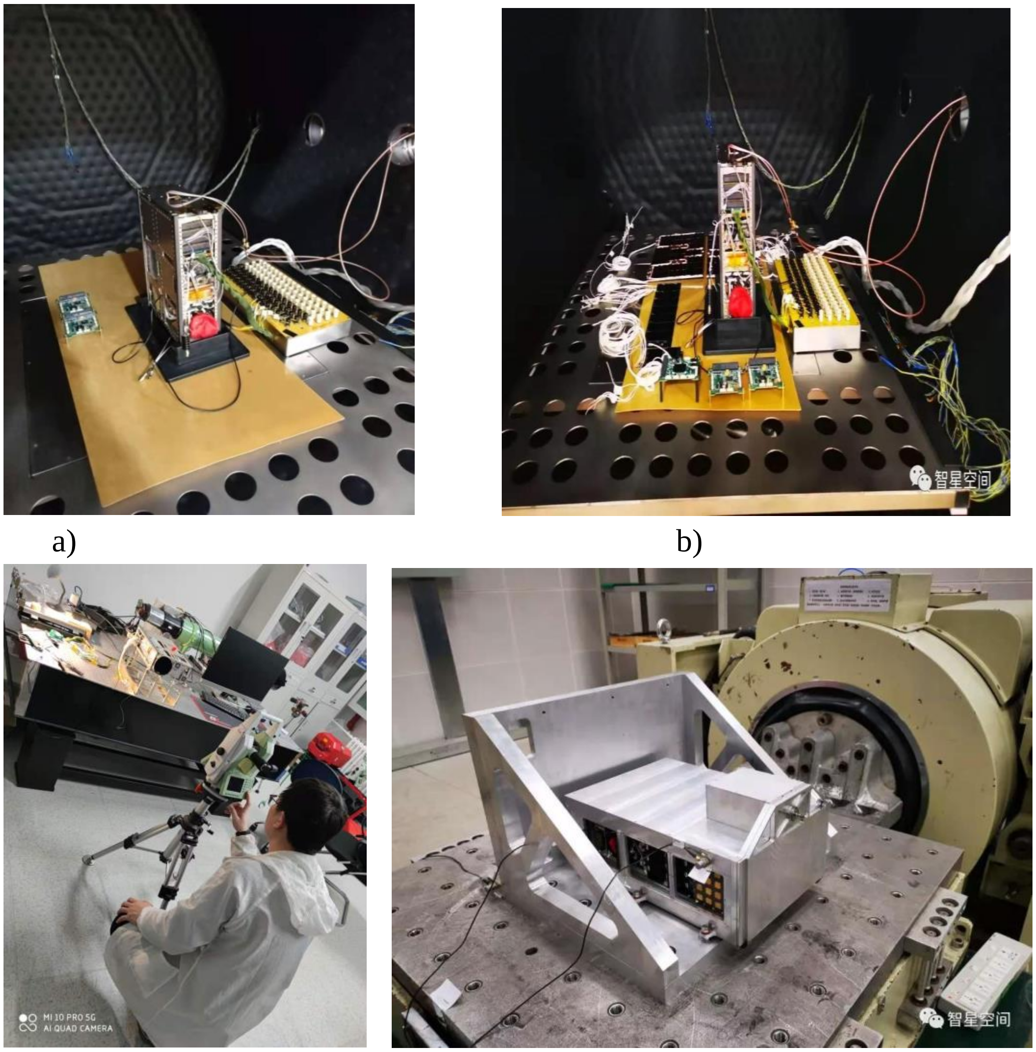
The Long March 8 carrier rocket adopts a core-stage bundled configuration with 2 boosters, with a total length of about 50.3 meters, a take-off mass of about 356 tons, a take-off thrust of about 480 tons, and a 700-kilometre sun-synchronous orbit with a carrying capacity of no less than 4.5 tons. The core structure of the rocket has a primary diameter of 3.35 meters, a secondary core diameter of 3 meters, a booster diameter of 2.25 meters, and a fairing diameter of 4.2 meters. The core level of the power system is equipped with two 120-ton YF-100 liquid oxygen kerosene engines, the second level of the core is equipped with two 8-ton YF-75 hydrogen-oxygen engines, and the booster is equipped with one 120-ton YF-100 liquid oxygen kerosene engine.

ET-SMART-RSS is the second Ethiopian satellite launched followed by ETRSS-1. ET-SMART-RSS has a higher resolution than ETRSS-1 and it has a 5.4m resolution and weighs 8.9kg From Chinese side ET-SMART-RSS is also called as Zhixing-1A. Its total cost is about 1.5 million USD in total funded jointly by the Belt & Road Initiative and SANY Group.

Table 2.1: ET-SMART-RSS Description

Satellite Name	**ET-SMART-RSS**
Category	Nano Satellite
Mass	8.9kg
Altitude	512km, Sun Synchronous Orbit
SWAZ	11.6km
Life Time	≥ 1 year
Payload Type	Multi-Spectral Camera (Red/Blue/Green/ near Infrared)
Mission	Remote Sensing Satellite for monitoring climate change, forest monitoring, water resource monitoring, agricultural monitoring, disaster monitoring
Resolution	5.4@512km
LTDN	12:00AM
Orbital Period	94.5min
Launch Site	WenChang Launch Center, Hainan Province, China
Launching Date	December 22, 2020
Date of Decay	October 21, 2023[53]

Figure 2.2: Launching of ET-SMART-RSS Satellite at Wenchang Spaceport



a) b)

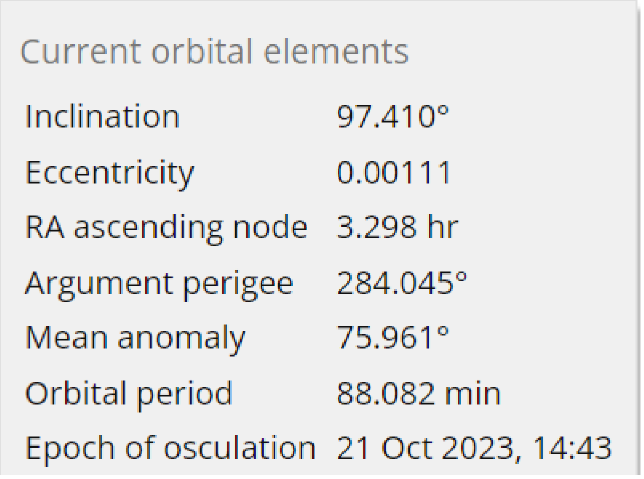
c) d)

Figure 2.3(a-d): Testing of ET-SMART-RSS Satellite at SMART Laboratory

Frequency Filing

The frequency filing with the International Telecommunication Union (ITU) was a critical step in ensuring that satellite missions like Ethiopia's ET-SMART-RSS CubeSat operate without causing or experiencing harmful interference with other satellites and ground-based communication systems. The process involves registering the satellite’s communication frequencies to obtain international recognition and protection under ITU regulations. The frequency filing documents are attached in Appendix (*See Appendices 1-8*).

Orbital Details of ET-SMART-RSS

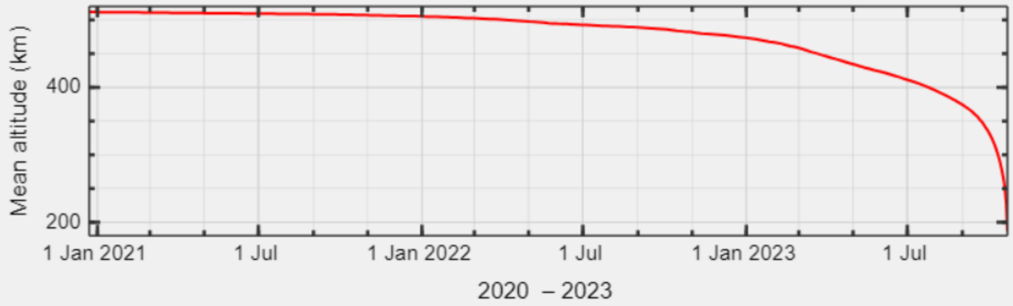


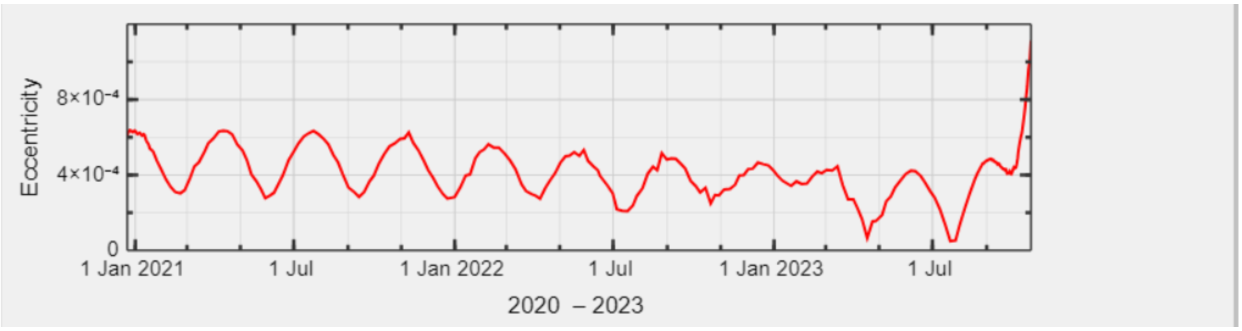
Current orbital elements

Inclination	97.410°
Eccentricity	0.00111
RA ascending node	3.298 hr
Argument perigee	284.045°
Mean anomaly	75.961°
Orbital period	88.082 min
Epoch of osculation	21 Oct 2023, 14:43

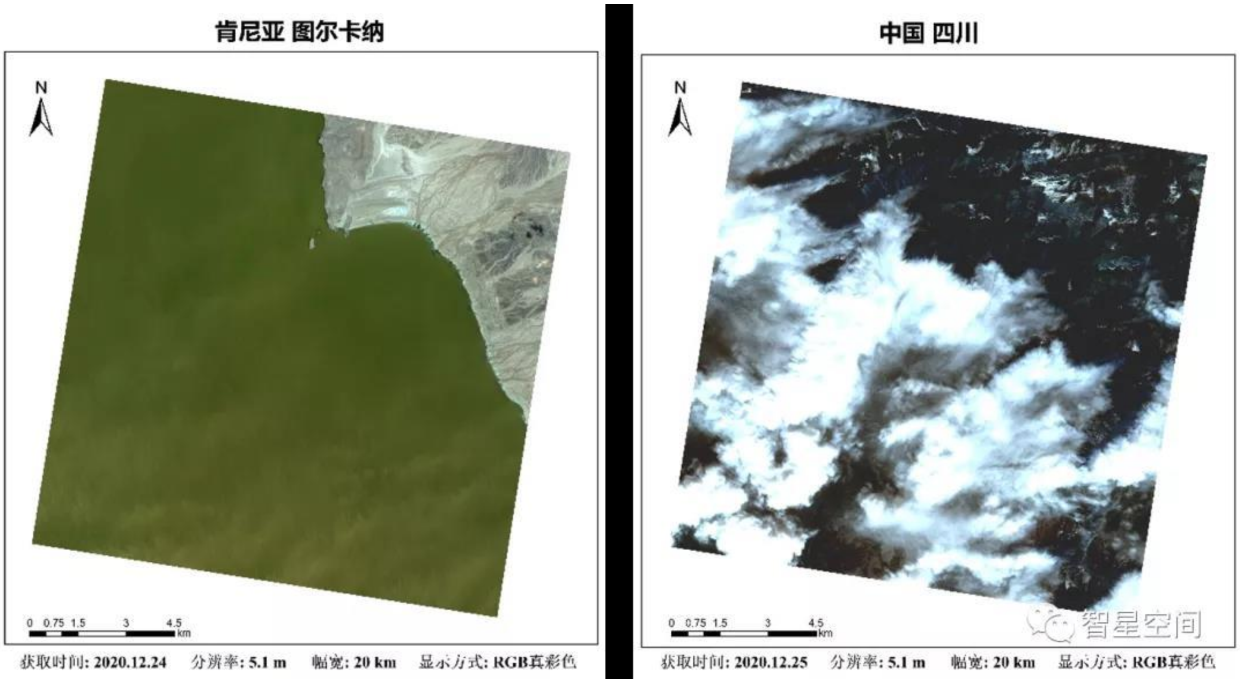
Orbital History

Drag the graphs below left or right to change the time range, or use your scroll wheel to zoom in or out.





Satellite Image from ET-SMART-RSS



Chapter Three

Methodology

3.1 Data Collection Methods

The data collection methods for this dissertation are by using computational approaches to gather accurate and relevant information for structural analysis. The key data collection methods are:

(i) **Design and Engineering Data Acquisition:** The first source of data is the detailed design and engineering specifications of the ET-SMART-RSS CubeSat. This includes technical drawings, material properties, geometric dimensions, and component layouts provided by the design and manufacturing teams. CAD models of the CubeSat are imported from software such as SolidWorks or Autodesk Inventor, which serve as the basis for computational simulations.

(ii) **Material Property Data:** Material data, such as Young's modulus, Poisson's ratio, density, thermal expansion coefficients, and failure thresholds, are gathered from material data sheets and standard engineering handbooks. This data is essential for assigning accurate material properties within the Finite Element Analysis (FEA) simulations.

(iii) **Environmental Load Data:** Data on environmental conditions experienced in Low Earth Orbit (LEO), such as temperature variations, radiation levels, and micrometeoroid and orbital debris (MMOD) impact probabilities, is collected from space environment databases like NASA's Space Environment Information System (SPENVIS) and other relevant satellite mission reports. This data is crucial for accurately simulating the thermal, mechanical, and impact loads in the FEA models.

(iv) **Literature and Comparative Data:** Data from existing literature on the structural analysis of nanosatellites and CubeSat missions is also collected to benchmark the ET-SMART-RSS analysis. This includes reviewing past CubeSat case studies, simulation methodologies, and material performance data published in peer-reviewed journals.

These data collection methods ensure that the computational models used for the structural analysis of the ET-SMART-RSS CubeSat are both accurate and validated, providing robust insights into its structural performance under the conditions experienced in Low Earth Orbit.

To properly execute Finite Element Analysis (FEA), we need to have the whole set of data regarding the structure we want to analyze. Therefore, the following data is taken from the 6U

CubeSat datasheet from Standard CubeSat platform. The material used for the satellite structure is Aluminum 6082-T6 with the following material properties.

Aluminum 6082 properties:

Aluminum is widely used in electronics, packaging, construction, machinery, and so on. According to the chemical composition, it is divided into alloy aluminum and pure aluminum. According to the processing shape, it is divided into aluminum coil, aluminum plate, aluminum sheet, aluminum strip, aluminum tube, aluminum rod, aluminum profile and so on. The mechanical properties are:

- Density: 2.7e^-6 kg/mm^3 (2700 kg/m^3)
- Young's modulus: 71970 MPa
- Poisson's Ratio: 0.33
- Tensile Yield strength: 259.2 MPa
- Tensile Ultimate strength: 318.6 MPa

Thermal analysis

- Isotropic Thermal conductivity: 0.172 W/mm. C (172 W/m. K)
- Specific heat constant pressure: 8.99e^05 MJ/kg.C (899 Jkg/K)
- Thermal expansion coefficient: 23.4 x 10^-6 K^-1
- The melting temperature: 585 – 650 C
- Solar Absorptivity: 0.7 to 0.9
- IR emissivity: 0.09 to 0.29

CubeSat dimension (HIGHLIGHTED FEATURES)

- Dimensions 6U: 100 x 226.3 x 366 mm
- Material: Aluminum 6082
- Four kill switches option
- Three roller switches option
- Customizable design
- Weight 6U*: 908 g * including bolts and 6 mounted rings

Structural specifications

3D: used for the thick structure and when stresses in the thickness

Elements (4 Element types)

- 1x Bottom element (+Z)
- 1x Top element (-Z)
- 2x side element
- 8x Ring element

Operational environment conditions: Low earth orbit (LEO)

- Altitude: 700 km
- Solar radiation:1361 W/m^2
- Albedo: 0.2 to 0.3
- Infrared radiation from the earth: 237 W/m^2
- Temperature: -65 to +125 C

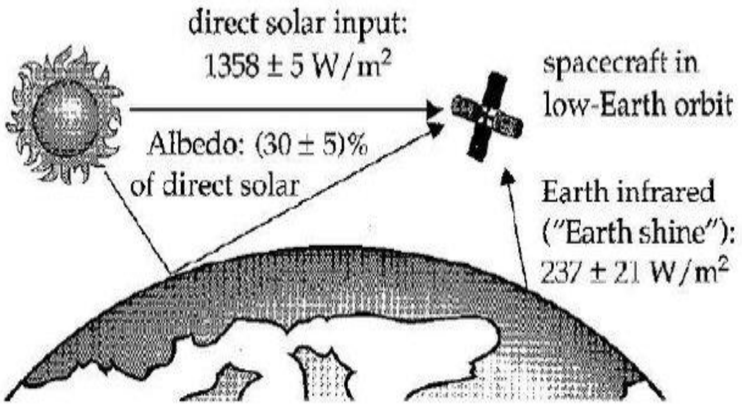


Figure 3.1. The operational environment of the CubeSat at LEO

3.2 Finite Element Analysis (FEA) Techniques

The finite element analysis (FEA) is a computational technique used to obtain approximate solutions of boundary value problems in engineering or used to predict how objects respond to various physical conditions, such as forces, vibrations, heat, and fluid flow. It is the process of predicting an object's behavior based on calculations made with the finite element method (FEM). FEA is the interpretation of the results FEM provides. FEA gives engineers insights into complex systems and structures, helping them make more informed design decisions.

The FEA techniques, applied using advanced simulation tools such as ANSYS and SCOMSOL Multiphysics, provide a robust framework for optimizing the design of the ET-SMART-RSS CubeSat, ensuring that it meets the demanding structural requirements of space missions.

The FEA Techniques Process

1. **Pre-process:** Define the physics and real-world conditions for the model.
2. **Process:** solving each equation.
3. **Post-process:** Compute results to analyze and interpret implications for the whole domain.

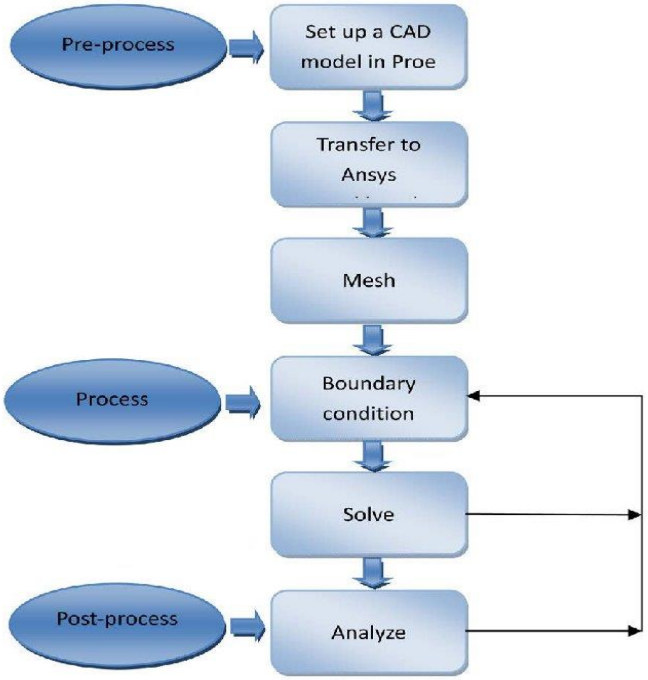


Figure 3.2. The Finite Element Analysis steps

Advantages of FEA Technique

- Time efficient
- Cost efficient
- Error reduction
- Design optimization
- Multi-physics simulations

- Handle complexity

Application of FEA Technique

- Mechanical Engineering: Aerospace/Automobile/Marine/
- Structural/Stress analysis
- Fluid flow
- Heat Transfer
- Soild mechanics

3.3 Computational Tools and Software

Computational tools are used for performing different analyses such as structural, thermal, fluid dynamics, and electromagnetic of real-world multiphysics simulation. There are many powerful computational software that tool allow engineers to perform analysis by following procedures of pre-processing, solving, and post-processing for a wide range of applications.

Some of the computational software is:

- ANSYS Workbench
- Abaqus
- SolidWorks simulations and
- Simscale

is where the key computational tasks occur including meshing, applying boundary conditions, simulating external forces, and post-processing the results. The Finite element analysis (FEA) was executed using a computational tool which is ANSYS Workbench for structural, modal, and thermal simulations analysis.

This dissertation employs a variety of advanced computational tools and software to conduct the structural analysis of the ET-SMART-RSS, Ethiopia's 6U CubeSat. These tools are integral to simulating the physical behaviors of the nanosatellite under diverse environmental conditions encountered in low Earth orbit (LEO). Among the primary software utilized is ANSYS, a highly regarded FEA platform known for its versatility in simulating static and dynamic structural conditions, thermal analysis, and material behavior. ANSYS allows for detailed modeling of the satellite's structural components, providing critical insights into stress distribution, deformation, and failure points under various load scenarios.

In addition to ANSYS, COMSOL Multiphysics is employed for multiphysics simulations, particularly where structural, thermal, and electromagnetic effects interact. This software's ability to couple different physical phenomena makes it ideal for capturing the complex interactions that nanosatellites experience in space. SolidWorks is also used in the early stages of the design process for CAD modeling of the CubeSat structure. SolidWorks facilitates the creation of highly detailed 3D models, which are then imported into the FEA software for further analysis.

These computational tools provide the foundation for a comprehensive structural analysis, enabling precise simulations and optimizations of the ET-SMART-RSS CubeSat's design. The integration of these software platforms ensures that the satellite's structural performance meets the rigorous demands of LEO missions.

3.4 Structural Analysis Techniques

Structural analysis is the determination of the effects of loads on physical structures and their components. The analysis is performed to evaluate the behavior of structures under different external loads and conditions. This includes buildings, bridges, vehicles, furniture, clothing, soil, prostheses, and biological tissue. It employs the fields of mechanics, materials science, and mathematics to compute a structure's deformations, stresses, and support reactions. Its purpose is to analyze the strength, stiffness, stability, and vibration of the structure under different loading conditions.

The structural analysis of the ET-SMART-RSS CubeSat, a 6U nanosatellite designed for operation in low Earth orbit (LEO), employs a range of sophisticated computational techniques to ensure the satellite's structural integrity under the harsh conditions of space. These techniques are crucial in evaluating the CubeSat's ability to withstand forces encountered during launch, deployment, and orbital operation.

a) Static Structural Analysis is the primary method used to evaluate the satellite's response to various loading conditions, including launch forces, internal component stresses, and external loads. This technique focuses on assessing stress distributions, deformation, and potential weak points in the satellite structure under a steady state of applied forces. The results of this analysis inform necessary design adjustments to enhance structural stability.

b) Modal Analysis is performed to determine the natural frequencies and mode shapes of the CubeSat. This technique is particularly important for avoiding resonance phenomena, which could lead to catastrophic failure during launch due to vibrations. Understanding the modal characteristics helps in adjusting the design to ensure that the natural frequencies of the CubeSat do not coincide with the frequencies of external vibrational forces.

c) Thermal Analysis simulates the extreme thermal conditions experienced in LEO, where the CubeSat is subjected to rapid temperature fluctuations between the sunlit and shadowed regions of orbit. This technique evaluates thermal expansion, contraction, and thermal stress effects on the satellite's structural components, ensuring the satellite remains functional across the broad temperature ranges experienced in space.

d) Transient Dynamic Analysis models the satellite's response to time-varying or impact loads, such as those generated by micro-meteoroid impacts or space debris collisions. This technique is essential for evaluating how the structure absorbs and dissipates shock over time, ensuring the satellite's durability and resilience.

These structural analysis techniques, when combined with advanced computational simulations, provide a thorough evaluation of the ET-SMART-RSS CubeSat's performance. The use of these techniques helps to optimize the satellite's design, ensuring it is capable of withstanding the dynamic and extreme conditions of LEO, thus enhancing mission success and satellite longevity.

3.5 Computational Simulation Setup

The structural analysis computational simulation setup involves multiple steps to ensure reliable and accurate results.

The computational simulation setup has the following steps

i. Modeling of the structure
ii. Assigning the material
iii. Define material properties
iv. Apply boundary conditions

v. Define loads
vi. Meshing the model
vii. Run the simulations/Solve
viii. Postprocessing results and
ix. Validation

The simulation setup for the structural analysis of the ET-SMART-RSS, Ethiopia's 6U CubeSat, is a critical phase of the research, ensuring that the computational models accurately reflect the physical conditions encountered in low Earth orbit (LEO). The setup involves careful definition of the CubeSat's geometric model, material properties, boundary conditions, and loading scenarios to replicate real-world operational environments. The first step in the simulation process is the geometric modeling of the CubeSat structure using CAD software such as SolidWorks. The detailed 3D model includes all key structural components, such as the satellite's chassis, solar panels, internal electronics housings, and deployment mechanisms. Once the geometry is defined, it is imported into FEA software like ANSYS or COMSOL Multiphysics, where further preprocessing occurs.

Material properties are assigned to each component based on the materials used in the CubeSat's construction. For instance, aerospace-grade aluminum is commonly used for the CubeSat's frame due to its strength-to-weight ratio, while other components may use materials like carbon fiber or specialized polymers. Each material is defined by its mechanical properties, including Young's modulus, Poisson's ratio, density, and thermal expansion coefficient.

Boundary conditions play a crucial role in the accuracy of the simulation. For the ET-SMART-RSS CubeSat, the boundary conditions are applied based on the specific phases of the mission being analyzed. During launch, for example, the CubeSat experiences fixed constraints at points of attachment to the launch vehicle, while in orbit, the satellite operates in a largely unconstrained environment except for the forces exerted by internal components and the thermal conditions of space.

Loading scenarios are simulated to mimic the forces experienced during various phases of the CubeSat's mission. These include static loads from mechanical stresses during launch, dynamic loads from vibrational forces, and thermal loads caused by the temperature fluctuations in LEO. Additionally, transient loads from potential space debris impacts are simulated to assess the satellite’s resilience to sudden shocks.

The meshing of the geometric model is another essential component of the simulation setup. The meshing process subdivides the CubeSat structure into small finite elements, where each element’s response to loads and boundary conditions can be individually calculated. Careful attention is paid to mesh density; finer meshes are used in areas with complex geometries or where high stresses are expected, while coarser meshes are applied to regions with less critical structural behavior to optimize computational resources.

The simulation setup is finalized by defining the solver settings within the FEA software. Appropriate solvers are selected based on the nature of the analysis (static, dynamic, thermal, etc.), and convergence criteria are established to ensure the accuracy and stability of the solutions. Simulation parameters, such as time steps for transient analysis or frequency ranges for modal analysis, are carefully selected to align with the expected physical phenomena during the CubeSat’s mission. By meticulously setting up the simulations to mirror real-world conditions, the analysis provides valuable insights into the structural performance of the ET-SMART-RSS CubeSat, ensuring that it meets the rigorous demands of spaceflight and orbital operation.

3.6 Case Study Approach

The case study approach employed in this dissertation focuses on the ET-SMART-RSS, Ethiopia’s 6U CubeSat, to demonstrate the application of structural analysis techniques for low Earth orbit (LEO) nanosatellites. This method offers an in-depth, real-world examination of the satellite's design, environmental interactions, and structural performance, enabling a detailed analysis that reflects the actual operational challenges faced by LEO nanosatellites. The ET-SMART-RSS is selected as a representative case due to its relevance as Ethiopia's first CubeSat mission, providing a unique opportunity to assess the structural demands placed on small satellites, particularly from emerging space programs.

In this approach, the CubeSat’s design is evaluated under the specific mechanical and thermal stresses that are expected during various mission phases, including launch, deployment, and in-orbit operation. By focusing on a single satellite, the case study allows for a highly targeted analysis, where finite element models are tailored to the precise specifications of the ET-SMART-RSS, taking into account its geometric constraints, material properties, and mission parameters. This specificity enables the identification of potential structural weaknesses and the optimization of design elements to enhance performance and longevity.

Moreover, the case study approach allows for the validation of computational methods through comparison with real mission data, such as pre-launch testing results and post-launch telemetry. This comparison ensures that the finite element simulations accurately predict the satellite’s structural behavior, providing a robust foundation for design recommendations and improvements. The insights gained from this case study extend beyond the ET-SMART-RSS, offering valuable lessons for the design, analysis, and testing of future CubeSats, particularly for countries with developing space programs, where resource constraints necessitate optimized and reliable satellite designs.

The case study is the structural analysis of standard 6U CubeSat structure using Finite element analysis (FEA) in ANSYS Workbench, which is developed to operate at low earth orbit (LEO) at an altitude of 700km using the aluminum 6082-T6 materials with a total weight of 908 grams. The 6U CubeSat structure is assumed to be placed on the P-POD vertical with the launch load for vertical 10g along the Y-axis and 2g along the lateral axis.

To assess the structural performance of the CubeSat under various mechanical loads and simulated LEO conditions including the thermal effects from solar radiation, IR from earth, and albedo that the CubeSat might encounter during launch and operation. The simulated LEO environment is created for analyzing for 30-minute duration on the space. The structure is empty without any component inside it.

Chapter Four

Analysis and Result

4.1 Design and Construction of ET-SMART-RSS

CubeSats, a class of nanosatellites, are a cost-efficient platform for science investigations, earth observation, and the capability of demonstrating a satellite constellation mission it also uses a standard size and form factor. The standard CubeSat size uses a “one unit” or “1U” measuring 10x10x10 cm and is extendable to larger sizes; 1.5, 2, 3, 6, and even 12U. ET-SMART-RSS is a 6U Cubesat having an overall size of 100 x 226.3 x 340.5 mm and weighing 8.9kg. It is a remote sensing satellite with a resolution of 5.4m. Details about the satellite are shown in Table 2.1.

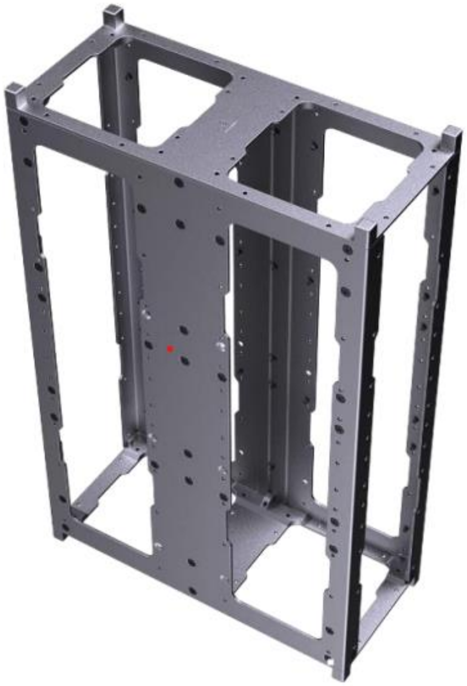


Figure 4.1. ET-SMART-RSS CubeSat Structure

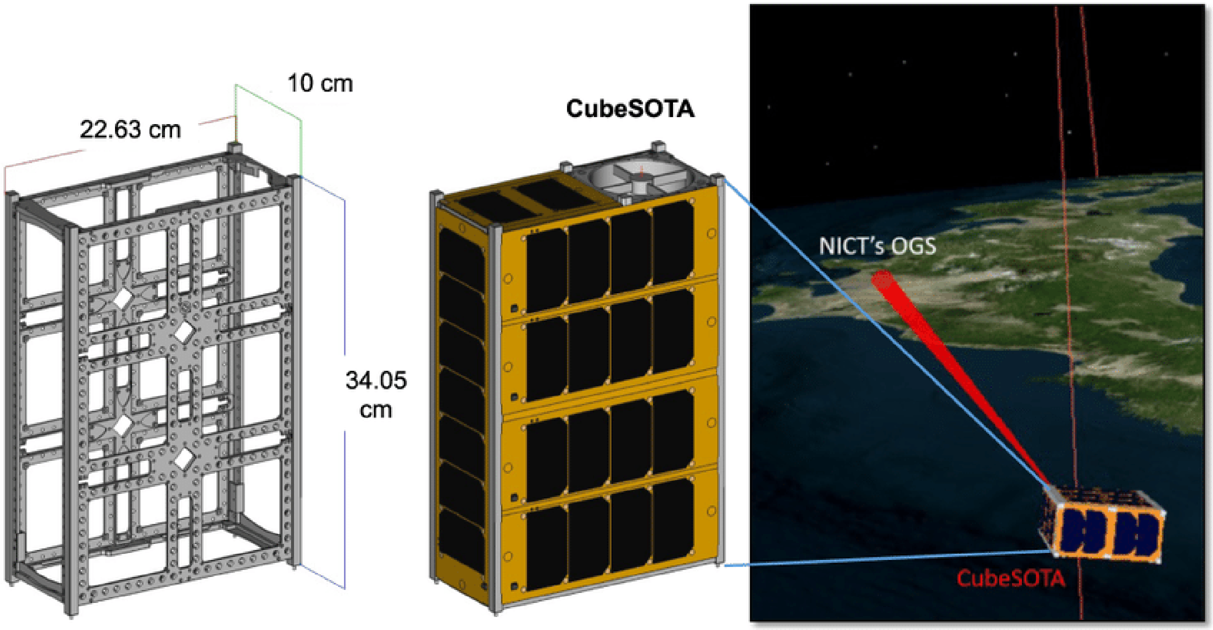


Figure 4.2. 6U CubeSat Structural frame and fully operational CubeSat onboard

For the structural analysis, the structure features considered are as follows:

- Dimensions: 100 x 226.3 x 340.5 mm
- Material: Aluminum 6082
- Four kill switches option
- Three roller switch option
- Customizable design
- Weight 6U: 8.9kg including bolts and mounted rings.

Elements (4 Element types)

- 1x Bottom element (+Z)
- 1x Top element (-Z)
- 2x side element
- 8x Ring element

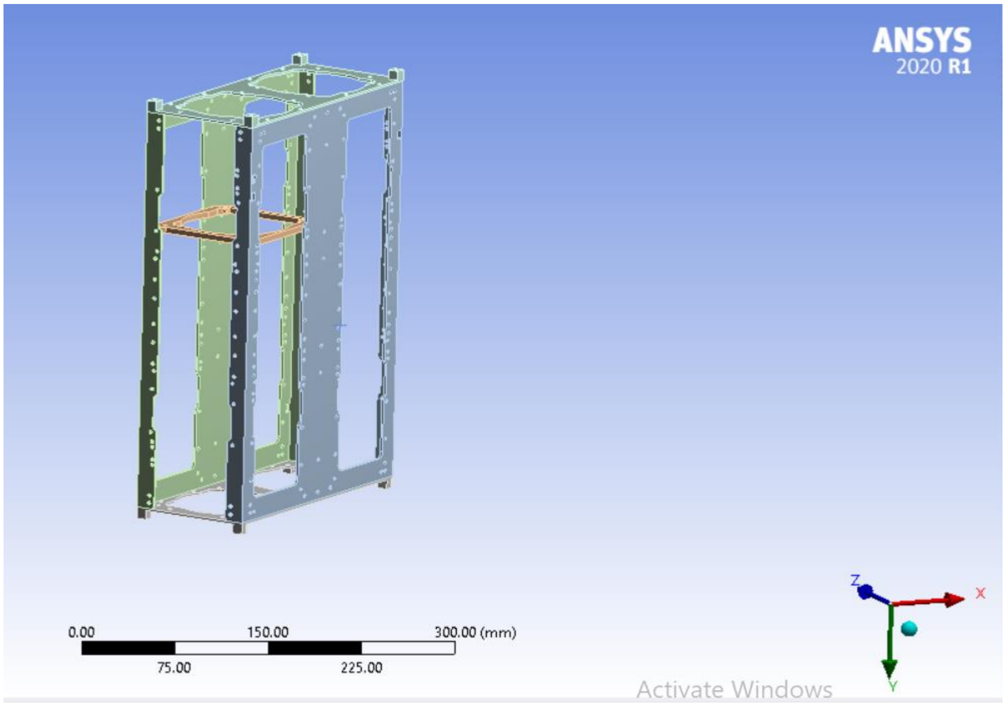


Figure 4.3. 6U CubeSat structure 3D model

4.2 Structural Analysis of ET-SMART-RSS

The structural analysis has been conducted on the ANSYS Workbench for different types of analysis such as

(1) Simulation setup

Mesh: 3D: used for the thick structure and when stresses in the thickness.

Applied: 2.5mm for mesh

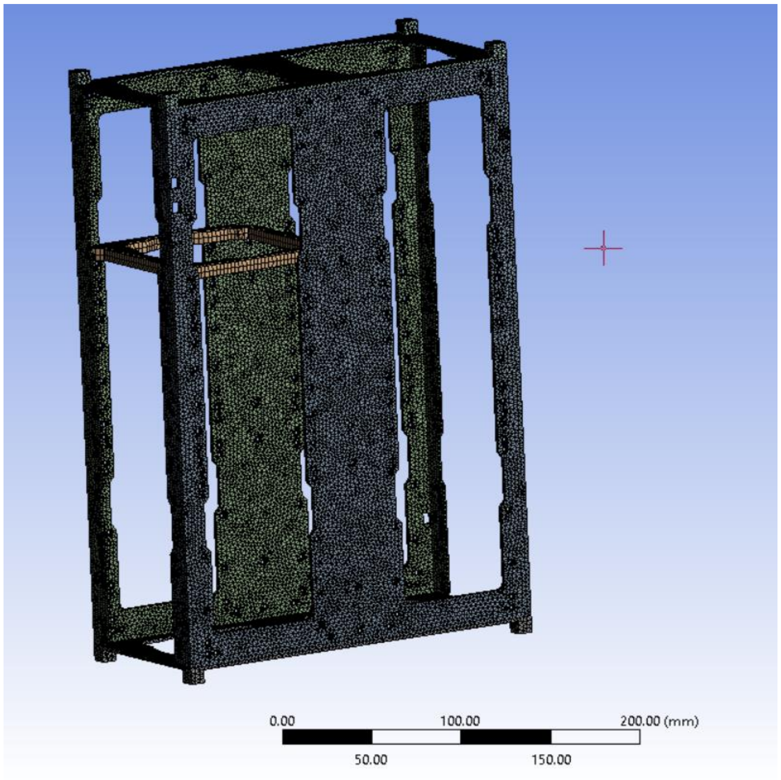


Figure 4.4. Meshed 6U CubeSat structure in ANSYS Workbench

Boundary condition which is a support location for the structure

a. Fixed support applied at the bottom element

Applied at the bottom element which is designed to be fixed to the launch vehicle

b. Frictionless support applied at the 2x side element

Applied at 2x sides of the structure for CubeSat deployment scenarios where the satellite is sliding along rails during launch or ejection from a deployer. It will allow the tangential motion but restrict movement perpendicular to the contact.

(2) Load application

a. Gravitational Load: self-weight Load

Standard earth gravity**:** which sets the gravity direction (usually -Y or downward) by entering the gravitational acceleration value 9.81 m/s^2 = -9806.6 mm/s2

b. Launch Acceleration Load

The launch acceleration load is the force that is subject to the CubeSat when the vehicle is launched to deploy the satellite into space. This load is much greater than that of gravity which is pulling back downward. It is known as the multiples of earth's gravity. For this case study, it is considered to be the average of 10g which means 10 times the acceleration due to gravity.

10g Axial load Y-axis = 10g = 10 x 9.81 m/s2 = 98.1 m/s2

= 98100 mm/s2

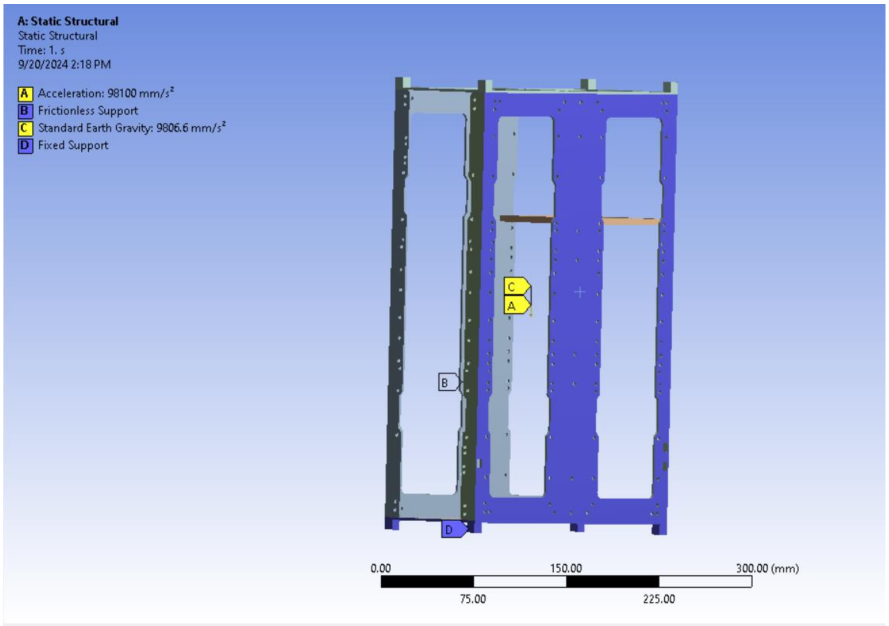


Figure 4.5. Solver setup on 6U CubeSat structure in ANSYS Workbench

4.3 Results and Findings

i) Static structural analysis

A static analysis calculates the effects of steady loading conditions on a structure, while ignoring inertia and damping effects, such as those caused by time-varying loads. A static analysis can, however, include steady inertia loads, such as gravity and rotational velocity, and time-varying loads that can be approximated as static equivalent loads (such as the static equivalent wind and seismic loads commonly defined in many building codes).

Static analysis determines the displacements, stresses, strains, and forces in structures caused by loads that do not induce significant inertia and damping effects.

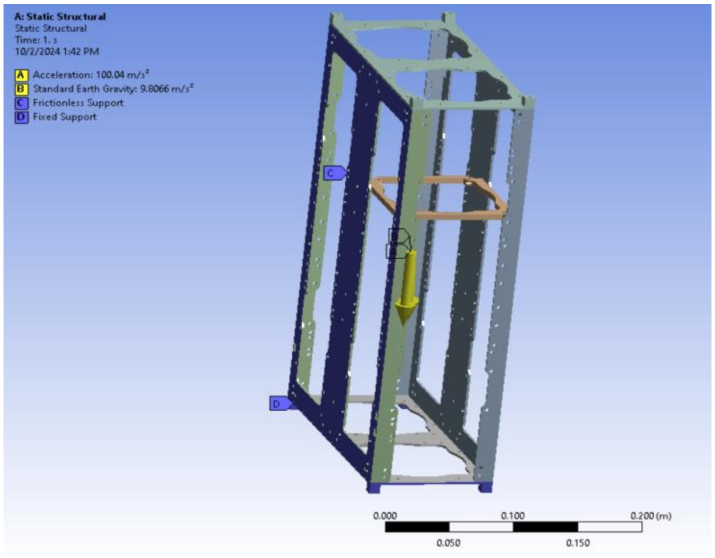


Figure4.6. Solver setup of static structural analysis

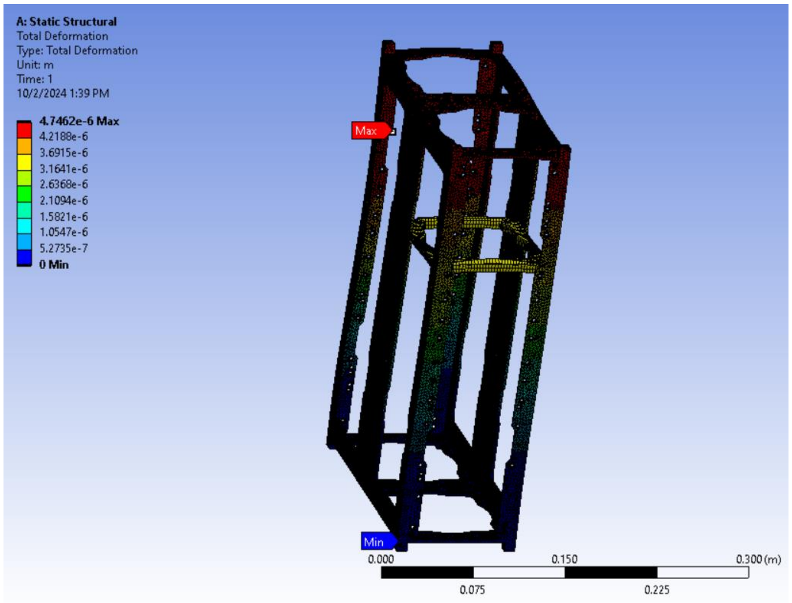


Figure4.7. Total deformation of 6U CubeSat structure

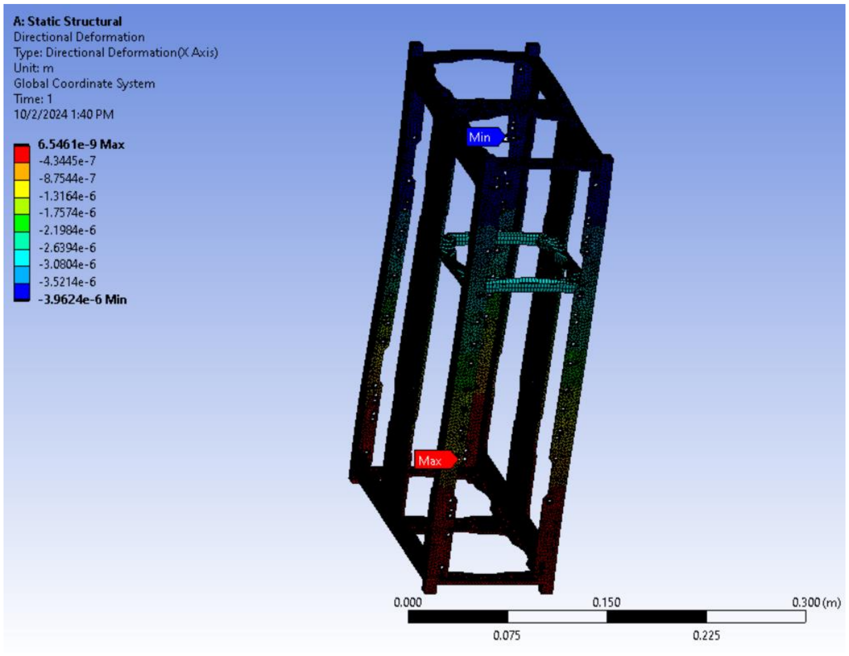


Figure 4.8. Directional deformation (X-axis) of 6U CubeSat structure

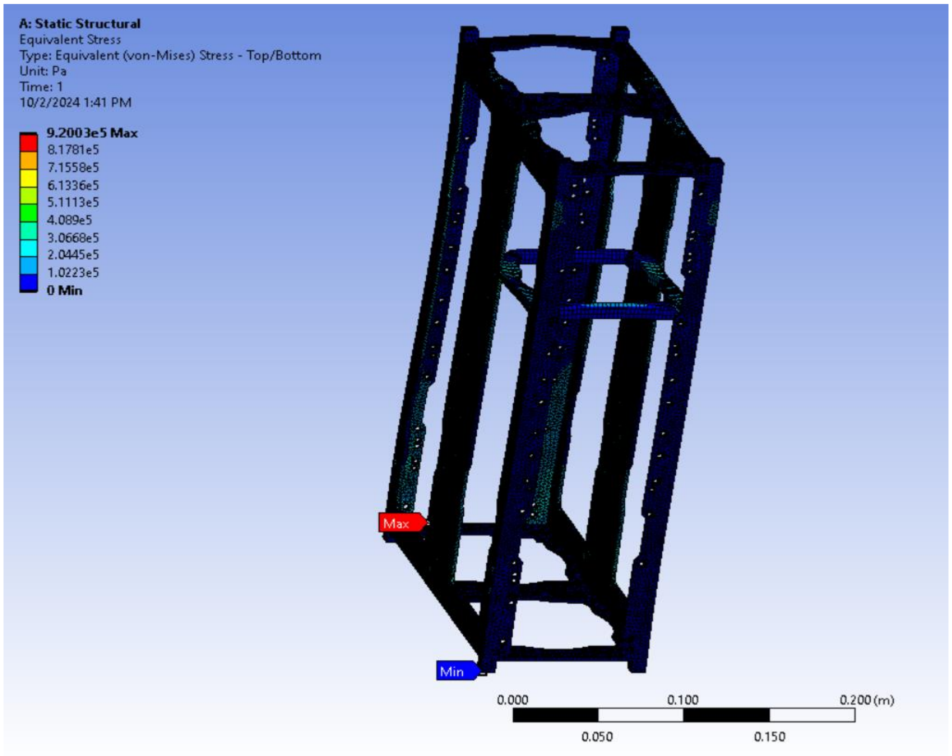


Figure 4.9. Von-Mise's stress of 6U CubeSat structure

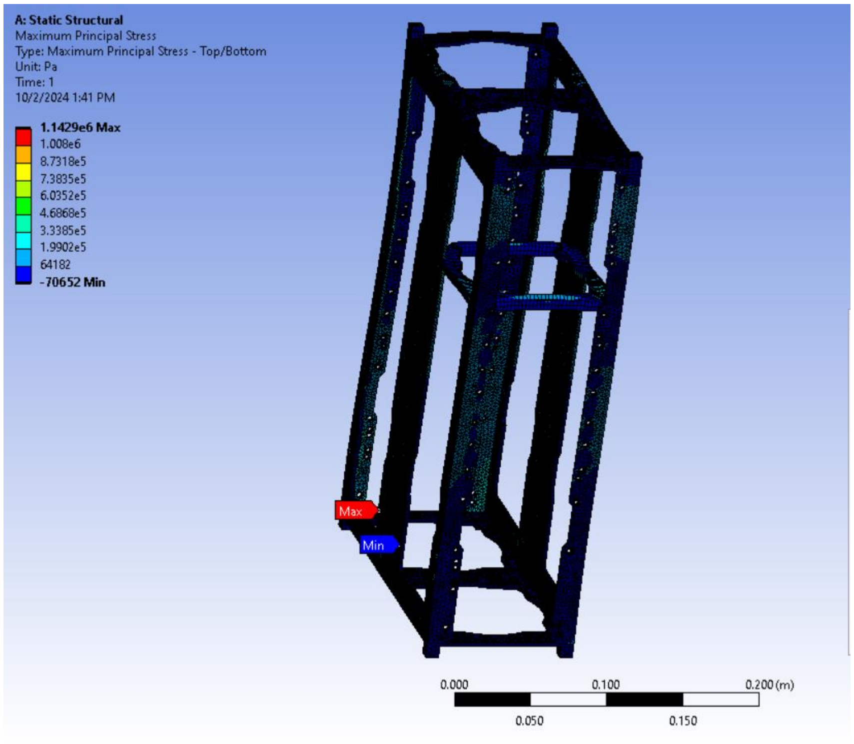


Figure 4.10. Maximum Principal Stress of 6U CubeSat structure

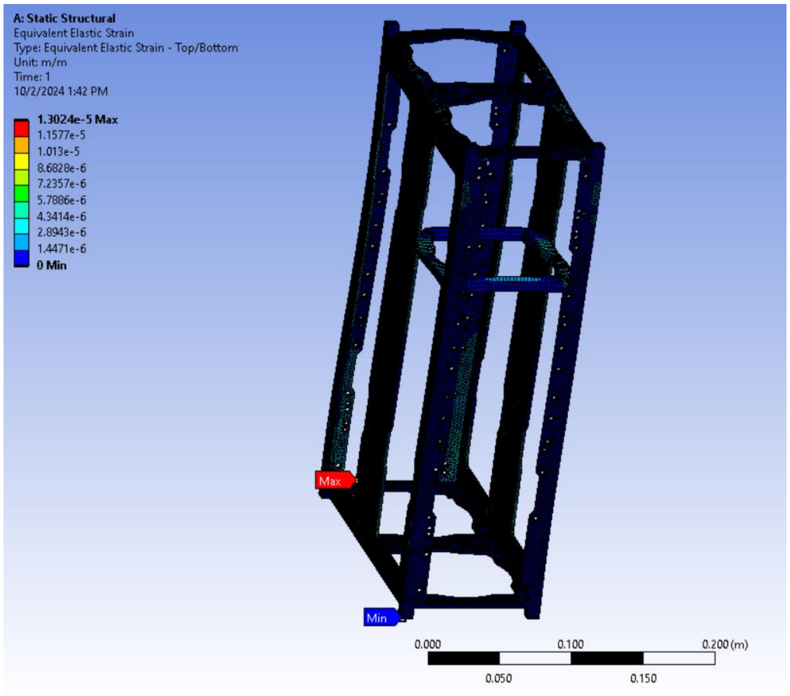


Figure 4.11. Equivalent Elastic strain of 6U CubeSat structure

ii) Transient Structural analysis

Transient structural analysis in ANSYS is also called a time-history analysis. This type of analysis is used to determine the dynamic response of a structure under the action of any general time-dependent loads. Transient analysis is used to determine the time-varying displacements, strains, stresses, and forces in a structure as it responds to any transient loads.

The time scale of the loading is such that the inertia or damping effects are considered to be important. If the inertia and damping effects are not important, this analysis can be avoided and a simple static analysis can be performed. A transient structural (ANSYS) analysis can be either linear or nonlinear. All types of nonlinearities are allowed including but not limited to large deformations, plasticity, contact, hyper elasticity etc.

To apply force on the CubeSat structure use the second law of Newton

F = m.a

a_total = 9.81 m/s2 + 10g(98.1m/s2) = 107.91 m/s2

m = 0.908 kg

F = m.a = 0.908 x 107.91 = 97.96 N

F = 97.96N along Y-axis

For the lateral axis along X and Z-axis

F = m.a

a_total = 2g(9.81m/s2)

m = 0.908 kg

F = m.a = 0.908 x 2x9.81 = 17.814 N

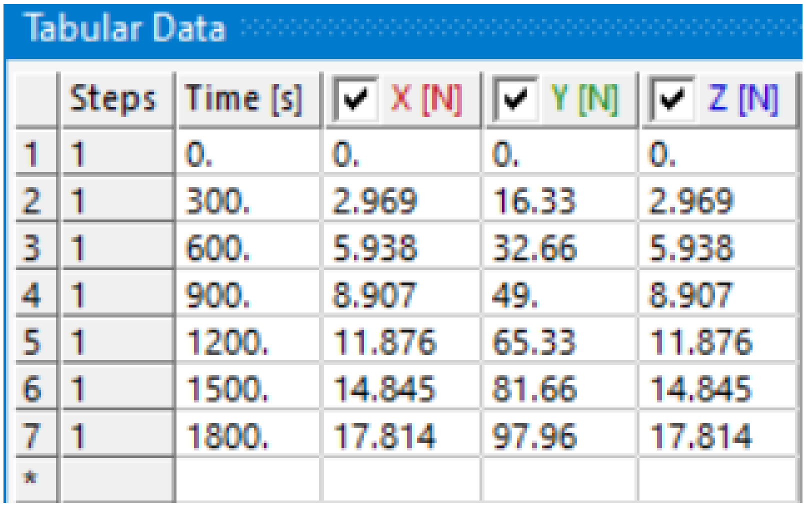
F = 17.814 N along the X and Z-axis

Simulation setup

For transient structural analysis of 6U CubeSat analysis

By considering the structure as linear for ramping the load.

Table 4.1. Transient analysis



Tabular Data

	Steps	Time [s]	☑ X [N]	☑ Y [N]	☑ Z [N]
1	1	0.	0.	0.	0.
2	1	300.	2.969	16.33	2.969
3	1	600.	5.938	32.66	5.938
4	1	900.	8.907	49.	8.907
5	1	1200.	11.876	65.33	11.876
6	1	1500.	14.845	81.66	14.845
7	1	1800.	17.814	97.96	17.814
*					

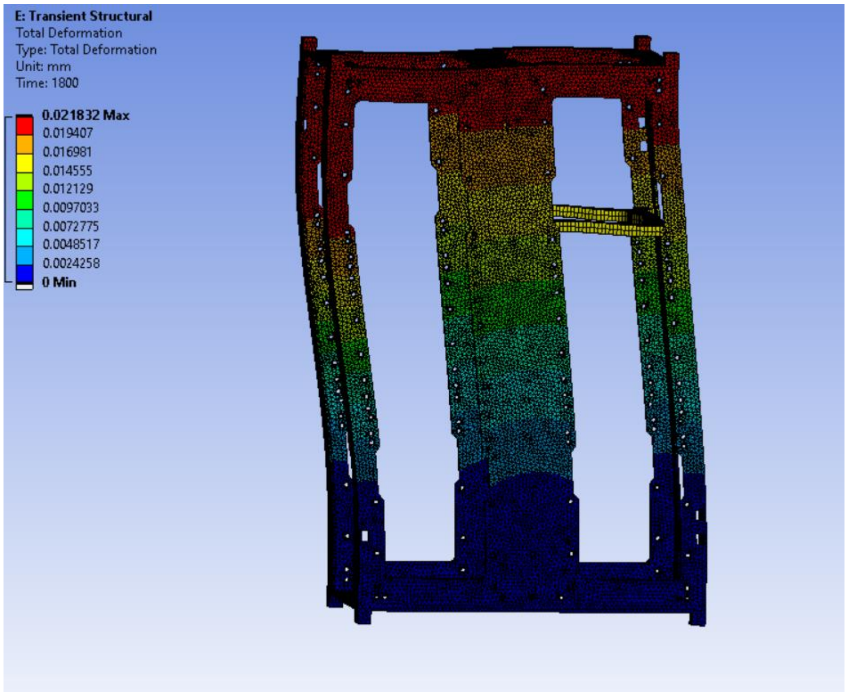


Figure 4.12. Total deformation of 6U CubeSat structure

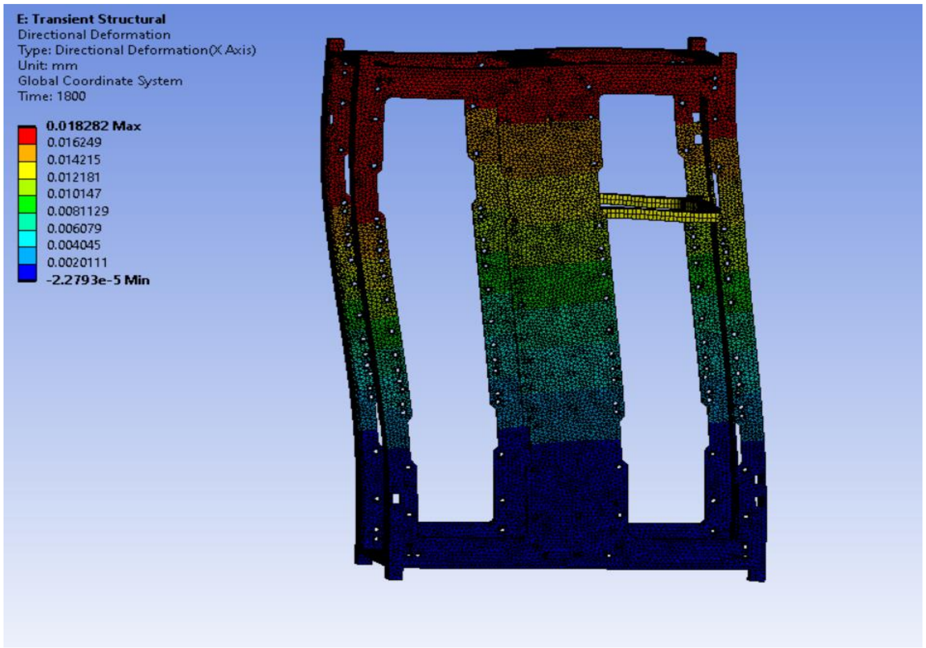


Figure. 4.13. Directional deformation along the X-axis of 6U CubeSat structure

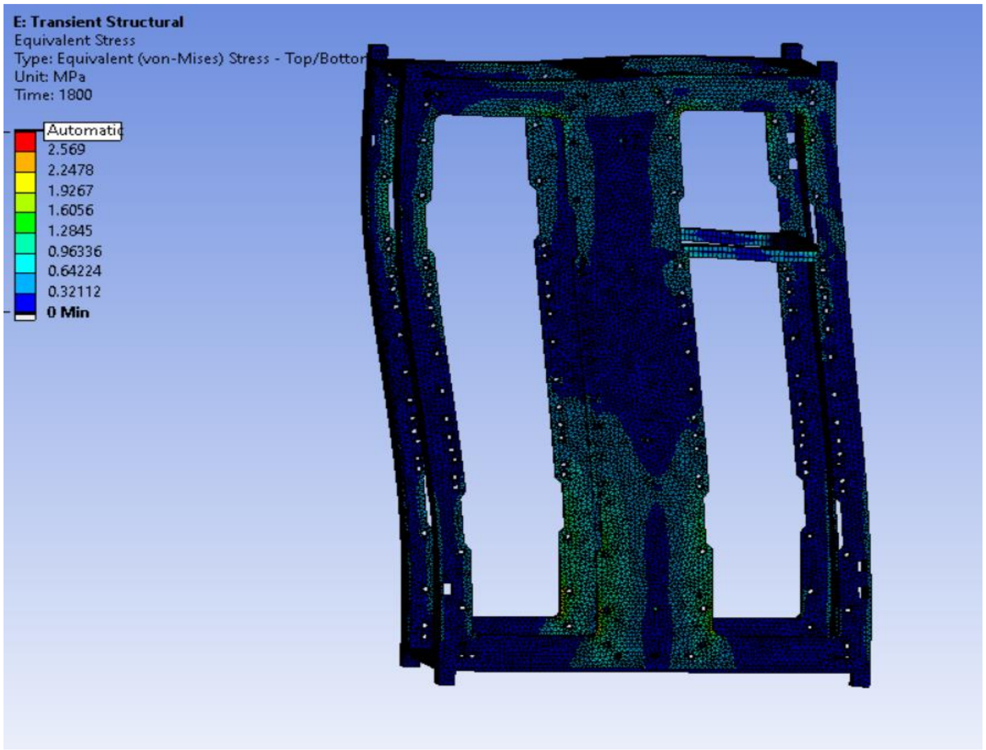


Figure 4.14. Equivalent Stress of 6U CubeSat structure

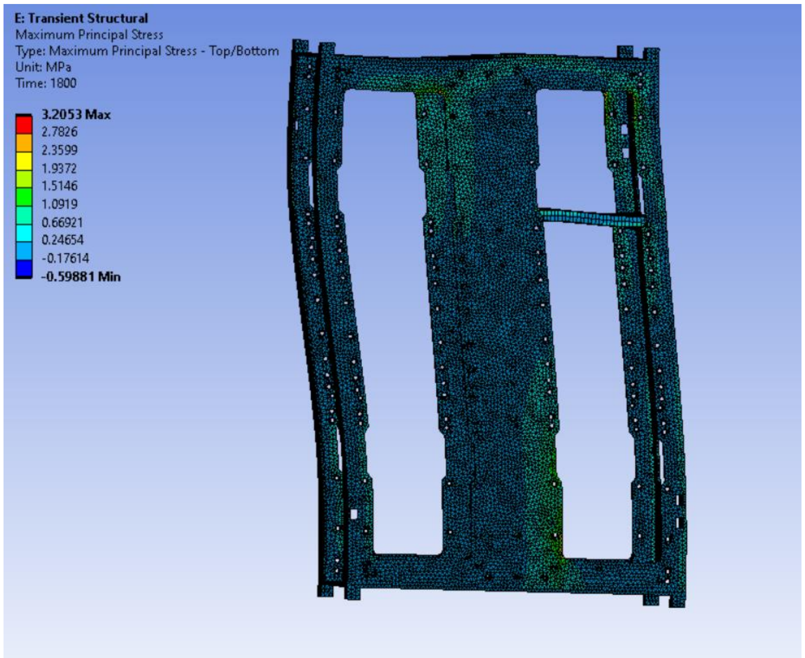


Figure 4.15. Maximum Stress of 6U CubeSat structure

iii) Modal Analysis of 6U

Modal analysis is the study of the dynamic properties of systems in the frequency domain. The goal of modal analysis in structural mechanics is to determine the natural mode shapes and frequencies of an object or structure during free vibration. The natural frequencies are frequencies at which the CubeSat will get excited and large displacements of the structure will occur when the CubeSat is subject to a vibration

After conducting the modal analysis for the empty 6U CubeSat structure to detect the fundamental frequencies, the results show that the first or lowest mode frequency is 331.23 Hz, which is greater than the acceptable minimum requirement for CubeSats of 100 Hz. This ensures that the structure will avoid resonance.

$$M \cdot \ddot{u} + C \cdot \dot{u} + K \cdot u = f(t).$$

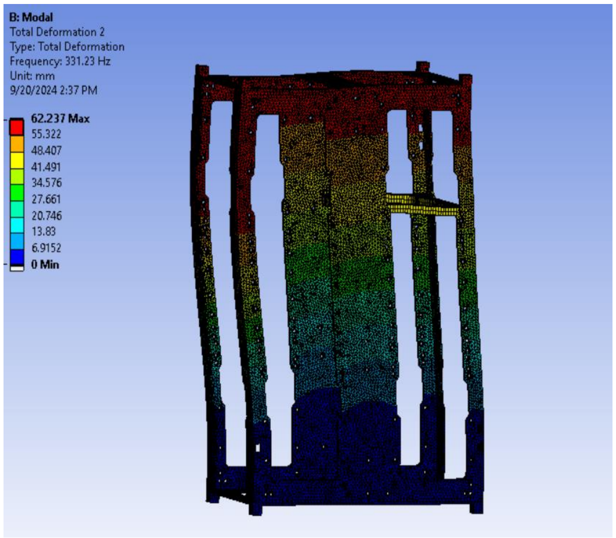
Where:

M, C, K: denoted the structural mass, damping and stiffness matrices

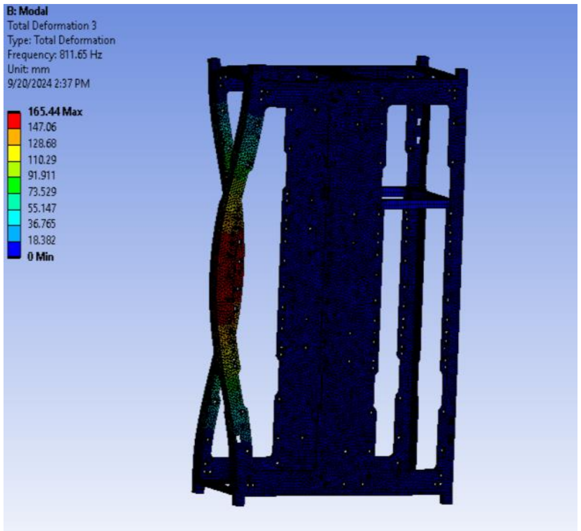
$\ddot{u}$, $\dot{u}$, u: the vectors of accelerations, velocities, and displacements respectively f(t): the vector of applied forces.

Table 4.2. The first 10 modes and frequencies of the CubeSat structure

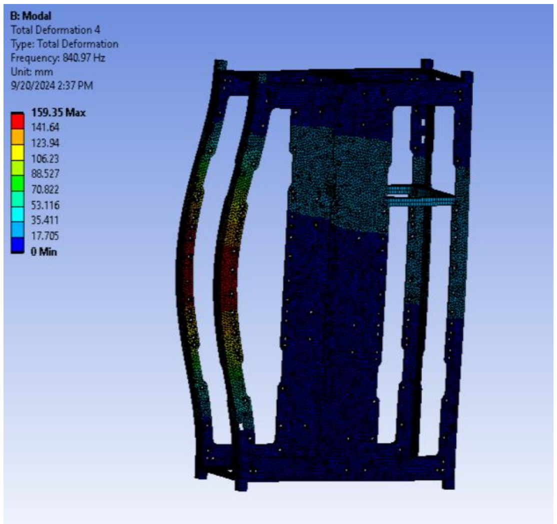
No	Mode	Frequency [Hz]
1	1	331.23
2	2	811.65
3	3	840.97
4	4	1325.1
5	5	1379.
6	6	1723.3
7	7	1784.5
8	8	1841.8
9	9	1958.5
10	10	1990.8



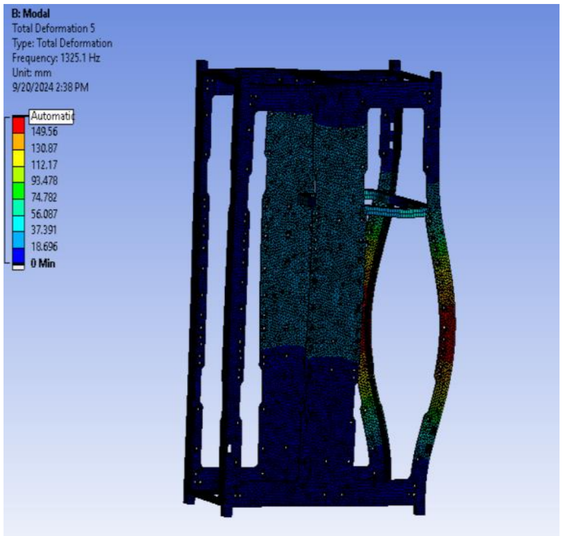
a) Mode one f_1 = 331.23 Hz, Def= 0.602m



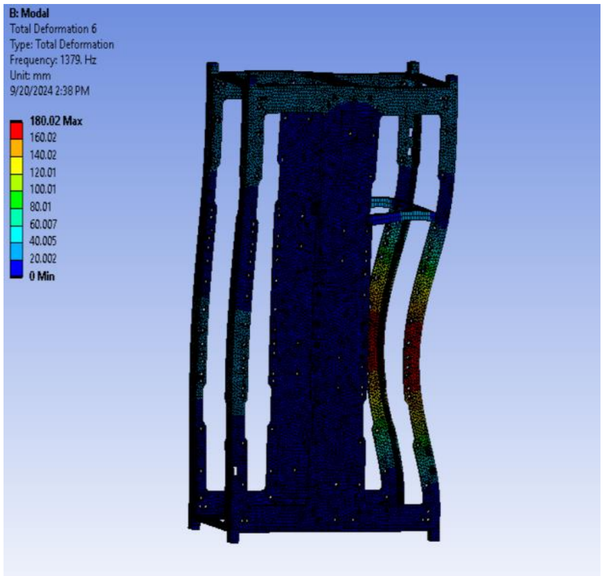
b) Mode two f_2 = 881.65 Hz Def =0.165m



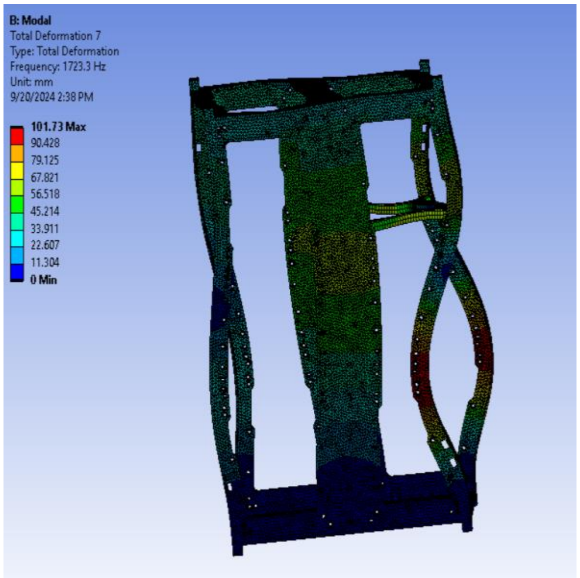
b) Mode three f_3 = 840.97 Hz Def=0.159m



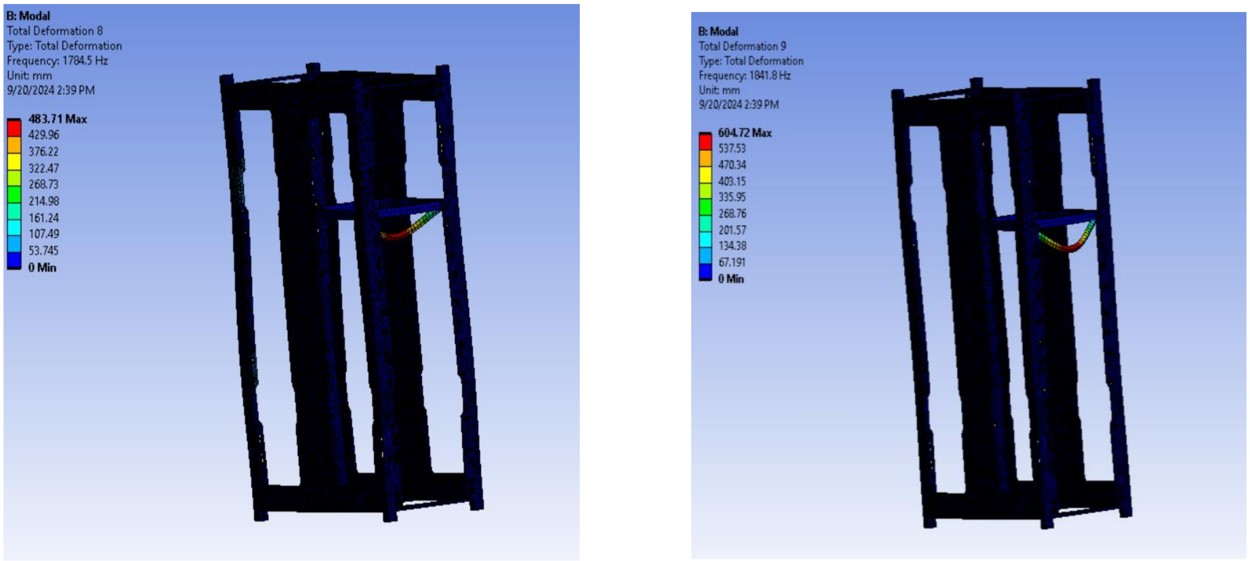
d) Mode four f_4 = 1325.1 Hz Def =



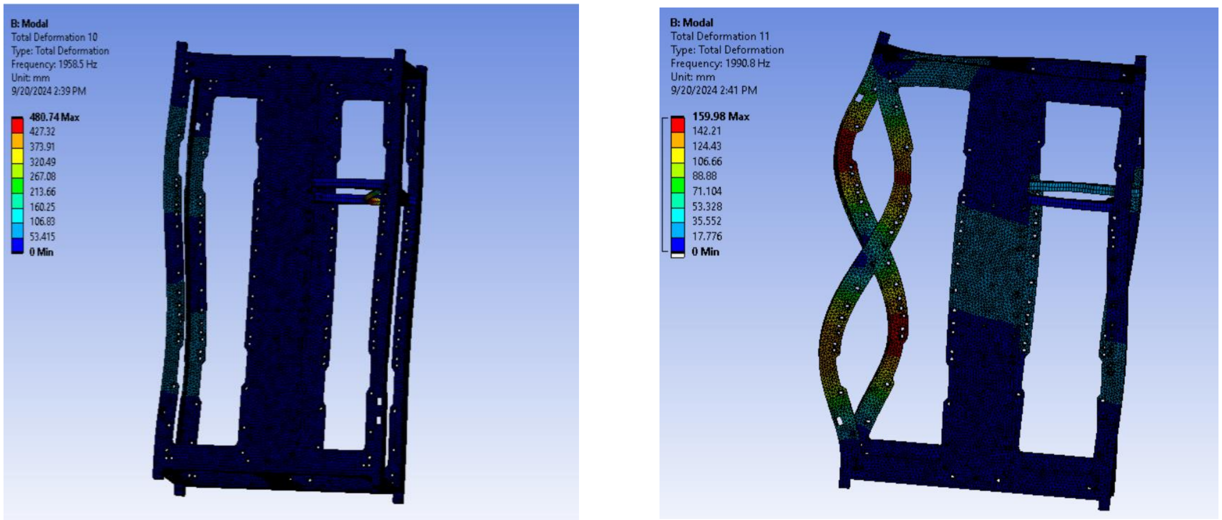
e) Mode five f_5 = 1379.0 Hz Def = 0.180m



f) Mode six f_6 = 1723.3 Hz Def = 0.101m



g) Mode seven f_7 = 1784.5 Hz, Def = 0.483 **h) Mode eight f_8 = 1841.5 Hz Def = 0.604m**



i) Mode nine f_9 = 1958.5 Hz, Def = 0.480m **j) Mode ten f_10 = 1990.8 Hz, Def = 0.159m**

Figure 4.16 (a – j). The first 10 modes with the natural frequency of the 6U CubeSat structure

iv) Random Vibration analysis

The loads on a structural system may not always be known or quantifiable with certainty. A random vibration analysis must follow a modal analysis that extracts the natural frequencies and mode shape. The excitation is applied in the form of Power Spectral Density (PSD). The PSD is a table of spectral values vs. frequency that captures the frequency content. A random vibration analysis enables one to determine the response of structures to vibration loads that are random in nature. A modal analysis that extracts the natural frequencies and mode shapes is a prerequisite.

The main purpose of performing this analysis is to identify the stress peaks, of each loading phase. As for its random excitations of frequencies higher than 100 Hz.

Table 4.3. Input for the random vibration as the PSD Displacement

SI NO	Mode	Frequency [Hz]	Deformation	mm2/Hz
1	1	331.23	0.0622	1.16802e-05
2	2	811.65	0.16544	3.37219e-05
3	3	840.97	0.15935	3.01942e-05
4	4	1325.1	0.16826	2.13655e-05
5	5	1379	0.18002	2.35005e-05
6	6	1723.3	0.10173	6.00533e-06
7	7	1784.5	0.48371	0.000131115
8	8	1841.8	0.60473	0.000198555
9	9	1958.5	0.48054	0.000117906
10	10	1990.8	0.15998	1.28559e-05

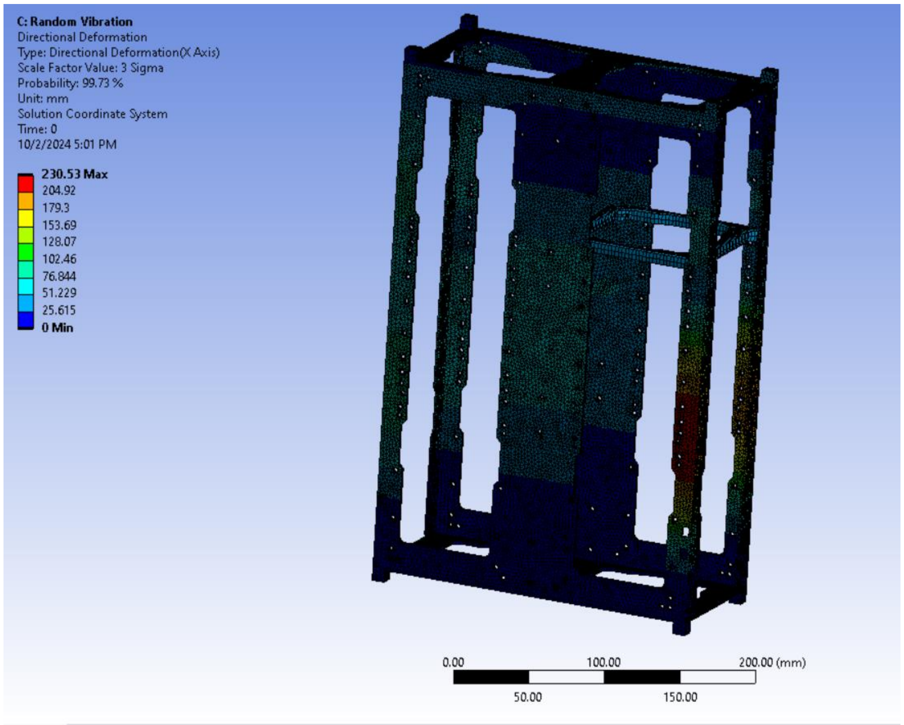

C: Random Vibration
Directional Deformation
Type: Directional Deformation(X Axis)
Scale Factor Value: 3 Sigma
Probability: 99.73 %
Unit: mm
Solution Coordinate System
Time: 0
10/2/2024 5:01 PM

Figure 4.17. Directional deformation along X-axis

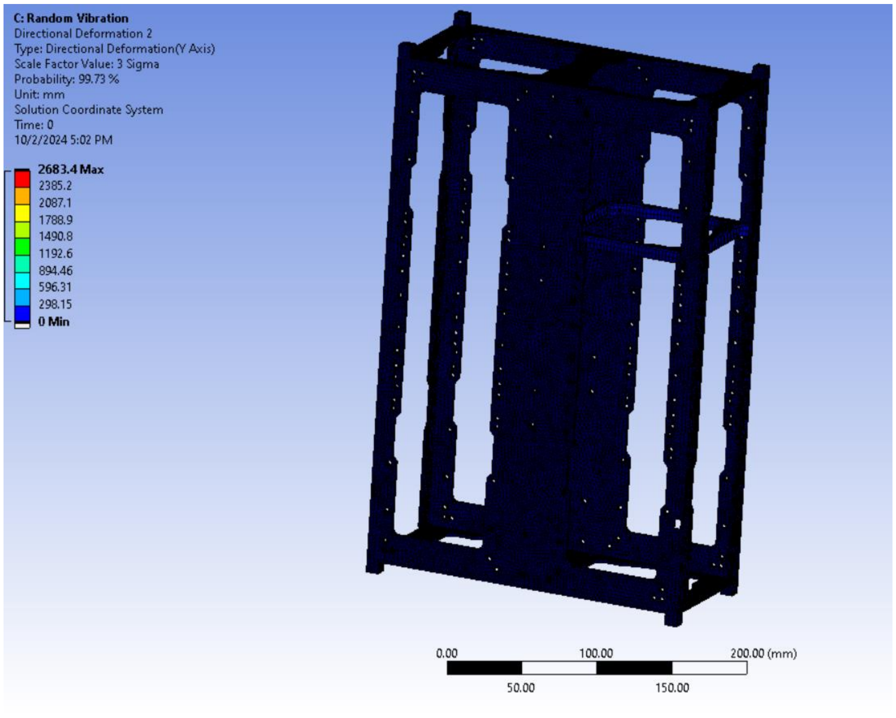
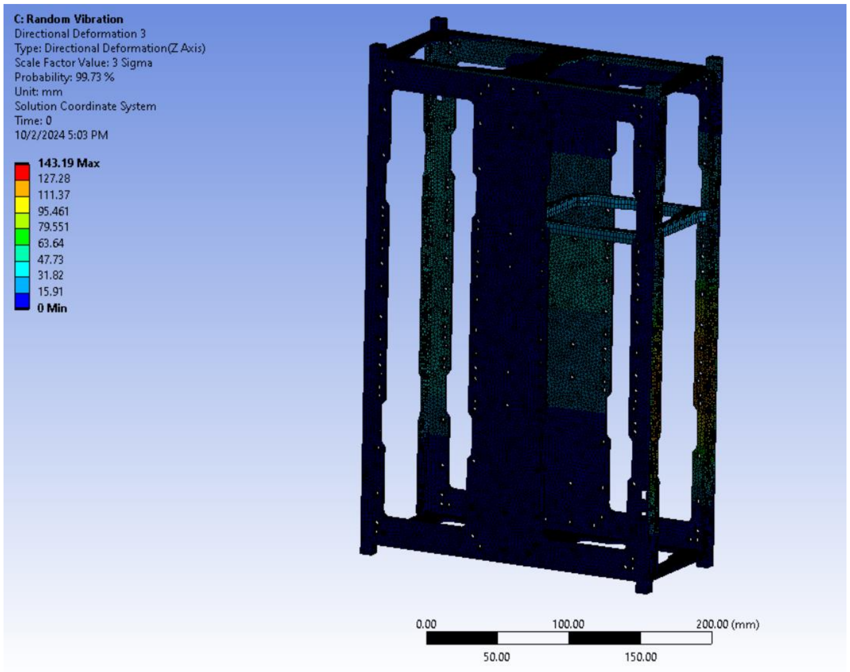
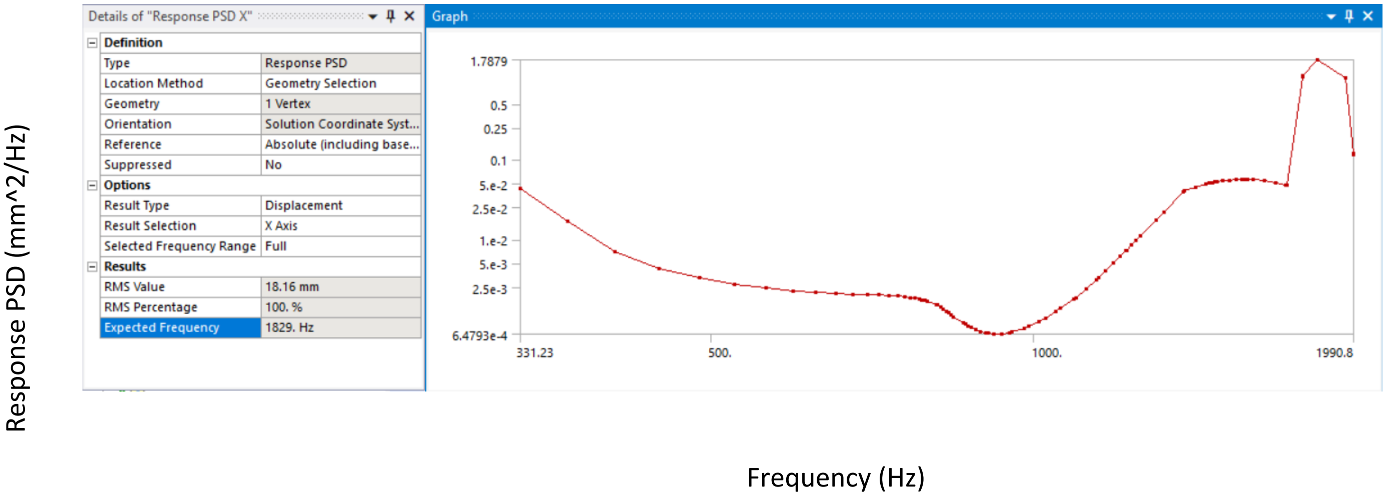

C: Random Vibration
Directional Deformation 2
Type: Directional Deformation(Y Axis)
Scale Factor Value: 3 Sigma
Probability: 99.73 %
Unit: mm
Solution Coordinate System
Time: 0
10/2/2024 5:02 PM

Figure 4.18. Directional deformation along y-axis



C: Random Vibration
Directional Deformation 3
Type: Directional Deformation(Z Axis)
Scale Factor Value: 3 Sigma
Probability: 99.73 %
Unit: mm
Solution Coordinate System
Time: 0
10/2/2024 5:03 PM

Figure 4.19. Directional deformation along Z-axis



Details of "Response PSD X"

Definition	
Type	Response PSD
Location Method	Geometry Selection
Geometry	1 Vertex
Orientation	Solution Coordinate Syst...
Reference	Absolute (including base...
Suppressed	No
Options	
Result Type	Displacement
Result Selection	X Axis
Selected Frequency Range	Full
Results	
RMS Value	18.16 mm
RMS Percentage	100. %
Expected Frequency	1829. Hz

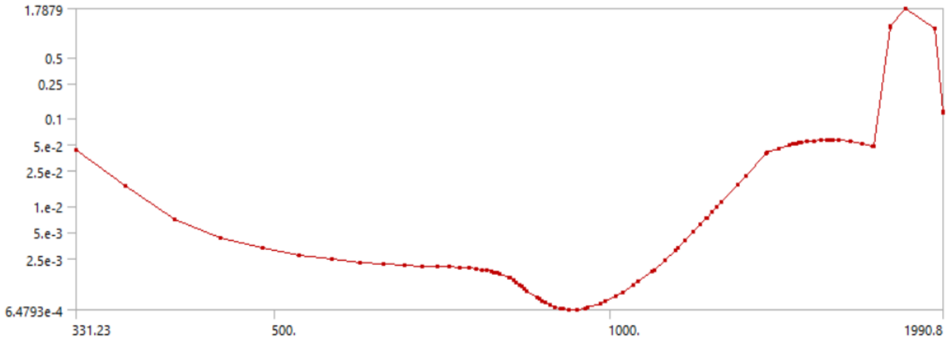
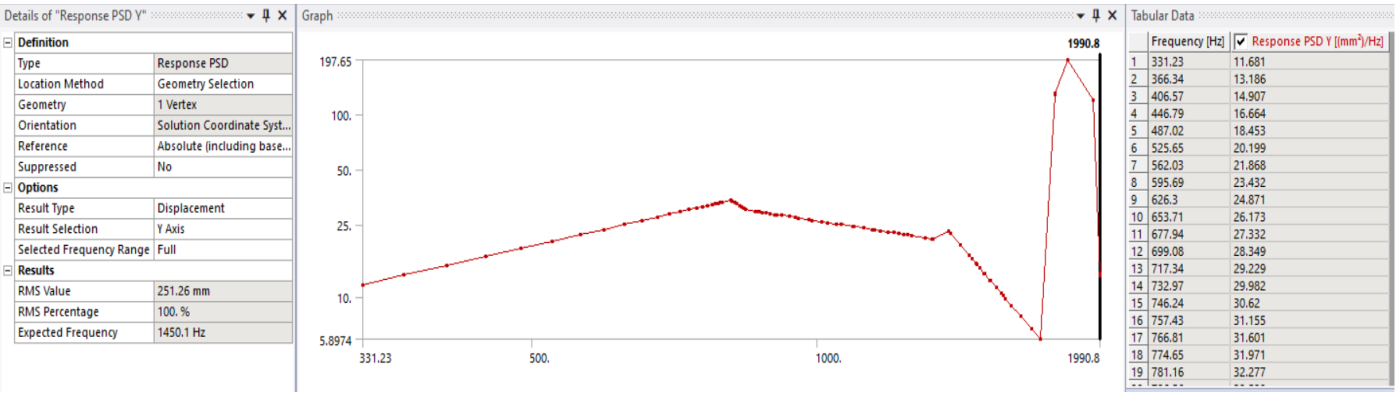


Figure4.20. Random Vibration RPSD along the X-axis



Definition	
Type	Response PSD
Location Method	Geometry Selection
Geometry	1 Vertex
Orientation	Solution Coordinate Syst...
Reference	Absolute (including base...
Suppressed	No
Options	
Result Type	Displacement
Result Selection	Y Axis
Selected Frequency Range	Full
Results	
RMS Value	251.26 mm
RMS Percentage	100. %
Expected Frequency	1450.1 Hz

	Frequency [Hz]	☑ Response PSD Y [(mm²)/Hz]
1	331.23	11.681
2	366.34	13.186
3	406.57	14.907
4	446.79	16.664
5	487.02	18.453
6	525.65	20.199
7	562.03	21.868
8	595.69	23.432
9	626.3	24.871
10	653.71	26.173
11	677.94	27.332
12	699.08	28.349
13	717.34	29.229
14	732.97	29.982
15	746.24	30.62
16	757.43	31.155
17	766.81	31.601
18	774.65	31.971
19	781.16	32.277

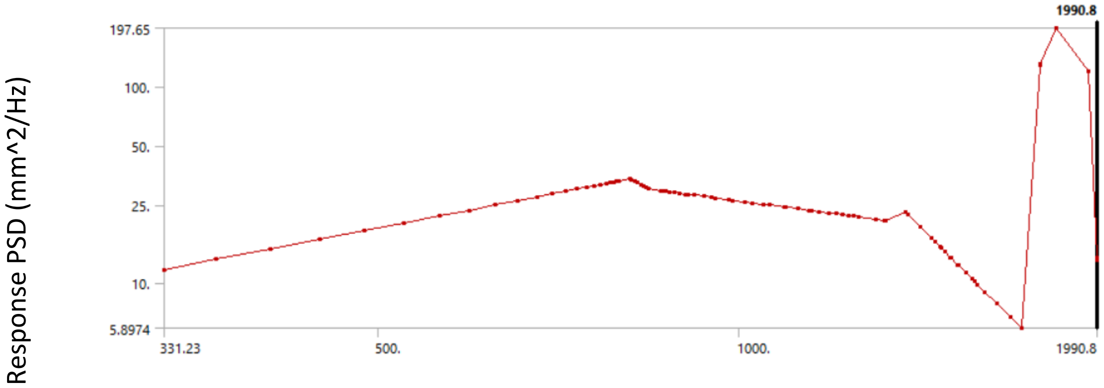
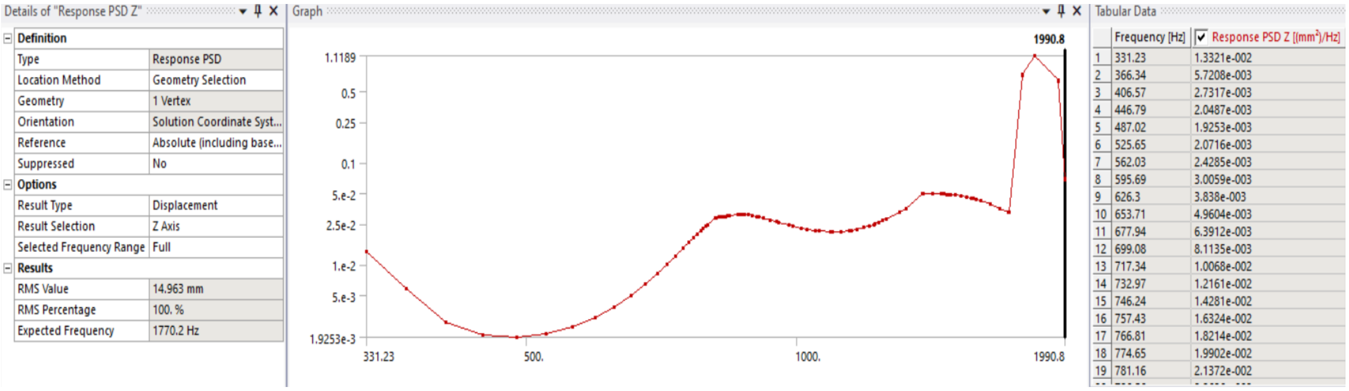


Figure 4.21. Random Vibration RPSD along the Y-axis



Definition	
Type	Response PSD
Location Method	Geometry Selection
Geometry	1 Vertex
Orientation	Solution Coordinate Syst...
Reference	Absolute (including base...
Suppressed	No
Options	
Result Type	Displacement
Result Selection	Z Axis
Selected Frequency Range	Full
Results	
RMS Value	14.963 mm
RMS Percentage	100. %
Expected Frequency	1770.2 Hz

	Frequency [Hz]	☑ Response PSD Z [(mm²)/Hz]
1	331.23	1.3321e-002
2	366.34	5.7208e-003
3	406.57	2.7317e-003
4	446.79	2.0487e-003
5	487.02	1.9253e-003
6	525.65	2.0716e-003
7	562.03	2.4285e-003
8	595.69	3.0059e-003
9	626.3	3.838e-003
10	653.71	4.9604e-003
11	677.94	6.3912e-003
12	699.08	8.1135e-003
13	717.34	1.0068e-002
14	732.97	1.2161e-002
15	746.24	1.4281e-002
16	757.43	1.6324e-002
17	766.81	1.8214e-002
18	774.65	1.9902e-002
19	781.16	2.1372e-002

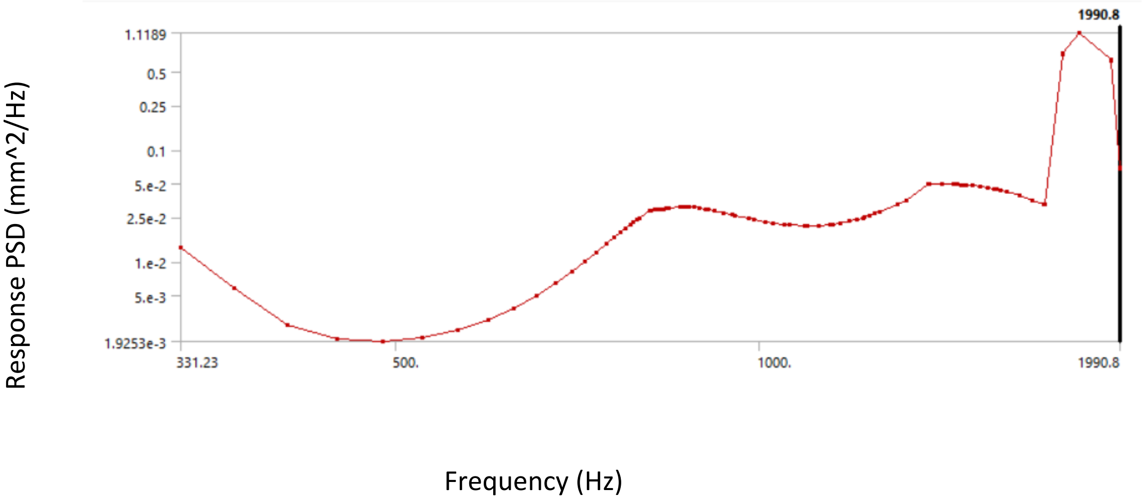


Figure 4.22 Random Vibration RPSD along the Z-axis

v) Thermal analysis

Thermal analysis is used to determine temperatures, thermal gradients, heat flow rates, and heat fluxes in an object that are caused by thermal loads that are independent and dependent on time. A thermal analysis calculates the effects of steady thermal loads on a system.

The purpose of the thermal design of a satellite is to maintain all of the systems of the satellite within their temperature limits for all mission phases. Also, for the evaluation of satellite thermal design, it is necessary to obtain the temperature distribution alone satellite within the specified range.

The operational environment of the 6U Enduro's CubeSat is low Earth orbit (LEO) at an altitude of 700 km, where thermal conditions are influenced by the following factors:

- Solar radiation
- Albedo (reflected sunlight from the earth)
- Infrared radiation from the earth

Table 4.4 Material properties of Al 6082 T6 which we use for thermal analysis

SI No.	Material properties	Values
1.	Thermal conductivity	172 W/m. K
2.	Specific heat constant pressure	899 J kg/K
3.	Density	2700 kg/m^2
4.	Thermal expansion coefficient	23.4 x 10^-6 /K
5.	Solar absorptivity	0.7
6.	IR emissivity	0.2

Table 4.5. The operational environment of the CubeSat at LEO

SI No.	Factors	Values
1.	Altitude	700 km
2.	Solar radiation	1361 W/m2
3.	Albedo	0.25
4.	IR from the earth	237 W/m2

Heat flux calculation for LEO and material used

- Heat flux from the earth's albedo (earth-reflected sunlight)

q_albedo = Albedo x Solar radiation

q_albedo = 0.25 x 1361 W/m2

Albedo flux =340.25 W/m2

- Solar radiation effect

q_solar = Solar radiation x solar absorptivity

q_solar = 1361 W/m2 x 0.7

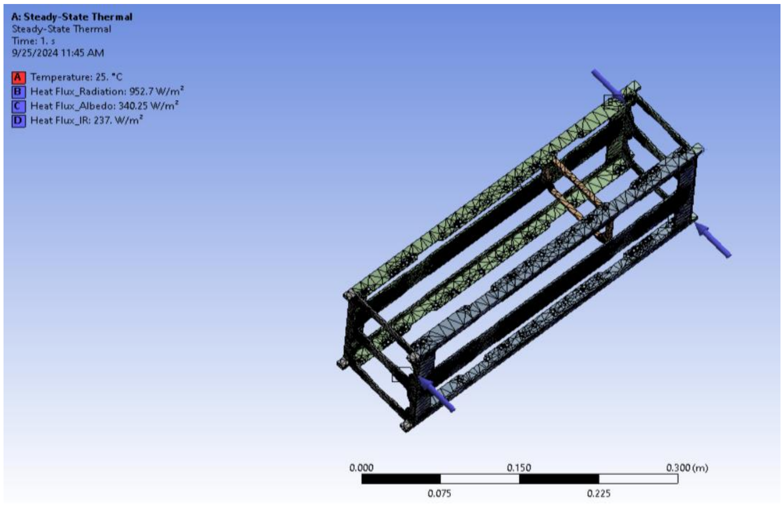
Heat flux = 952.7 W/m2

- IR from the earth's surface

q_IR = 237 W/m2

a. **Steady-State Thermal Analysis**:

To evaluate temperature distribution under constant thermal loads which is independent of time. All the necessary inputs are applied with ambient room temperature and heat flux for LEO.

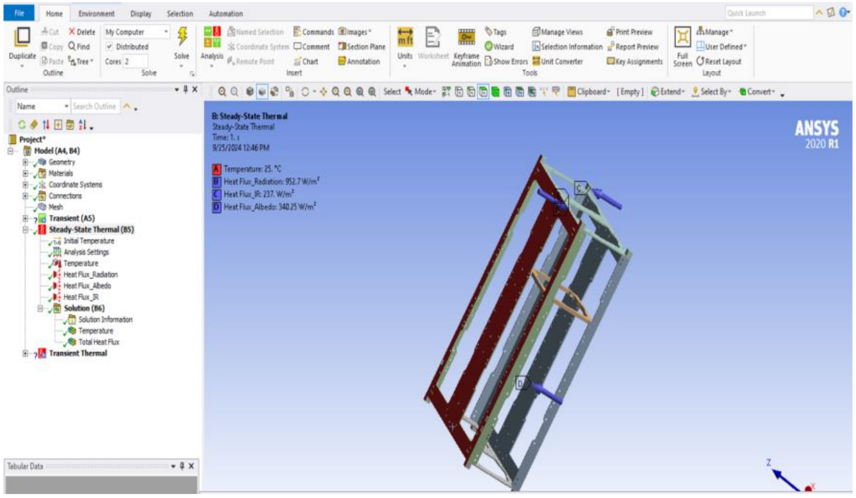


A: Steady-State Thermal
Steady-State Thermal
Time: 1. s
9/25/2024 11:45 AM

A Temperature: 25. °C
B Heat Flux_Radiation: 952.7 W/m²
C Heat Flux_Albedo: 340.25 W/m²
D Heat Flux_IR: 237. W/m²

Figure4.23. Mesh for the steady-state thermal analysis

Simulation setup for thermal analysis to create a simulated Low earth orbit for an accurate result



Project*
Model (A4, B4)
  Geometry
  Materials
  Coordinate Systems
  Connections
  Mesh
  Transient (A5)
  Steady-State Thermal (B5)
    Initial Temperature
    Analysis Settings
    Temperature
    Heat Flux_Radiation
    Heat Flux_Albedo
    Heat Flux_IR
    Solution (B6)
      Solution Information
      Temperature
      Total Heat Flux
  Transient Thermal

B: Steady-State Thermal
Steady-State Thermal
Time: 1. s
9/25/2024 12:46 PM

A Temperature: 25. °C
B Heat Flux_Radiation: 952.7 W/m²
C Heat Flux_IR: 237. W/m²
D Heat Flux_Albedo: 340.25 W/m²

Figure4.24. Solver setup for the steady-state thermal analysis

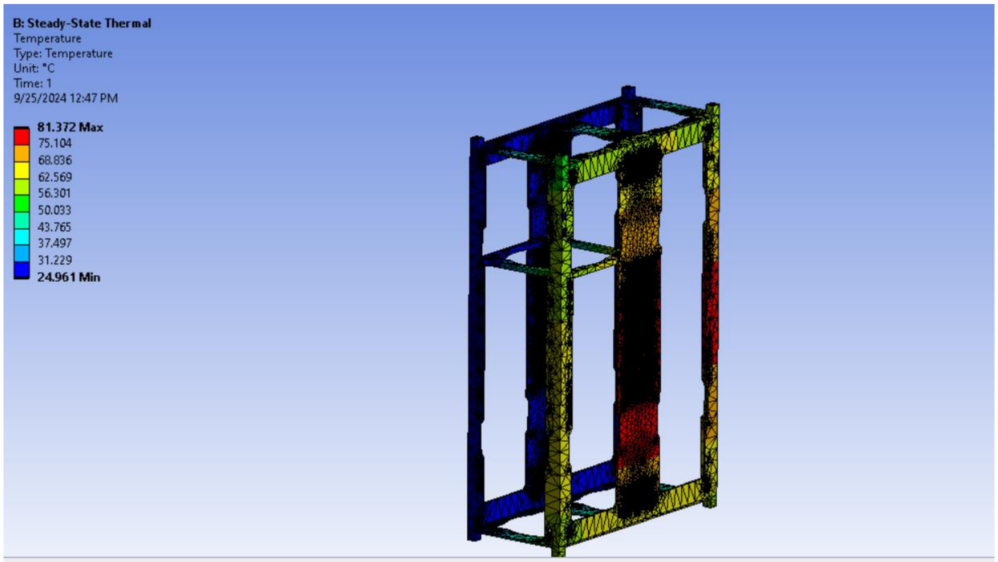


Figure 4.25. Temperature distribution for the steady-state thermal analysis

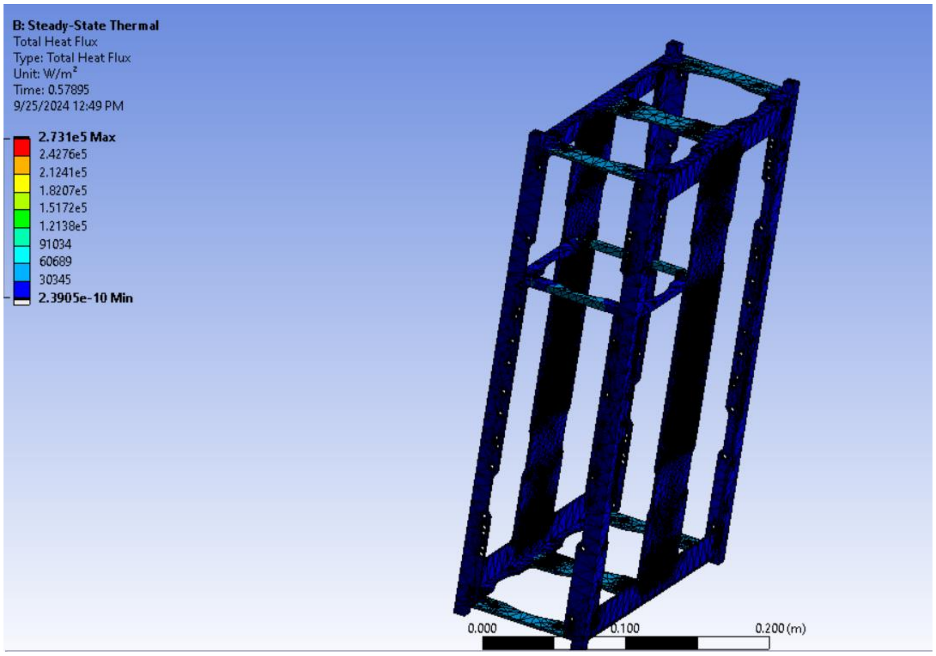
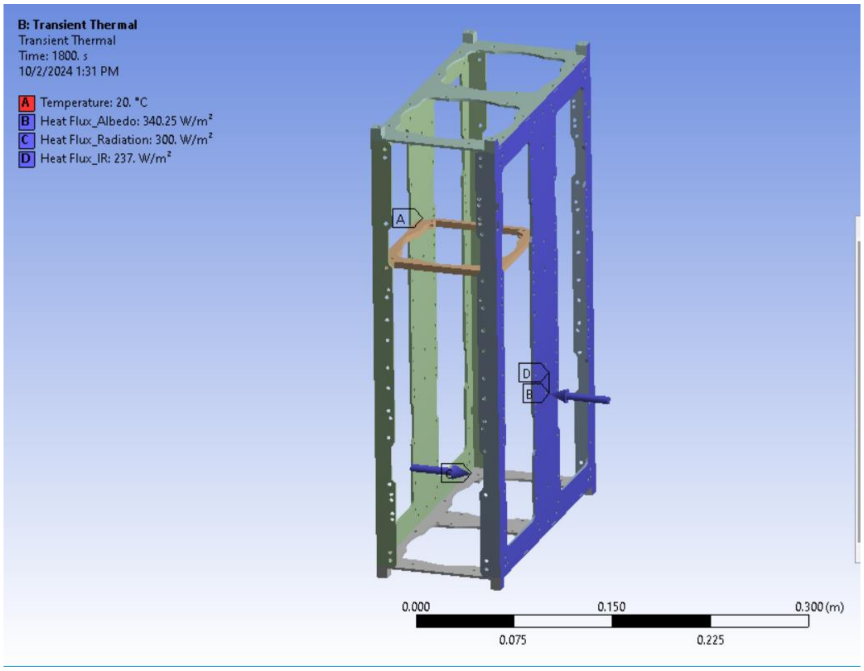


Figure 4.26. Total heat flux for the steady-state thermal analysis

b. Transient-state of Thermal Analysis

Transient Analysis is the thermal analysis that is dependent on time. It is conducting transient thermal analysis to accurately simulate temperature fluctuations during different mission phases (launch, deployment, operation). Thoroughly assess worst-case scenarios, including maximum solar exposure and eclipse conditions when the CubeSat enters Earth's shadow.

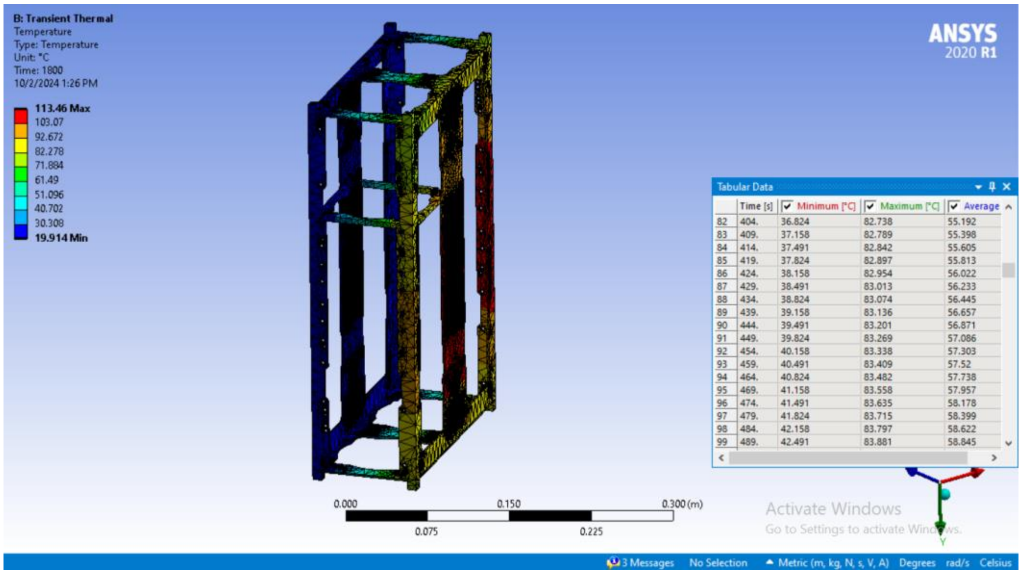
Simulation setup for Transient thermal analysis



B: Transient Thermal
Transient Thermal
Time: 1800. s
10/2/2024 1:31 PM

A Temperature: 20. °C
B Heat Flux_Albedo: 340.25 W/m²
C Heat Flux_Radiation: 300. W/m²
D Heat Flux_IR: 237. W/m²

Figure 4.24. Solver setup for transient thermal analysis of the 6U CubeSat structure

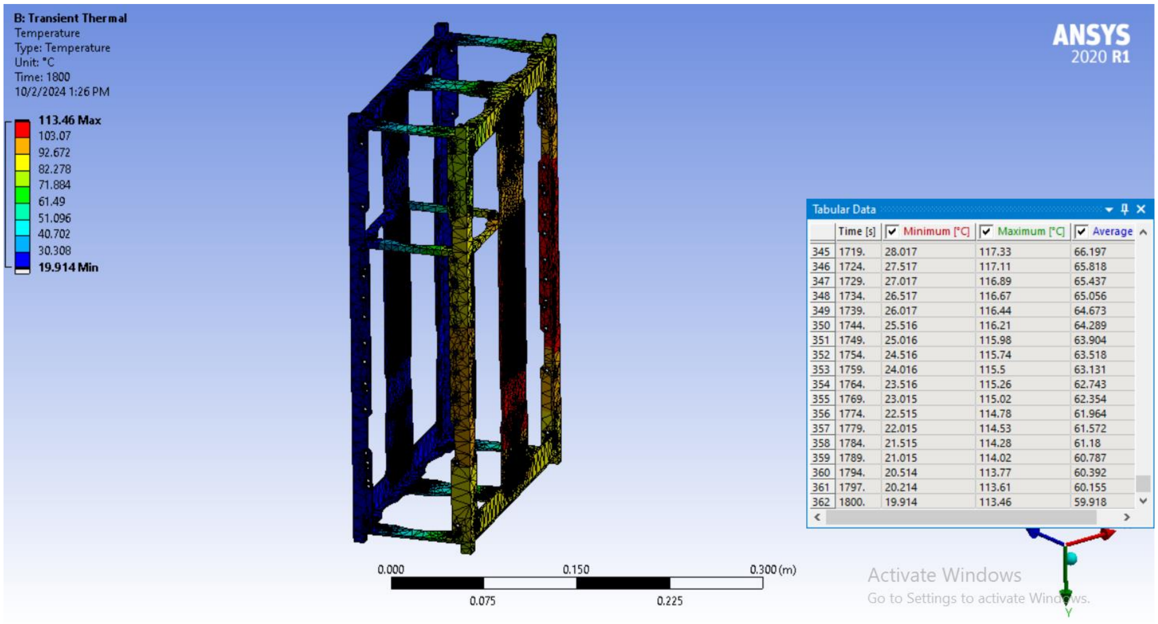


B: Transient Thermal
Temperature
Type: Temperature
Unit: °C
Time: 1800
10/2/2024 1:26 PM

Tabular Data

	Time [s]	☑ Minimum [°C]	☑ Maximum [°C]	☑ Average
82	404.	36.824	82.738	55.192
83	409.	37.158	82.789	55.398
84	414.	37.491	82.842	55.605
85	419.	37.824	82.897	55.813
86	424.	38.158	82.954	56.022
87	429.	38.491	83.013	56.233
88	434.	38.824	83.074	56.445
89	439.	39.158	83.136	56.657
90	444.	39.491	83.201	56.871
91	449.	39.824	83.269	57.086
92	454.	40.158	83.338	57.303
93	459.	40.491	83.409	57.52
94	464.	40.824	83.482	57.738
95	469.	41.158	83.558	57.957
96	474.	41.491	83.635	58.178
97	479.	41.824	83.715	58.399
98	484.	42.158	83.797	58.622
99	489.	42.491	83.881	58.845

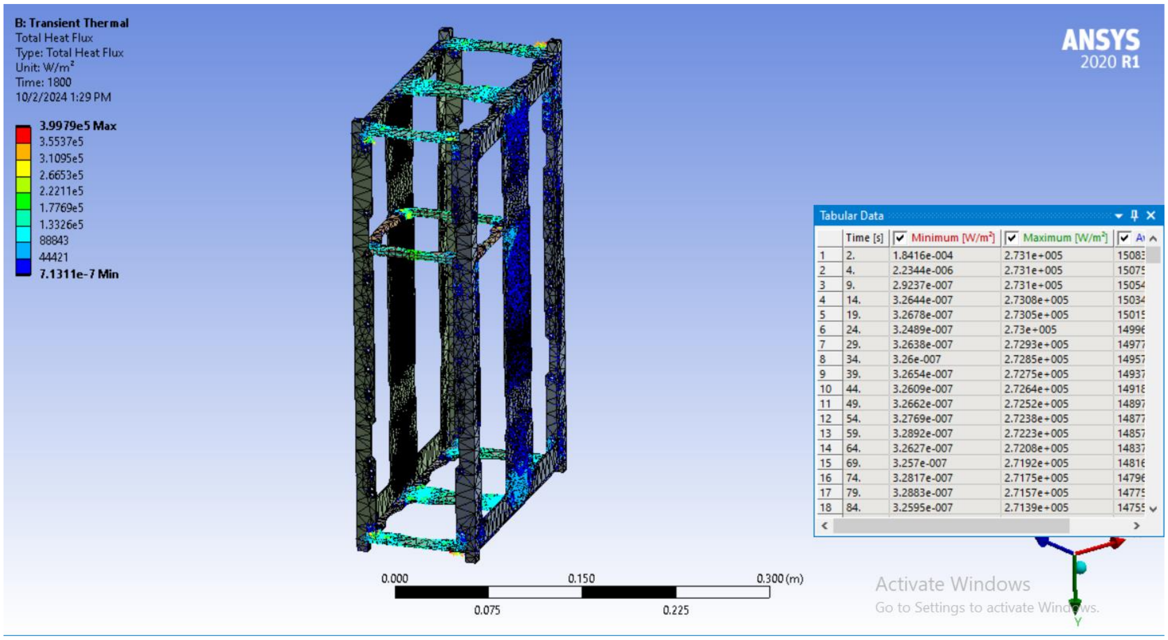
Figure 4.26. Temperature distribution for transient thermal analysis of the 6U CubeSat structure



Tabular Data

	Time [s]	☑ Minimum [°C]	☑ Maximum [°C]	☑ Average
345	1719.	28.017	117.33	66.197
346	1724.	27.517	117.11	65.818
347	1729.	27.017	116.89	65.437
348	1734.	26.517	116.67	65.056
349	1739.	26.017	116.44	64.673
350	1744.	25.516	116.21	64.289
351	1749.	25.016	115.98	63.904
352	1754.	24.516	115.74	63.518
353	1759.	24.016	115.5	63.131
354	1764.	23.516	115.26	62.743
355	1769.	23.015	115.02	62.354
356	1774.	22.515	114.78	61.964
357	1779.	22.015	114.53	61.572
358	1784.	21.515	114.28	61.18
359	1789.	21.015	114.02	60.787
360	1794.	20.514	113.77	60.392
361	1797.	20.214	113.61	60.155
362	1800.	19.914	113.46	59.918

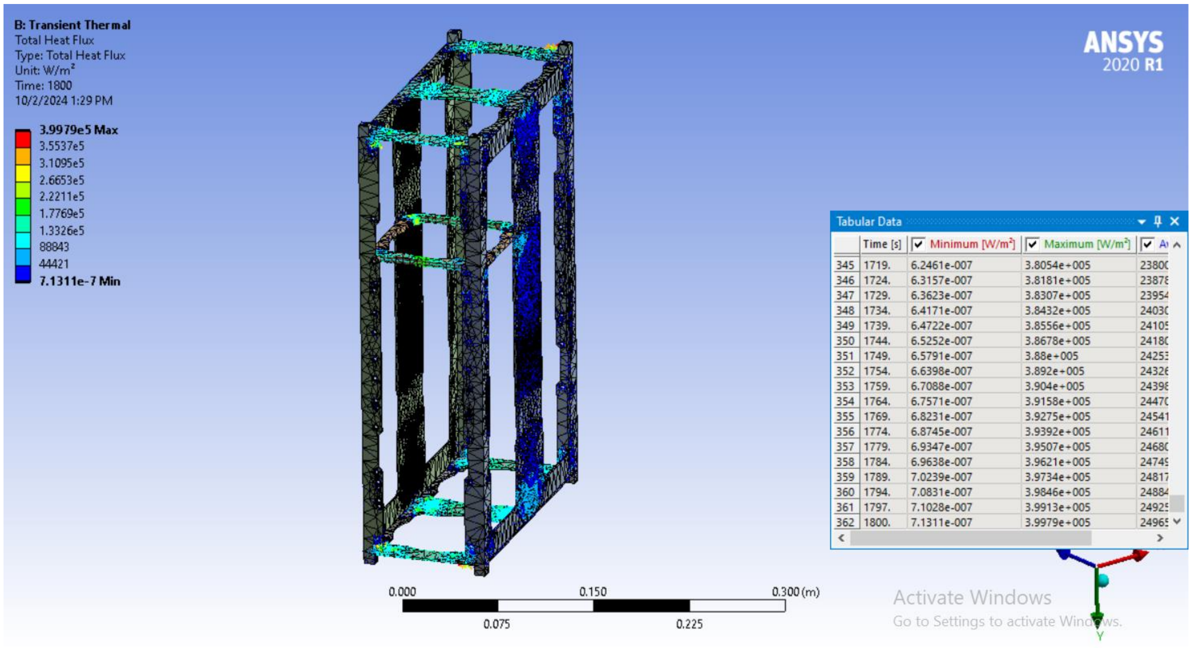
Figure 4.27. Final Temperature distribution for transient thermal analysis of the 6U CubeSat structure



Tabular Data

	Time [s]	☑ Minimum [W/m²]	☑ Maximum [W/m²]	☑ A
1	2.	1.8416e-004	2.731e+005	15083
2	4.	2.2344e-006	2.731e+005	15075
3	9.	2.9237e-007	2.731e+005	15054
4	14.	3.2644e-007	2.7308e+005	15034
5	19.	3.2678e-007	2.7305e+005	15015
6	24.	3.2489e-007	2.73e+005	14996
7	29.	3.2638e-007	2.7293e+005	14977
8	34.	3.26e-007	2.7285e+005	14957
9	39.	3.2654e-007	2.7275e+005	14937
10	44.	3.2609e-007	2.7264e+005	14918
11	49.	3.2662e-007	2.7252e+005	14897
12	54.	3.2769e-007	2.7238e+005	14877
13	59.	3.2892e-007	2.7223e+005	14857
14	64.	3.2627e-007	2.7208e+005	14837
15	69.	3.257e-007	2.7192e+005	14816
16	74.	3.2817e-007	2.7175e+005	14796
17	79.	3.2883e-007	2.7157e+005	14775
18	84.	3.2595e-007	2.7139e+005	14755

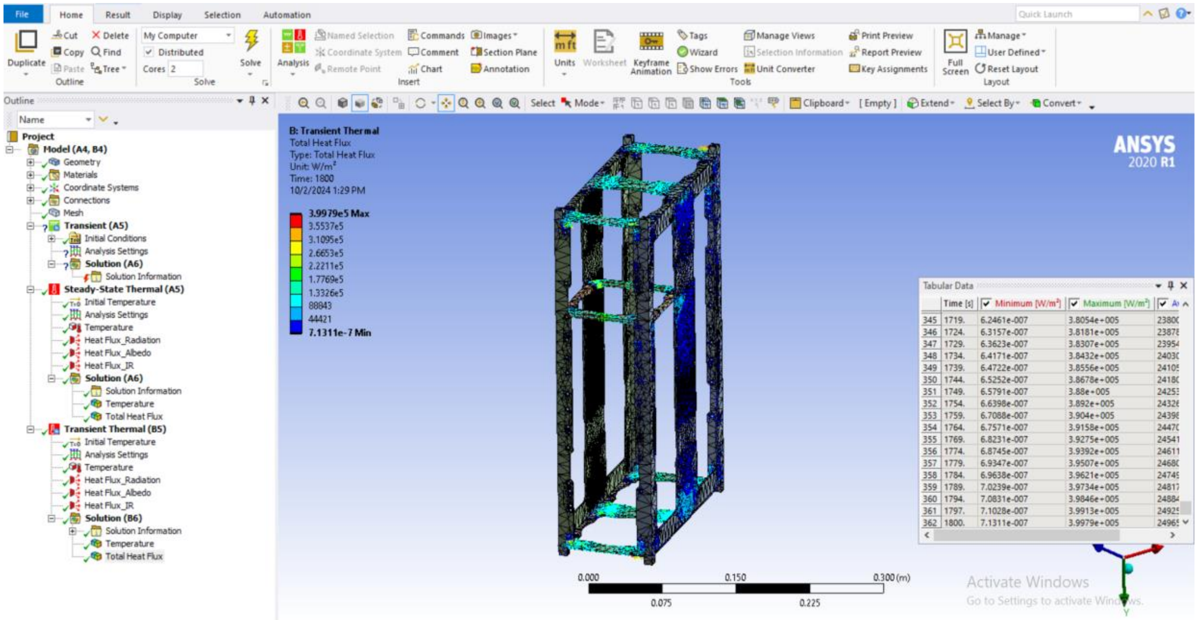
Figure 4.28. First Total heat flux for transient thermal analysis of the 6U CubeSat structure



Tabular Data

	Time [s]	☑ Minimum [W/m²]	☑ Maximum [W/m²]	☑ A
345	1719.	6.2461e-007	3.8054e+005	2380
346	1724.	6.3157e-007	3.8181e+005	2387
347	1729.	6.3623e-007	3.8307e+005	2395
348	1734.	6.4171e-007	3.8432e+005	2403
349	1739.	6.4722e-007	3.8556e+005	2410
350	1744.	6.5252e-007	3.8678e+005	2418
351	1749.	6.5791e-007	3.88e+005	2425
352	1754.	6.6398e-007	3.892e+005	2432
353	1759.	6.7088e-007	3.904e+005	2439
354	1764.	6.7571e-007	3.9158e+005	2447
355	1769.	6.8231e-007	3.9275e+005	24541
356	1774.	6.8745e-007	3.9392e+005	24611
357	1779.	6.9347e-007	3.9507e+005	2468
358	1784.	6.9638e-007	3.9621e+005	2474
359	1789.	7.0239e-007	3.9734e+005	24817
360	1794.	7.0831e-007	3.9846e+005	2488
361	1797.	7.1028e-007	3.9913e+005	2492
362	1800.	7.1311e-007	3.9979e+005	2496

Figure 4.29. Final Total heat flux for transient thermal analysis of the 6U CubeSat structure



Tabular Data

	Time [s]	☑ Minimum [W/m²]	☑ Maximum [W/m²]	☑ A
345	1719.	6.2461e-007	3.8054e+005	2380
346	1724.	6.3157e-007	3.8181e+005	2387
347	1729.	6.3623e-007	3.8307e+005	2395
348	1734.	6.4171e-007	3.8432e+005	2403
349	1739.	6.4722e-007	3.8556e+005	2410
350	1744.	6.5252e-007	3.8678e+005	2418
351	1749.	6.5791e-007	3.88e+005	2425
352	1754.	6.6398e-007	3.892e+005	2432
353	1759.	6.7088e-007	3.904e+005	2439
354	1764.	6.7571e-007	3.9158e+005	2447
355	1769.	6.8231e-007	3.9275e+005	24541
356	1774.	6.8745e-007	3.9392e+005	24611
357	1779.	6.9347e-007	3.9507e+005	2468
358	1784.	6.9638e-007	3.9621e+005	2474
359	1789.	7.0239e-007	3.9734e+005	24817
360	1794.	7.0831e-007	3.9846e+005	2488
361	1797.	7.1028e-007	3.9913e+005	2492
362	1800.	7.1311e-007	3.9979e+005	2496

Figure 4.30. Final Total heat flux for transient thermal analysis of the 6U CubeSat structure

Chapter Five

Discussion

5.1 Interpretation of Results

The results from computational analysis of the ET-SMART-RSS, Ethiopia’s 6U CubeSat, structural analysis provide key insights into the satellite's ability to withstand the harsh conditions of low Earth orbit (LEO) and the mechanical stresses encountered during launch. The finite element analysis (FEA) simulations, which were focused on assessing structural integrity under static, dynamic, thermal, and vibrational loads, reveal several critical aspects of the satellite’s performance.

Static Structural Analysis

One of the main findings is the **distribution of stress and deformation** across the CubeSat’s structure during launch. The maximum equivalent stress determined by the CubeSat's static structural analysis was 0.920MPa, far less than the yield strength of aluminum 6082-T6 (259.2 MPa). To preserve structural integrity, the stresses produced on the CubeSat structure design cannot be greater than the yield strength of the materials used. As a result, the material's yield strength must be greater than the von Mises stress. This result shows that the mechanical loads—namely, the forces of gravity and launch acceleration—that the CubeSat structure must endure during launch can be maintained.

Regarding the safety factor, for the safety factor is greater than 1.0, the structure can withstand the forces put on it without failing. Higher safety factors provide a higher level of certainty for structural integrity.

In our case,

SF=Admissible Stress / Maximum stress

Maximum stress produced = 0.920 MPa

Admissible stress of material = 259.2 MPa

SF = 259.2 MPa / 0.920 MPa

SF = 281.74

This analysis shows a high value of the Safety factor of 281.74 for the 6U CubeSat structure, which is due to minimal loads (which include 10g vertical load and 2g lateral load) on the empty CubeSat structure, resulting in low stress (0.920 MPa) compared to the material's high yield strength (259.2 MPa). The absence of components inside the CubeSat leads to low stress. The total deformation of 4.746 e^-6 m signifies that there is a small displacement, which helps to maintain the structural integrity and functionality of the CubeSat.

The directional deformation of 6.546 e^-7 m in the X-axis shows stability with almost very small deformation in that specific direction. The maximum principal stress of 1.14 MPa is well below the yield strength of Aluminum 6082 (259.2 MPa), which confirms that the structure is safe against failure under the given loading conditions. The equivalent elastic strain of 1.30 x 10^-5 m/m indicates very low levels of strain, which is typical for a well-designed structure under static loads.

In general, the static structural analysis shows that the satellite experiences its highest stress concentrations around the attachment points to the launch vehicle. These areas, primarily located at the corners of the CubeSat's frame, require reinforcement or optimized design modifications to prevent potential failure. The stress values observed are within acceptable limits according to the material properties, confirming that the choice of aerospace-grade aluminum for the frame is suitable. However, localized deformation indicates the need for additional support structures in areas of high stress to enhance durability.

Modal Mnalysis

The 6U CubeSat Structure modal analysis showed that its initial natural frequency was 331.23 Hz, which is far higher than the required minimum of 100 Hz for CubeSats to avoid resonance. The succeeding modes also stayed within reasonable bounds, ensuring that the structure was not exposed to damaging resonance vibrations. The increase in the natural frequency increases the structure's stiffness.

The modal analysis results indicate that the CubeSat's natural frequencies are sufficiently separated from the launch vehicle's vibration frequencies, reducing the risk of resonance during launch. This ensures structural stability during the high-vibration phase of the mission. The harmonic response analysis further validates that the design can withstand periodic vibrations, with no significant amplification of displacements observed within the critical frequency range. This confirms the CubeSat’s resilience to vibrational loads typical during launch.

Random Vibration Analysis

Random vibrational loads caused small deformations in the CubeSat that fell within an acceptable range. The CubeSat's minimal maximum displacement suggests that it is structurally stable and will not bend significantly during launch or from random vibrations while in orbit. By selecting the maximum deformation points from the previous analysis and using the initial condition as modal analysis the following results as been shown from the analysis the Root Mean Square (RMS) displacement values of random vibration analysis are **Y-axis:** 251.26 mm, **X-axis:** 18.16 mm, and **Z-axis:** 14.963 mm. This indicates the Y-axis experiences the highest displacement, suggesting that this direction is most susceptible to vibrational loads.

Steady-State Thermal Analysis

The temperature distribution range determined in the steady-state thermal analysis was 24.961°C to 81.372°C, which is within the operating temperature range of Low Earth Orbit (LEO) temperatures, which normally range from -65°C to 125°C. Due to albedo radiation and infrared radiation from Earth, the CubeSat showed efficient heat dissipation on its sun-facing side and maintained a moderate temperature on its Earth-facing side. receives significant reflected sunlight from Earth (especially if it is in a low Earth orbit), this could contribute more heat to certain surfaces than direct solar radiation does to the sun-facing side.

Transient-state Thermal Analysis

To simulate the 6U CubeSat structure thermal behavior for 30 minutes, temperature distribution fluctuations as the CubeSat moved between Earth's shadow and sunshine were captured using the transient thermal analysis. The transient-state thermal analysis result reveals that there was a rapid increase in temperature during solar exposure as well as a cooling when the phase transitioned into the earth's shadow phase.

- **Steady Maximum: 81.372°C and Transient Maximum:113.46 °C**
  The CubeSat may not be fully exposed to the maximum solar radiation or its material and design may be able to dissipate heat effectively because this temperature is much below the LEO environment maximum of 125°C.
- **Steady Minimum: 24.961°C and Transient Minimum:19.91 °C**

  The minimum temperature is greater than the -65°C LEO minimum. This shows that the extreme cold of the space environment is not even approaching the coldest portion of the CubeSat. This might be because the CubeSat is constantly receiving heat from Earth's albedo and infrared radiation, which keeps it from cooling to temperatures comparable to those in space.

- The transient temperature in the thermal analysis of the 6U CubeSat is higher than the steady-state temperature due to the dynamic nature of thermal conditions experienced during its low earth orbit. During transient analysis, the CubeSat rapidly heats up when exposed to direct solar radiation, causing to large temperature rises that can exceed the steady-state maximum, which reflects a long-term average when thermal equilibrium is attained.

In terms of thermal analysis, the results demonstrate that the CubeSat can endure the extreme temperature variations in LEO, with thermal expansion remaining within safe limits. The thermal stress is well-distributed across the structure, indicating that the materials chosen for the CubeSat’s construction can effectively handle the rapid transitions between hot and cold temperatures in orbit. This minimizes the risk of thermal fatigue or warping, ensuring the satellite’s long-term operational integrity.

The transient dynamic analysis, simulating impacts from space debris, shows that while the CubeSat is designed to absorb small impacts, larger debris poses a significant threat, particularly to the solar panels and external components. The structural frame demonstrates good resilience, but areas such as the deployable solar arrays are more vulnerable to damage. These results suggest potential areas for further design optimization or the incorporation of protective shielding.

In conclusion, the interpretation of the simulation results validates that the ET-SMART-RSS CubeSat’s structural design is largely robust and capable of withstanding the mechanical and thermal demands of its mission in LEO. However, the analysis also highlights specific areas for improvement, such as reinforcing high-stress regions and enhancing the protection of external components. These insights provide critical feedback for future CubeSat design iterations, improving the reliability and performance of nanosatellites for space missions.

5.2 Practical Implications

The results of this dissertation carry significant practical implications for both the design and operation of nanosatellites, particularly for missions in low Earth orbit (LEO) and space programs in developing nations like Ethiopia. The successful application of computational methods, such as Finite Element Analysis (FEA), demonstrates that small satellite programs can achieve high levels of structural integrity without the need for expensive physical testing in the early stages of development. This has far-reaching effects on the cost, time, and resource allocation in satellite design.

Static Structural analysis

- Structural Integrity: Ensuring structural integrity during deployment, robust enough to withstand launch loads without losing yield or failing.
- Material Efficiency: Aluminum 6082-T6, which is validated and capable of supporting necessary loads while keeping an overall low weight, is essential for the construction of CubeSats.

Modal Analysis Results: First natural frequency of **331.23 Hz**, well above the minimum requirement of **100 Hz**.

- **Avoiding Resonance:** By preventing damaging resonance during launch vibrations, natural frequencies over the threshold lower the chance of structural failure.
- **Vibration Resistance:** Capacity to withstand dynamic forces in orbit and during launch, avoiding resonance frequencies that can interfere with performance.

Random vibration

- **Structural Stability:** Confirms that the CubeSat can endure launch and orbital vibrations without considerable deformation, maintaining operational integrity.

• **Reinforcement Concentration:** Determines which axis is most prone to vibrations, the Y-axis, and directs engineers to reinforce it in the design.

Thermal Analysis

- **Steady-State Thermal Analysis Results**: Temperature range of **24.961°C to 81.372°C**, within operational limits for LEO.
- **Thermal Stability**: Ensures functionality within expected environmental conditions in LEO, with effective heat dissipation and temperature regulation.

Transient Thermal Analysis

- **Transient Thermal Analysis Results**: Simulated thermal behavior over 30 minutes, capturing rapid heating during solar exposure and cooling in shadow.
- **Heat Cycling Management**: The structure can endure repeated thermal cycles without critical temperature changes, minimizing thermal fatigue.

One major implication is the optimization of CubeSat design based on stress and deformation data. The analysis identifies critical stress points, especially at the mounting interfaces during launch, and highlights regions that are more susceptible to structural failure. As a result, design engineers can prioritize reinforcing these areas, using minimal additional material to strengthen the satellite while maintaining its lightweight nature, crucial for reducing launch costs. This optimization leads to a more robust design without unnecessary increases in weight, making the CubeSat more cost-effective and efficient.

The results also suggest improvements in **vibration tolerance** through resonance avoidance, which has practical benefits during the satellite's launch. By ensuring that the CubeSat's natural frequencies do not coincide with the frequencies generated during the launch phase, the risk of structural damage due to resonance is minimized. This insight can be directly applied to future CubeSat missions by incorporating vibration isolators or designing structural components that avoid resonance with the launch vehicle's dynamics. This contributes to higher success rates for CubeSat deployments, particularly for emerging space programs.

Furthermore, the thermal analysis confirms that the **material selection** and structural design of the ET-SMART-RSS CubeSat can withstand the extreme temperature fluctuations in LEO. This has practical implications for the long-term operation of the satellite, ensuring that the materials do not degrade prematurely under thermal cycling. By confirming that thermal stresses are manageable within the existing design, the satellite can maintain its operational integrity over an extended period, reducing the likelihood of mission failure due to thermal-induced damage. This is particularly critical for missions from countries with limited resources to replace or repair satellites once deployed.

The impact analysis, particularly regarding space debris, underscores the need for enhanced protective measures for sensitive components like solar panels. For future CubeSat missions, this suggests practical design changes, such as incorporating debris shields or more resilient materials for exposed components. These adjustments could significantly increase the CubeSat's survivability in the increasingly congested LEO environment.

Finally, the results have broader implications for the growth of space programs in developing nations. The successful structural analysis of the ET-SMART-RSS using computational methods shows that resource-limited countries can still achieve robust satellite designs by leveraging affordable simulation tools. This empowers countries like Ethiopia to independently develop, test, and launch CubeSats without relying on extensive external support. The findings encourage the adoption of computational engineering practices in space programs, making space exploration more accessible and sustainable for emerging nations.

In conclusion, the practical implications of this research extend to optimized CubeSat design, enhanced launch survivability, improved thermal management, and increased durability against space debris, all of which contribute to more reliable and cost-effective nanosatellite missions. These results are particularly beneficial for the long-term sustainability and success of space programs in developing countries, where resource efficiency and design optimization are critical.

5.3 Limitations of the Research

The assumption for the material property is uniform or linear through the FEA analysis for Al6082-T6 material.

Considering the average nanosatellite launch design load for the CubeSat, FEA analysis, which is going to affect the accuracy of the result. Analyzing the uncovered 6U CubeSat structure with outer surface coverage like solar panels or deployers.

While this research provides valuable insights into the structural analysis of the ET-SMART-RSS CubeSat using computational methods, several limitations must be acknowledged. First, reliance on computational simulations for structural analysis introduces inherent uncertainties. Finite Element Analysis (FEA) and other simulation tools are highly dependent on the accuracy of the input data, including material properties, boundary conditions, and load assumptions. In the absence of full-scale physical testing, there is a potential mismatch between simulated behavior and real-world performance, especially under unpredictable or extreme conditions in space.

Second, the study primarily focused on idealized environmental conditions, such as launch vibrations, and thermal cycling based on existing datasets and models. However, the actual space environment may present more complex and dynamic challenges, including variable radiation effects, micrometeoroid impacts, or unanticipated thermal behavior due to the CubeSat's interaction with other spacecraft or space debris. These factors are difficult to fully replicate in simulations, potentially limiting the study's ability to predict all real-world scenarios the satellite might encounter.

Additionally, the limited availability of mission-specific data from the ET-SMART-RSS CubeSat poses a challenge. Since this research was considered only the pre-launch scenarios, there is a lack of empirical in-orbit data to validate the simulation results. Post-launch telemetry and operational feedback would provide critical data to compare and refine the simulation models. Without this real-world data, the findings remain theoretical to some extent, limiting the ability to fully assess the CubeSat's long-term performance in orbit.

Another limitation is the scope of the structural analysis, which focused on mechanical and thermal stresses but does not encompass other critical factors such as radiation shielding, electrical system performance, or communication systems integration. While structural integrity is vital, these other factors also play crucial roles in mission success, and their interactions with the CubeSat's structural design are not fully explored in this study.

Finally, the research is constrained by the computational resources available for simulations. Although high-fidelity FEA models were used, limitations in computational power necessitated the use of simplified models and meshing techniques in certain cases, which could affect the precision of the results. Higher-resolution models with more detailed simulations would require significant computational capacity, potentially leading to more accurate insights but were not feasible within the scope of this study.

In summary, the primary limitations of this research include the dependency on computational simulations without extensive physical validation, the idealized nature of environmental models, limited access to real-world mission data, and constraints in the scope of analysis and computational resources. These limitations highlight areas for future research, including the need for post-launch data integration, more comprehensive environmental modeling, and cross-disciplinary analysis of CubeSat systems.

Chapter Six

Conclusion and Recommendation

6.1 Summary of Findings

This research on the structural analysis of the ET-SMART-RSS, Ethiopia's 6U CubeSat, using computational methods, provides critical insights into the satellite's mechanical performance under various conditions encountered in low Earth orbit (LEO). The Finite element analysis (FEA) results confirm that the 6U CubeSat structure with a very lightweight (908 grams) and with applied boundary conditions as well as launch load is suitable for Low Earth Orbit (LEO) operation, enduring launch loads, maintaining the structural integrity, avoiding resonance frequencies, and maintaining operational temperature limits.

Through Finite Element Analysis (FEA) and other simulation techniques, several key findings were identified:

i) **Stress and Deformation Distribution**: The analysis shows that the CubeSat experiences the highest stress concentrations around its mounting points during launch. These areas, primarily at the structural joints, are potential points of failure if not adequately reinforced. However, the overall stress levels remain within the acceptable limits of the materials used, suggesting that the CubeSat's structural design is robust, though slight reinforcements could improve performance.

ii) **Vibration and Resonance Avoidance**: Modal analyses reveal that the CubeSat's natural frequencies are safely outside the range of the launch vehicle's vibrational frequencies, reducing the risk of resonance and structural damage during launch. This indicates that the CubeSat's design is resilient to the vibrational stresses typically experienced during rocket launch phases.

iii) **Thermal Performance**: The thermal analysis shows that the ET-SMART-RSS CubeSat can handle the extreme temperature variations in LEO, with thermal expansion and stress well within the operational limits of the chosen materials. This confirms that the CubeSat's structural integrity will remain stable during its mission, despite the rapid heating and cooling cycles in space.

These findings demonstrate that the ET-SMART-RSS CubeSat is structurally sound for its intended mission, although certain areas, such as stress concentration zones and external component vulnerability, could benefit from further optimization. The analysis also highlights the value of computational simulations in assessing nanosatellite performance, particularly for space programs in developing nations.

6.2 Contributions to Knowledge

This study provides the analysis made to see the structural and thermal performance of CubeSats using Aluminum 6082-T6 which is lightweight under typical LEO conditions, emphasizing the importance of modal analysis and thermal behavior.

The research contributes significantly to the field of nanosatellite engineering, particularly in the application of computational methods to assess and optimize CubeSat designs. The key contributions to knowledge include:

1. **Application of Advanced Computational Methods**: This dissertation demonstrates the effective use of Finite Element Analysis (FEA) and other computational techniques in evaluating the structural integrity of CubeSats. By utilizing industry-standard tools such as ANSYS and COMSOL Multiphysics, the study showcases how detailed simulations can be used to predict and mitigate structural weaknesses in small satellites, offering a cost-effective alternative to extensive physical testing.
2. **Structural Optimization of CubeSats for LEO**: The research provides specific insights into the stress distribution, vibration responses, and thermal behavior of a CubeSat operating in low Earth orbit (LEO). The identification of stress concentration zones and resonance frequencies offers practical guidance for optimizing CubeSat designs, ensuring better structural performance during launch and in-orbit operation. This is particularly relevant for CubeSat developers aiming to enhance the durability and reliability of small satellites.
3. **Framework for Emerging Space Programs**: By focusing on Ethiopia's ET-SMART-RSS CubeSat, this research contributes to the growing body of knowledge supporting space

initiatives in developing nations. It provides a blueprint for using computational methods in the design and testing of nanosatellites in resource-limited settings, reducing the dependency on expensive and inaccessible testing facilities.

4. **Contribution to Sustainable Space Exploration**: The findings of this research help advance the design of reliable, cost-effective nanosatellites, contributing to the sustainability of space exploration. By providing a methodology for optimizing satellite structures through computational modeling, this work supports the development of durable, long-lasting CubeSats, which can reduce the overall cost and risk of space missions.

In summary, this dissertation contributes to both the theoretical understanding and practical application of structural analysis in nanosatellite engineering, with particular relevance to developing space programs and the global CubeSat community.

6.4 Recommendations for Future Research

Based on the findings and limitations of this study, several avenues for future research are recommended to further enhance the structural analysis and performance optimization of CubeSats:

1. **Integration of In-Orbit Data for Model Validation**: One of the primary limitations of this research is the reliance on pre-launch computational simulations without access to real-time mission data. Future research should incorporate in-orbit telemetry and operational data from CubeSats like ET-SMART-RSS to validate and refine the simulation models. This would improve the accuracy of predictions and provide a more comprehensive understanding of the satellite's structural behavior in actual space conditions.
2. **Multi-Physics Simulation Coupling**: While this study focused on mechanical and thermal stresses, future work should explore the integration of other critical factors, such as radiation effects and electrical system performance, into the structural analysis. Coupling multi-physics simulations—combining thermal, mechanical, electromagnetic, and radiation effects—would provide a more holistic evaluation of CubeSat performance in LEO, addressing the complex interactions between these environmental variables.
3. **Advanced Space Debris Impact Simulations**: Space debris poses an increasing threat to nanosatellites, especially in LEO. Future research should delve deeper into high-velocity

impact simulations, using more sophisticated models for debris size, velocity, and impact angles. Additionally, the exploration of advanced protective materials or innovative shielding techniques would help enhance CubeSat durability against such collisions.

4. **Exploration of Alternative Materials**: This research used conventional aerospace materials, such as aluminum, for the CubeSat structure. Future studies could investigate the use of novel materials like carbon composites, shape memory alloys, or 3D-printed components that offer lighter, stronger, or more adaptive structural properties. These materials could improve structural resilience while reducing weight, enhancing the CubeSat's overall performance and cost-effectiveness.
5. **Long-Term Durability Testing**: The effects of long-term exposure to the space environment on material degradation—such as atomic oxygen erosion, thermal fatigue, and radiation damage—should be a focus for future research. Incorporating durability testing into the design process would provide critical insights into the lifespan and performance stability of CubeSats, particularly for missions expected to operate over several years.
6. **Vibration and Shock Isolation Systems**: While this study confirmed that the ET-SMART-RSS CubeSat can avoid resonance during launch, future research could explore the design and integration of advanced vibration and shock isolation systems. These systems could further mitigate the effects of launch-induced vibrations, reducing structural stress and extending the operational life of nanosatellites.
7. **Comparative Case Studies Across Missions**: To generalize the findings of this research, future studies should conduct comparative structural analyses across different CubeSat missions and form factors (e.g., 1U, 3U, 12U). Such cross-case comparisons would help identify common structural challenges and optimization strategies, making the research more applicable to a wider range of nanosatellite designs and missions.

These recommendations highlight the potential for advancing CubeSat structural analysis through enhanced simulation accuracy, novel materials, and deeper exploration of environmental effects, ultimately contributing to the development of more robust and resilient nanosatellites.

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APPENDIX 1:

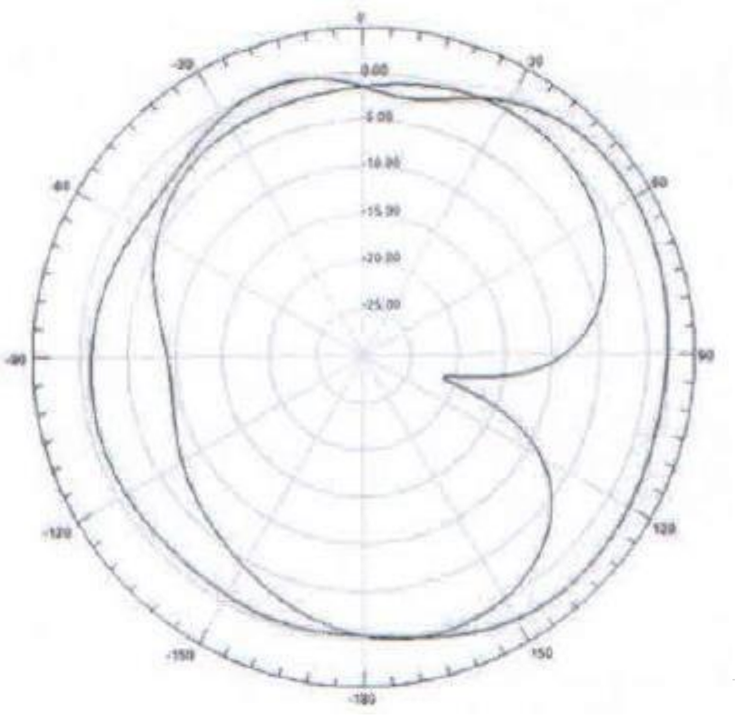
All satellites in the ET-SMART-RSS satellite network will be operational at the same time.

APPENDIX 2:

VHF BAND CO-POLAR RADIATION PATTERN DIAGRAM

Beam: UBV f = 149.8MHZ Gmax = *1 dBi

Note: This diagram shows UBV beam both H (horizontal Polarization) and V (Vertical Polarization) antenna radiation patterns.

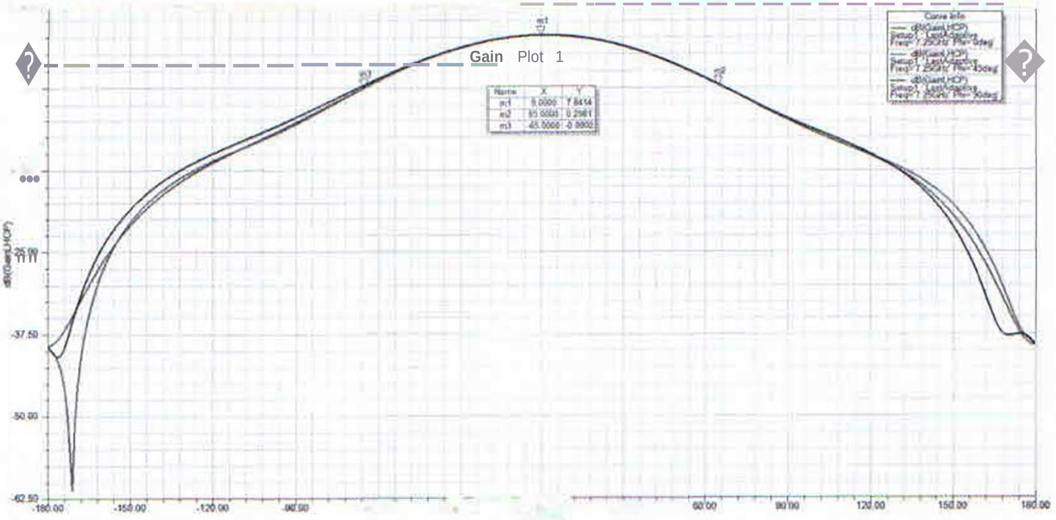


APPENDIX 3:

X BAND CO-POLAR RADIATION PATTERN DIAGRAM

Beam: UXB f=7248 MHz Gmax = 7 dBi

Note: This diagram shows UXB beam both CR (Circular Direct polarization) and CL (Circular indirect polarization) antenna radiation patterns.

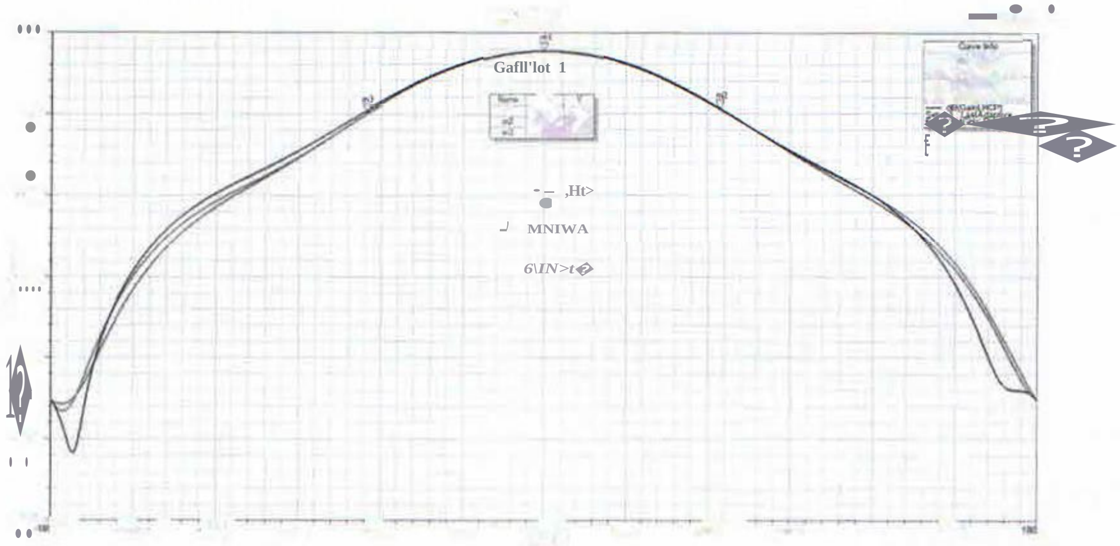


APPENDIX 4:

X BAND CO-POLAR RADIATION PATTERN DIAGRAM

Beam: DXB f=8160.0MHz Gmax = 7 dBi

Note: This diagram shows DXB beam both CR (Circular Direct polarization) and CL (Circular Indirect polarization) antenna radiation patterns.



APPENDIX 5:

X BAND CO-POLAR RADIATION PATTERN DIAGRAM

Beam: XDD f=8212 MHz Gmax = 14 dBi

Note: This diagram shows XDD beam both CR (Circular Direct polarization) and CL (Circular Indirect polarization) antenna radiation patterns.

APPENDIX 6:

UHF BAND CO-POLAR RADIATION PATTERN DIAGRAM

Beam: DBU f=401.9 MHz Gmax = -I dBi

Note: This diagram shows DBU beam both H (Horizontal polarization) and V (Vertical polarization) antenna radiation patterns.

APPENDIX 7:

SAR BAND CO-POLAR RADIATION PATTERN DIAGRAM

Beam: XSAR f=9.6 GHz Gmax = 46 dBi

Note: This diagram shows XSAR beam both H (Horizontal polarization) in earth-to- Space and H (Horizontal polarization) in Space-to-earth antenna radiation patterns.

APPENDIX 8

ET-SMART-RSS Satellite Network API and CRC Data Verification Instructions

1. Check the results with BR SOFT Validation software

For the ET-SMART-RSS API database, use the software tool of ITU to check that there are no fatal errors, only 12 warning errors appear. Two of the warning errors are that the network name ET-SMART-RSS cannot be found in the ITU database; 10 warning errors are because there is no official operator code. The inspection results are as follows:

ET-SMART-RSS API.mdb

Ntc ID: 2 Adm: ETHIOPIA-ECA Sat Name: ET-SMART-RSS Action: A Status: 01 D_RCV: 2018-12-06

Fatal Errors: 0 Warnings: 12

Beam	E/R	Grp id	Table	Field	Value	Row	Valerr	Rule	F/W	Ap4 Ref	Error Message
			non_geo	sat_name	ET-SMART-RSS		200	2	W	A.1.a	Satellite name not in ref table
			non_geo	sat_name	ET-SMART-RSS		200	3	W	A.1.a	Invalid satellite name or action-code value
UXB	R	12	grp	op_agcy	999		605	3	W	A.3.a	value = 999 ; please provide details in attachment
UXB	R	30	grp	op_agcy	999		605	3	W	A.3.a	value = 999 ; please provide details in attachment
XSAR	R	29	grp	op_agcy	999		605	3	W	A.3.a	value = 999 ; please provide details in attachment
DBU	E	35	grp	op_agcy	999		605	3	W	A.3.a	value = 999 ; please provide details in attachment

Beam	E/R	Grp id	Table	Field	Value	Row	Valerr	Rule	F/W	Ap4 Ref	Error Message
DBU	E	36	grp	op_agcy	999		605	3	W	A.3.a	value = 999 ; please provide details in attachment
DXB	E	3	grp	op_agcy	999		605	3	W	A.3.a	value = 999 ; please provide details in attachment
DXB	E	39	grp	op_agcy	999		605	3	W	A.3.a	value = 999 ; please provide details in attachment
XDD	E	1	grp	op_agcy	999		605	3	W	A.3.a	value = 999 ; please provide details in attachment
XDD	E	33	grp	op_agcy	999		605	3	W	A.3.a	value = 999 ; please provide details in attachment
XSAR	E	38	grp	op_agcy	999		605	3	W	A.3.a	value = 999 ; please provide details in attachment

Figure 1: ET-SMART-RSS API satellite network inspection results

For the ET-SMART-RSS CRC database, the software tool of the ITU checked that there were no fatal errors, and only 4 warning errors occurred. Two of the warning errors are that the network name ET-SMART-RSS cannot be found in the ITU database; the two warning errors are because there is no official operator code. The inspection results are as follows:

Ntc ID: 1   Adm: ETHIOPIA-ECA   Sat Name: ET-SMART-RSS Action: A Status: 01   D_RCV: 2018-12-13

Fatal Errors: 0   Warnings: 4

Beam	E/R	Grp id	Table	Field	Value	Row	Valerr	Rule	F/W	Ap4 Ref	Error Message
			non_geo	sat_name	ET-SMART-RSS		200	2	W	A.1.a	Satellite name not in ref table
			non_geo	sat_name	ET-SMART-RSS		200	3	W	A.1.a	Invalid satellite name or action-code value
UBV	R	1	grp	op_agcy	999		605	3	W	A.3.a	value = 999 ; please provide details in attachment
UBV	R	2	grp	op_agcy	999		605	3	W	A.3.a	value = 999 ; please provide details in attachment

2. Check the PFD verification result of the flux density from the downlink beam to the ground

According to Table 21-4 of Article 21.16 of the Radio Regulations, calculate the flux density PFD of the X-band downlink beam to the ground within the range of 0-90 elevation angle and not exceed the limits given in Table 21-4. The calculation results are as follows:

	XDD beam 375M digital carrier			XDD beam 100M digital carrier			DXB beam telemetry		
Elevation	0-5	0 - 25	25-90	0-5	0 - 25	25-90	0-5	0 - 25	25-90
The maximum PFD requirement to	-150	-150+0.5(d-5)	-140	-150	-150+0.5(d-5)	-140	-150	-150+0.5(d-5)	-140

the ground does not exceed （dB(W/m2) per 4 kHz）									
Track height （km）	2077	1031	500	2077	1031	500	2077	1031	500
10*log(4*Pi()*d2)	137.34	131.26	124.97	137.34	131.26	124.97	137.34	131.26	124.97
Satellite beam gain	14.00	14.00	14.00	14.00	14.00	14.00	7.00	7.00	7.00
Satellite transmit power spectral density（dBW）	-71.00	-71.00	-71.00	-77.00	-77.00	-77.00	-68.20	-68.20	-68.20
Beam EIRP maximum spectral density（dBW/Hz）	-57.00	-57.00	-57.00	-63.00	-63.00	-63.00	-61.20	-61.20	-61.20
PFD accounting（dB(W/m2) per 4 kHz）	-158.32	-152.24	-145.95	-164.32	-158.24	-151.95	-162.52	-156.44	-150.15

From the PFD calculation results in the table, the flux density of the X-band downlink beams XDD and DXB to the ground meets the limit requirements in Table 21-4 of No. 21.16 of the Radio Regulations.

For XSAR beams, the frequency range is 9300-9900MHz, which is an active remote sensing service. According to the footnote 21.16.8 of the Radio Regulations, the equation for calculating the average power energy density PFD of the active EESS load to the ground is: $pfd(\delta)=P+10\log(\tau)+10\log(PRF)-30-10\log(Bc)+G_t(\delta)-10\log\left(4\pi d^2(\delta)\right)$

Downlink PFD Accounting for Smart Star Series Satellite SAR Band

1	Transmit carrier frequency（M Hz）	9.6	9.6	9.6	9.6	9.6
2	Transmission system	SAR	SAR	SAR	SAR	SAR
3	Transmission bandwidth (MHz)	600	600	600	600	600
4	satellite downlink transmit power (dBW)	27.8	27.8	27.8	27.8	27.8
5	POWER SPECTRAL DENSITY OF DOWNLINK SATELLITE LAUNCH (dBW/Hz)	-60.0	-60.0	-60.0	-60.0	-60.0
6	EIRP (dBW)	48.8	50.8	63.8	73.8	73.8
7	orbital altitude (km)	500	500	500	500	500
8	elevation（δ）	**5.7**	**15**	**25**	**53**	**90**
9	Farthest space transfer distance（km）（δ）	2078	2078	2078	1032	500
10	Satellite antenna side lobe gain (dB) （δ）	21	23	36	46	46
11	SAR pulse length τ (μs)	50	50	50	50	50
12	SAR pulse repetition frequency(kHz)	5	5	5	5	5
13		-122.35	-120.35	-107.35	-91.27	-84.97

	PFD calculation results (RR. 21.16.8)					
	The following are the PFD requirements for the 9900-10400MHz band					
	Elevation range	0-5.7	5.7-53			53-90
	The maximum PFD requirement to the ground should not exceed (dB (W / m2) per 1MHz)	-113	-109+25log(d-5)			-66.6
		-113	-84	-76.5	-67.0	-66.6
	Accounting result	Meets the requirement	Meet the requirement	Meet the requirement	Meet the requirement	Meet the requirement

Ground elevation angle 5.7 °, On a 500km track, The corresponding satellite base angle is 67.33 °, SAR antenna maximum gain 46dB deviation 55 ° Calculation, At this time, it is about 12.33 ° beside the maximum gain point, Read the pattern, At this time, the maximum gain value is 46dB-25dB, About 21dB

Ground elevation angle 15 °, On a 500km track, The corresponding satellite base angle is 63.6 °, SAR antenna maximum gain 46dB deviation 55 ° Calculation, At this time, it is about 8.6 ° beside the maximum gain point, Read the pattern, At this time, the maximum gain value is 46dB-232dB, About 23dB

Ground elevation angle 25 °, On a 500km track, The corresponding satellite base angle is 57.2 °, SAR antenna maximum gain 46dB deviation 55 ° Calculation, At this time, it is about 2.2 ° beside the maximum gain point, Read the pattern, At this time, the maximum gain value is 46dB-10dB, About 36dB