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Optimal thermal design parameters of educational remote sensing satellite

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Abstract

Remote sensing satellites are like space mirrors that help map land use, monitor disasters, and track environmental changes. They provide valuable data for various applications, from urban planning to climate research. The problem is that space temperatures vary drastically, ranging from 120°C in direct sunlight due to the Sun's intense radiation. This condition is called worst-case hot temperature —since there is no atmosphere to block or moderate it—to as low as -180°C when in Earth's shadow, and this is called worst-case cold temperature. Satellites are equipped with electronic systems that must function within specified temperature limits (from -10°C to 50°C) over their operational lifespans, making it essential to manage thermal conditions to maintain these limits. To address this issue, we used a thermal control system (both passive and active), which will be discussed further in this paper. However, there is a research and knowledge gap in the literature addressing the design and control of remote-sensing satellites in low Earth orbit. This investigation aims to fill this knowledge gap by developing a comprehensive thermal analysis and thermal control model for the "Space Sight MED 2025" remote sensing satellite in low Earth orbit. The developed computational thermal analysis clearly defines the satellite subsystems' worst-case hot and cold temperatures. Two extreme scenarios of extreme hot and extreme cold sun fluxes were considered in a passive system mode. The radiators' areas, temperatures, and locations on the satellite panels were analyzed under the hot scenario. At the same time, the power and operating conditions of the heaters were evaluated based on the cold scenario. Five heaters, each with an 8-watt power rating of 40 watts. Results showed that the 0.5871m² of radiator area is required. The temperatures of the electronic and electrical equipment should range from −7°C to+40°C. However, due to its high sensitivity to temperature changes, the battery should be kept in lower temperatures from 2°C to +28°C.

1. Introduction

Remote sensing satellite is a manufactured satellite that provides invaluable data and capabilities across a wide range of applications, including monitoring land use and environmental conditions, supporting precision agriculture and forestry management, mapping urban areas and infrastructure,

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Nomenclature

A	Area (m^2)
a	Albedo factor (-)
c	Specific heat (J/kgK)
F	View factor (-)
h	Altitude (m)
k	Thermal conductivity (W/mK)
L	Length (m)
$\dot{Q}$	Rate of heat transfer (W)
$\dot{q}$	Heat flux (W/m^2)
R	Radius (m or km)
$\hat{s}$	Solar heating rate step multiplier (-)
T	Temperature (K)
t	Time (s)

Greek letters

α	Absorptivity (-)
β	Beta angle
$\mathcal{E}$	Emissivity (-)
ρ	Density (kg/m^3)
σ	Stefan-Boltzmann constant (5.67×10^{-8} W/ m^{2}K^4)
τ	Orbital period (s)

Subscripts

c	Cold
h	Hot

Abbreviations

AU	Astronomical Unit
CTA	Computational Thermal Analysis
EPS	Electric Power System
EF	Eclipse Fraction
GPS	Global Positioning System
IB	Interference Blocks
LEO	Low Earth Orbit
MBEI	Multi-Band Earth Imager
MLI	Multi-Layer Insulation
MR SAT	Missouri-Rolla Satellite
MRS SAT	Missouri-Rolla Second Satellite
Nad	Nader Side
OBC	On Board Computer
OSRs	Optical Solar Reflectors
PTC	Passive Thermal Control
RW	Reaction Wheels (x, y, z)
SF	Store & Forward communication
TCS	Thermal Control Subsystem
TD	Temperature Disturb
Tel	Telemetry
UHF	Ultra-High Frequency
VHF	Very High Frequency
WCC	Worst-Case Cold temperature
WCH	Worst-Case Hot temperature
Zen	Zenith side

aiding disaster response and climate research, assisting in geological exploration and mineral resource identification, and contributing to defense and national security efforts - making them an essential tool for scientific, commercial, and governmental organizations in their efforts to understand, manage, and protect the Earth and its resources. These satellites are outfitted with electronic systems that must function within specified temperature limits over their operational life spans (from -10^{o}C to 50^{o}C). Managing thermal conditions involves three primary stages: design, analysis, and testing. After a thermal analysis, the thermal design undergoes refinement and validation through thermal balance tests. Thermal control methods are broadly classified into two categories: passive and active. Passive methods like multi-layer insulation (MLI), optical solar reflectors (OSRs), thermal interface fillers, and specialized thermal coatings like second surface mirrors do not consume power. In contrast, active methods, including heaters and thermistors, require electricity. The thermal control subsystem (TCS) is one of the key components that maintains the required temperature settings for other satellite subsystems and devices throughout the mission. Given the importance of thermal control systems, research in this area is ongoing, and recent advancements have led to significant improvements. Innovative techniques, particularly for small satellites in Low Earth Orbit (LEO), have emerged to address the challenges of extreme space temperatures. Smith et al. (2020) highlighted the development of advanced materials like aerogels and high-emissivity coatings, which provide excellent thermal insulation while minimizing weight, a crucial factor for small satellites with strict mass constraints. Jones and Patel (2019) explored using phase change materials (PCMs) in satellite designs. PCMs absorb excess heat during sunlight exposure and release it when the satellite passes through Earth's shadow, effectively regulating internal temperatures without the need for active thermal control. This passive approach is cost-effective and energy-efficient, making it ideal for educational and low-budget satellite missions. Another key advancement is the increased use of Computational Thermal Analysis (CTA) tools, such as Thermal Desktop and COMSOL Multiphysics. Liu et al. (2021) demonstrated how these tools improve the accuracy of satellite thermal designs by enabling detailed simulations of extreme thermal environments, reducing the need for extensive in-orbit testing. These tools allow engineers to predict satellite performance under worst-case thermal conditions, ensuring mission success, particularly for small-scale satellite operations. Satellite thermal modeling is achieved by calculating the thermal budget equation, considering the maximum and minimum heat rejection from internal devices installed on the interior surface of the panel and external fluxes Sommer's [9] carried out study on the BIROS satellite involved thermal control design and analysis to ensure optimal performance in space. The study examined various thermal control techniques, including radiators and heat pipes, to manage the satellite's heat. The analysis showed that the thermal control system successfully maintained component temperatures within the desired range, even during mission-critical operations. S. Carpino et al. research, published in Acta Astronautical in 2015 [12], described the thermal analysis conducted on a nanosatellite created at Politecnico di Torino. The study included an overview of the key mission parameters and spacecraft design to set the analysis's boundary conditions and thermal environment. The results were analyzed and discussed in detail. The newly developed tool exhibited outstanding modeling capabilities, and the temperature distributions were confirmed with commercial software. B. Johnson's research, which was published in the International Journal of Satellite Communications and Networking in 2018 [16], evaluated the thermal performance of the EchoStar XVII communication satellite. Their study included simulations and in-orbit measurements to assess the temperature distribution across the satellite. The findings showed that the thermal control strategies, including heat pipes and thermal blankets, successfully maintained stable temperatures for the satellite's critical components. T. Nomura's research, published in Transactions of the Japan Society for Aeronautical and Space Sciences journal in 2016 [13], conducted a thermal analysis on the Horyu-IV satellite, focusing on its thermal design and passive thermal control methods. Unlike other studies, the scientific value added by this study is about the computational thermal analysis of the impact of radiators and heaters on the satellite thermal performance to achieve the optimal thermal design for low earth orbit. The study highlighted the effectiveness of using multi-layer insulation and heat pipes to maintain the temperature of critical components within operational limits. The analysis results were validated through thermal vacuum tests. The paper will guide you through the entire process, starting from the satellite design and moving to the thermal effects impacting the satellite, followed by the mathematical modeling and heat transfer mechanisms. It will then delve into the satellite's thermal design, present the numerical model, and cover the thermal analysis, ultimately leading to the results and conclusions, with references provided at the end.

2. Design of space sight "MED 2025"

Fusion Software and calculations designed the satellite and housing were done in the design for all locations of the satellite system. The satellite contains a large group of components that help it perform its functions effectively, and it also includes a group of safety circuits that maintain the efficiency of the components. It also consists of antennas and transponders that receive and retransmit signals. Instructions will be sent to the satellite via Very High Frequency (VHF) and Ultra High Frequency (UHF) radio waves. S-Band microwaves will be used to transmit data. Solar cells will provide the satellite energy, part of which will be stored in a battery to provide energy in periods of low or nil solar radiation, for instance, when the satellite traverses Earth's shadow, that will be distributed between the previously referred components by a special circuitry, the Electric Power System (EPS). The processing of instructions and the coordination of all the component tasks will be performed by an onboard computer (OBC). Figure 1 shows the sketch and the real design of the satellite.

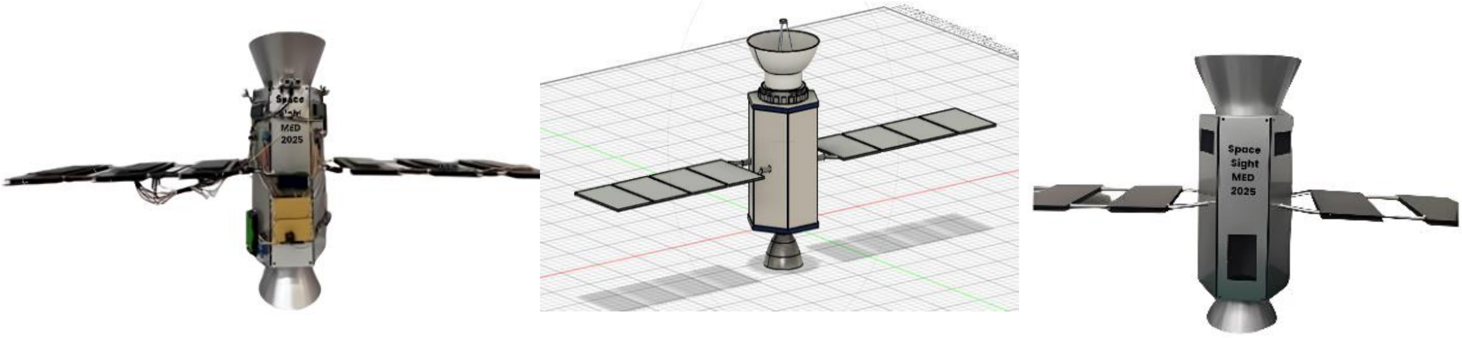

Fig. 1. Space Sight Med 2025, sketch, and real design

2.1. Thermal effects on a space satellite

Write Satellites' operational lifespan and performance rely heavily on the impact of the thermal environment in space [24,25]. This dynamic environment undergoes periodic changes throughout the satellite's operational phase. Every component within a spacecraft must maintain a specific range of temperatures to ensure its survival and operational efficiency throughout every mission stage. These temperatures are determined by the balance of heat entering, being stored, and exiting the spacecraft. The diagram below offers a simplified depiction of the heat transfer into and out of an orbiting satellite. While the diagram portrays Earth as the orbited celestial body, the principle applies to any planet or object around which a spacecraft orbits. The values Q_g, $Q_{out\mathrm{Rad}}$, and $Q_{s\ \mathrm{absored}}$ are measured in Watts, according to the international system of units (S.I.).

At the same time, q_{solar}, q_{albedo}, and $q_{planetshine}$ are presented as heat fluxes, measured in Watts per square meter in S.I. Figure 2 depicts the external thermal factors affecting a satellite. The primary heat source for a satellite is the direct solar flux, which is significantly intense. The spectral makeup of solar radiation is a crucial factor as it directly impacts the intensity of the solar flux. Simplifying thermal modeling,

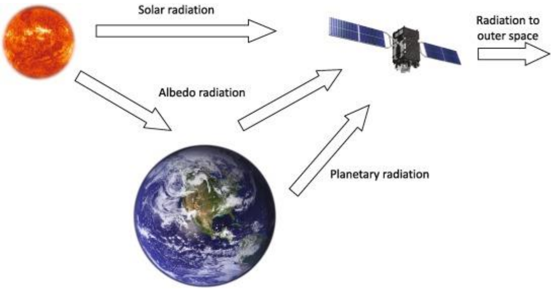

Fig. 2. Schematic view of the external loads on a satellite

The Sun can be considered a black-body radiator at a temperature of 5762 K.

The direct solar flux varies depending on the distance from the Sun, with an average value of 1367 W/m² at 1 astronomical unit (A.U.) or 149.5 million kilometers. This flux can be expressed as a function of the distance between a celestial body and the Sun in astronomical units, as in Eq. (1).

$$\dot{Q}_{solar} = \frac{1367.5}{(AU)^2} \tag{1}$$

The heat the spacecraft absorbs due to the direct solar flux can be analytically written, as shown in Eq. (2).

$$\dot{Q}_{solar} = \alpha \times q_{solar} \times A_{solar} \times cos\ (\theta) \tag{2}$$

The equation suggests that the absorbed heat energy is contingent on several factors, including the distance from the Sun, the thermo-optical properties of the surface, and the exposed area. Albedo, the reflected solar radiation from the illuminated side of a celestial body, serves as an additional heat source for satellites. The satellite's position influences this form of radiation and undergoes significant variations with changes in orbital altitude. The heat absorbed by the spacecraft from Albedo can be approximated using Eq. (3).

$$\dot{Q}_{Albedo} = a \times q_{Albedo} \times A_{Albedo} \times F_{s/c-p} \times cos\,(\phi) \tag{3}$$

In this analytical representation, the planet is considered a reflective sphere. Another form of radiant heat input for a satellite is planetary radiation, known as outgoing long-wave radiation. This occurs because planets absorb certain radiation and emit it as infrared rays. The amount of planetary radiation varies across the planet's surface due to differing thermo-optical properties. The heat absorbed by the spacecraft from planetary infrared radiation can be calculated using Eq. (4).

$$\dot{Q}_{planet} = \varepsilon \times q_{planet} \times A_{planet} \times F_{s/c-p} \tag{4}$$

The fourth heat source originates from the internal electronics integrated into a satellite. This heat generation varies depending on the quantity of heat energy collected from external sources, the conversion of heat into electrical energy, and the power consumption of electronics, which leads to heat production. Satellites operating in the space environment encounter harsh conditions dominated by a vacuum. Consequently, cooling certain satellite components proves to be highly challenging, while there are situations where heating is necessary based on their position relative to the Sun. Typically, satellite design is determined by considering periodic solar conditions and the daily fluctuations in both solar maximum and minimum levels.

2.2. Mathematical modeling and heat transfer mechanism of the satellite

Conduction, a heat transfer method, occurs when microscopic particles collide and diffuse [25,26]. Heat can be transferred through any medium via conduction, but the thermal conductivity rate can vary significantly among different materials. Conduction is primarily responsible for heat transfer within a satellite. Materials can be selected based on their conductive properties to manage the thermal conditions of a spacecraft, and insulators can be applied to reduce the conduction rate. Conduction heat transfer is governed by Fourier's Law, which considers the rate of conduction, temperature gradient, and the direction of energy flow. The differential form of Fourier's Law of thermal conduction is expressed as shown in Eq. (5).

$$\vec{q} = -k \times \nabla T \tag{5}$$

Hence, the amount of heat transfer via conduction can be described in Eq. (6).

$$Q = \frac{A}{L} \times k \times (\mathrm{T}_h - \mathrm{T}_c) \tag{6}$$

Thermal conductivity over time in 3-D space can be determined according to Eq. (7).

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial_T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial_T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial_T}{\partial z}\right) = \rho \times c \times \frac{\partial_T}{\partial t} \tag{7}$$

Radiation, a different heat transfer method, occurs through the movement of particles or electromagnetic waves. An orbiting spacecraft encounters three forms of radiation: direct solar flux, Albedo, and planetary infrared. Radiation heat transfer follows Stefan-Boltzmann's Law, which defines the radiation rate based on a black body's absolute temperature. The fundamental equation governing radiation heat transfer is expressed as shown in Eq. (8).

$$Q = \varepsilon \times \sigma \times A \times \left(\mathrm{T_1}^4 - \mathrm{T_2}^4\right) \tag{8}$$

The management of thermal energy within a spacecraft is significantly impacted by environmental heat. The primary sources of ecological heating during a satellite's orbital service include direct solar flux, Albedo, and planetary-infrared energies. Essentially, achieving a comprehensive thermal balance for a satellite involves managing the energy transmitted by the satellite against the energy received from the external environment and the energy dissipated by the internal electronic components. Thus, the energy balance equation for the satellite can be expressed according to Eq. (9).

$$C\frac{dT}{dt} = \dot{Q}_{in} - \dot{Q}_{out} \tag{9}$$

where $\dot{Q}_{in} = \dot{Q}_{solar} + \dot{Q}_{Albedo} + \dot{Q}_{planet} + \dot{Q}_{internal}$ and $\dot{Q}_{out} = \dot{Q}_{radiation}$

The external loads of direct solar, Albedo, and planet-infrared and the internal heat dissipation load from the electronic equipment are heat inputs to a satellite. In contrast, the radiated heat from that is output.

Hence, the balance equation can be given according to Eq. (10).

$$C\frac{dT}{dt} = \dot{Q}_{solar} + \dot{Q}_{Albedo} + \dot{Q}_{planet} + \dot{Q}_{internal} - \dot{Q}_{radiation} \tag{10}$$

Mathematically representing the physical system of a satellite involves defining a simplified geometry that includes only the essential thermal details. This simplified geometry is known as a geometrical mathematical model. Once the geometry is determined, it is discretized into a network of nodes. The energy balance equation for each node can be expressed according to Eq. (11).

$$C_i\frac{dT_i}{dt} = \dot{Q}_{in,i} + \sum_{j=1}^{n} K_{ij}\left(T_j - T_i\right) + \sum_{j=0}^{n} \sigma R_{ij}\left({T_j}^4 - {T_i}^4\right) \tag{11}$$

Notice that the satellite's thermal behavior is approximated using a simplified geometry that includes only the essential thermal details. This simplification assumes that the satellite can be broken down into a limited number of uniform surfaces and nodes, reducing computational complexity. However, this assumption can introduce some inaccuracies, particularly in regions where heat distribution may be non-uniform, such as areas near electronic components or where material properties change. The modeling process also assumes that external heat sources, like solar flux and Albedo, remain constant during each simulation phase. These values can fluctuate due to variations in the satellite's orientation and orbit. Additionally, the internal heat generation from electronic components is considered constant, while actual heat production might vary depending on the satellite's operational status. Utilizing the balance equation across all segmented nodes of the satellite yields a set of ordinary differential equations. The solution to these equations provides the temperature distribution across the satellite. The matrices representing conductive and radioactive thermal loads, combined with the vectors for internal and external thermal loads, collectively establish a thermal-mathematical model for the satellite. This model validates thermal balance predictions throughout the satellite's lifecycle.

3. Satellite thermal design

In this study, a satellite model with six expandable solar panels was developed, including 28 electronic devices and Bluetooth modules acting as an antenna. The satellite's design and component layout are detailed below: The satellite's core is hexagonal, constructed from aluminum 7075 alloy containing 3% titanium for enhanced protection against rust, corrosion, and external elements. Its dimensions are 41×17 cm, comprising two cone-like sections. The larger upper cone represents the antenna housing, while the smaller lower cone signifies the thruster area. The upper cone has diameters of 12 cm (small) and 19 cm (large), while the lower cone has diameters of 9 cm (small) and 15 cm (large). Additionally, the satellite includes two side panels for solar cell installation, seamlessly integrated into the main body, resulting in a final assembled size of 130 x 55 cm. Fig. 3 describes the main component of the satellite. The satellite's internal electronic components are mounted on the inner surfaces of the main body's (+X) and (−X) panels, as well as the main body's (+Y) and (−Y) panels. Some electronic equipment, like magnetometers and sun sensors, are on the (−Z) panel outside the satellite. The antennas, represented by Bluetooth modules, are on the (+Z) panel outside the satellite. The satellite's main body features a thermal conductivity of 167 W/mK and a thickness of 0.001 m. Thermal interface fillers are used between the panels and electronic equipment to improve thermal conductivity and prevent overheating. The dry contact value between the equipment and panels, assuming no thermal interface material with high conductance values, is 300 W/m^{2}K. All electronic equipment is coated with black paint to ensure a uniform temperature distribution within the satellite.

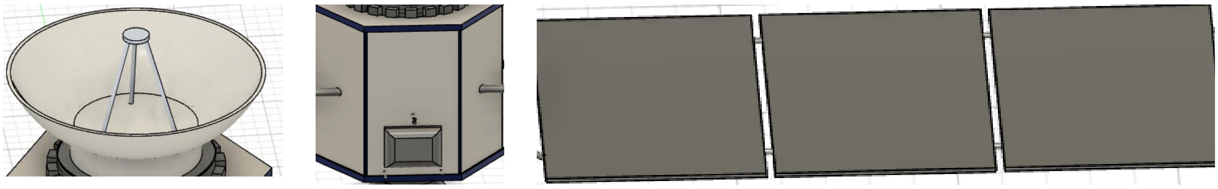
(a) (b) (c)

Fig. 3. Space Sight Med 2025, a): cone, b): main body, and c): solar panels.

Maintaining specific temperature ranges for the electronic equipment throughout the mission is crucial to prevent thermal fatigue, overcooling, or overheating. Table 1 [27, 8] shows each satellite subsystem's operating temperature range (Tmin, Tmax). Operation outside these ranges should be avoided. The selection of aluminum 7075 alloy for the structural design of Space Sight MED 2025 is well-justified due to its exceptional thermal and mechanical properties. With thermal conductivity values ranging from 130 to 160 W/mK, aluminum 7075 ensures efficient heat dissipation across the satellite's body, preventing localized overheating that could damage sensitive electronic components. Its high strength-to-weight ratio makes it an ideal choice for aerospace applications, where minimizing mass is critical to reducing launch costs. Beyond its thermal efficiency, aluminum 7075 is highly corrosion-resistant, allowing the satellite to endure the harsh conditions of space. Studies by Fortescue and Stark (2017) confirm that aluminum alloys, particularly 7075, have been successfully used in numerous space missions due to their durability and ability to maintain structural integrity under fluctuating temperature conditions. However, materials such as carbon fiber composites and titanium alloys are also gaining traction in satellite design. These materials offer improved thermal stability and exhibit even lower thermal expansion coefficients, which could benefit missions exposed to extreme temperature variations. Although these materials are more expensive, they provide long-term structural performance and thermal regulation advantages, potentially reducing the need for extensive active thermal control systems.

3.1. Numerical model

The numerical model of the thermal analyses and simulations for the satellite [21,22] was developed using the Thermal Desktop software. This software computes the thermal radiation between nodes and the surrounding environment. The Monte Carlo ray-tracing method was applied to solve the radiative transfer equation. This method dynamically calculated external orbital radiative heat fluxes during the mission and the radiative transfer interactions among components. The radiation falling on and scattered from outer surfaces was assumed to be diffuse. In the simulations, space temperature was set at 4 K, and the initial temperature of the entire system was 273 K to ensure convergence to the coldest and hottest conditions. The simulation included five million mesh elements for ten revolutions of the satellite, with each revolution lasting 90 minutes. This study demonstrates a satellite's detailed thermal design and control, considering radiators and heaters to optimize performance for other components and subsystems. During the simulation, 887,254 random rays were projected onto the satellite, and each representative item of equipment, the main body, and the solar panels emitted 11,324 rays. The operating conditions for the satellite are detailed in Table 2.

Table 1: Operating temperature ranges for satellite equipment.

Component	T_{min} (°C)	T_{max} (°C)
Batteries	-2	28
Electronics components	-7	40
Solar panels	-100	110
Camera	0	50
Antennas (Bluetooth module)	-70	100
Sun Sensors	-20	50
Main Structure	-90	90
Magnetometer	-20	50

Table 2: Operating parameters for the satellite.

Orbit Type	Sun-Synchronous
Revolution	10 Rev.
Altitude	820 Km
Launch Year	2025
Solar Time	22:30:00
Time Per Rev	90 min
Space Temp	4 K

3.2. Satellite thermal analysis

Thermal assessment is employed to analyze and regulate the temperature distribution of the equipment while it operates in space [1, 2]. The positioning of electronic components must be maintained within specific temperature ranges throughout the satellite's operational lifespan. Two scenarios impact the satellite's thermal control system design: the hot case and the cold case. The hot case exposes the satellite to the highest external heat flux. The primary objectives are to determine the necessary radiator area and identify optimal radiator placements on the satellite. Conversely, the cold case involves the lowest external heat flux. The aim is to calculate the power requirements for heaters and thermistors. The critical parameters for each scenario we use within the Thermal desktop software to implement our analysis are outlined in Table 3.

Table 3: Parameters for the hot and cold cases.

Parameter	Hot Scenario	Cold Scenario
Solar Flux	1367 W/m²	1326 W/m² (0 W/m² for eclipse)
Albedo Factor	0.35	0.20
Beta angle	27	22
Earth Temp	252.4 K	248 K
Earth IR	258 W/m²	258 W/m²
Absorptivity of Radiator	0.24	0.14
Space Temp	4 K	4 K

3.3.1. Software limitations

Thermal Desktop is a widely recognized tool for thermal modeling in space systems, offering powerful capabilities for analyzing heat transfer, radiation, and conduction in complex environments like low Earth orbit (LEO). However, like all simulation tools, it has certain limitations that can introduce potential uncertainties in the results.

1. Accuracy of Radiative Heat Transfer Calculations

Thermal Desktop uses a simplified approach for calculating radiative heat transfer between satellite surfaces and the surrounding space. While this method is generally effective, it assumes that surfaces emit and absorb radiation uniformly. In real-world scenarios, the satellite's surfaces may have non-uniform properties or encounter varying thermal loads due to the complex environment, such as fluctuating solar flux or shadowing effects. This assumption can lead to minor inaccuracies, particularly in areas where radiative exchange plays a significant role in temperature control.

2. Mesh Resolution and Discretization

The accuracy of any thermal simulation is highly dependent on the mesh resolution used to model the satellite's structure. In the current study, the satellite was discretized into finite elements to represent its geometry and thermal properties. However, if the mesh is too coarse, it can miss subtle thermal gradients or local hotspots that could affect the satellite's performance. Conversely, increasing the mesh resolution improves accuracy but requires significantly more computational resources and time, which can be a limiting factor in large, complex models.

3. Assumptions in Material Properties

Thermal Desktop relies on predefined material properties such as thermal conductivity, specific heat, and emissivity. In some cases, these values may be based on average or nominal data rather than exact measurements from the particular batch of materials used in the satellite. Variations in material properties due to manufacturing inconsistencies or operational degradation (e.g., thermal cycling or space environment exposure) can introduce uncertainties into the thermal model.

4. Solar and Albedo Models

In modeling the external thermal environment, solar flux and Albedo (reflected solar radiation) are key factors. Thermal Desktop uses standard values for these inputs based on the satellite's orbit and orientation. However, these values can vary in practice due to changes in the satellite's position, attitude, or proximity to celestial bodies (like the Earth or Moon). These variations can affect the thermal load on the satellite and lead to discrepancies between the simulated and actual thermal behavior.

3.3.2. Comparison with Alternative Software:

1. ANSYS Fluent: A popular alternative, it offers advanced computational fluid dynamics (CFD) and thermal modeling capabilities. It provides a more detailed handling of fluid flow and heat transfer, which can be useful for modeling complex geometries and finer thermal details. However, it requires greater computational resources and setup complexity.

2. COMSOL Multiphysics: provides a flexible platform for thermal simulations with a strong focus on Multiphysics (i.e., coupling thermal, mechanical, and electromagnetic effects). It allows for more intricate coupling between different physics domains, which can provide a more holistic understanding of the satellite's thermal behavior. However, it may require more customization and expertise in model setup.

3. ThermXL: This tool offers simplified thermal models and is especially suitable for quick calculations. While it is less robust than Thermal Desktop or ANSYS, it is often used for preliminary designs to provide rapid estimations of thermal performance. Its main drawback is the lack of detailed customization and lower accuracy in complex thermal environments.

4. Systema Thermica: Like the Thermal Desktop program, Systema Thermica is widely used in the space industry for satellite thermal analysis. It uses a ray-tracing method to model radiative heat transfer, which can be more accurate in certain cases where non-uniform surface properties or orientations need to be considered. A comparison between the results from Thermal Desktop and Systema Thermica would help validate the thermal model, especially in terms of radiative heat transfer accuracy.

3.4 Reasons for Selecting Thermal Desktop

1**. Designed for Space Applications**: Thermal Desktop is specifically built for satellite and spacecraft thermal analysis, unlike tools like ANSYS or COMSOL , which are more general-purpose. It has built-in models for space environments (like solar radiation and Earth's Albedo), making it easier and quicker to set up satellite simulations.

2. Easy to Use for Satellite Models: Setting up satellite models is simpler and more intuitive in the Thermal Desktop. Tools like COMSOL or ANSYS can be more complex and time-consuming to configure, especially for space-specific scenarios. Thermal Desktop is streamlined for aerospace work, saving engineers time.

3. Integrates with SINDA/FLUINT: Thermal Desktop integrates with SINDA/FLUINT, a powerful tool used specifically for modeling spacecraft's thermal and fluid systems. This makes it great for projects involving fluid cooling systems (like heat pipes), which is harder to do with other software.

4. Trusted in the Space Industry: Thermal Desktop is widely used by NASA and major aerospace companies. This means it's a trusted, well-validated tool in the industry, which adds credibility to your work when using it.

5. Better for Radiative Heat Transfer: In space, heat transfer mainly happens through radiation (since there's no air for convection). Thermal Desktop excels at modeling this type of heat transfer, making it more accurate for predicting how satellites will behave in space compared to other software.

6. Cost-Effective and Time-Saving: Since Thermal Desktop is specialized for spacecraft, it's more focused and less complicated than broader tools like ANSYS or COMSOL, making it more cost-effective and easier to use for satellite missions, especially for smaller projects or educational missions.

4. Results and discussion

4.1. Results

Fig. 4,5,6,7, and 8 explain the satellite drawing on the thermal desktop before running the case, the satellite simplified drawing on the thermal desktop before running the case, the satellite location and the orbital shape in the hot case, and the satellite drawing after being thermally analyzed in the cold case, and the satellite drawing after being thermally analyzed in the hot case. The critical parameters of both hot and cold scenario conditions are presented in Table 4. Each scenario has two cases that differ in the number of nodes used in the analysis, four and forty nodes for each case. The maximum and minimum temperatures to which the various components of the satellite will be exposed were determined in both hot and cold scenarios, as shown in Tables 4 and 5.

4.2. Discussion

4.2.1. Hot Scenario: although all the components in the hot scenario don't go over their operational higher limit, the electronic components, batteries, and Sun sensor operate near their upper-temperature thresholds during the hot scenario. While these temperatures are within the operational limits, they approach the maximum allowable values as in table 6:

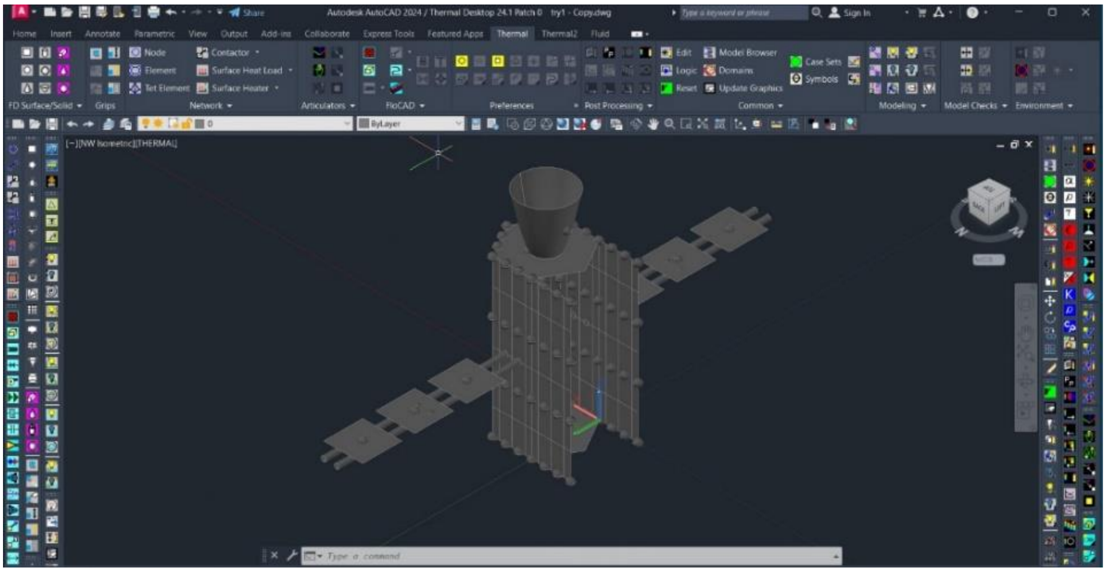

Fig.4. The satellite drawing on the thermal desktop before running the case.

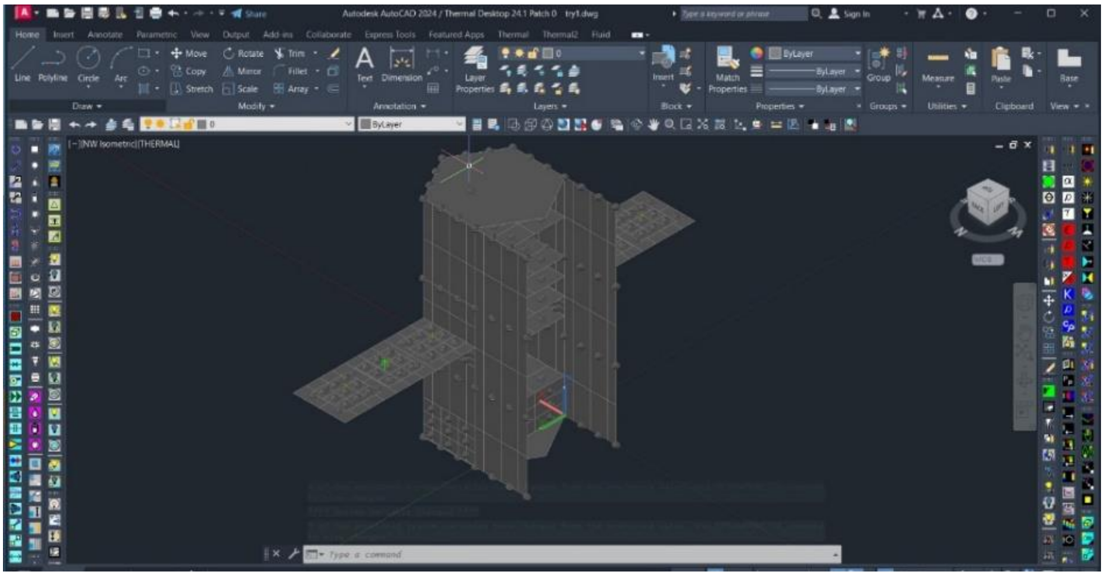

Fig.5. The satellite simplified drawing on the thermal desktop before running the case.

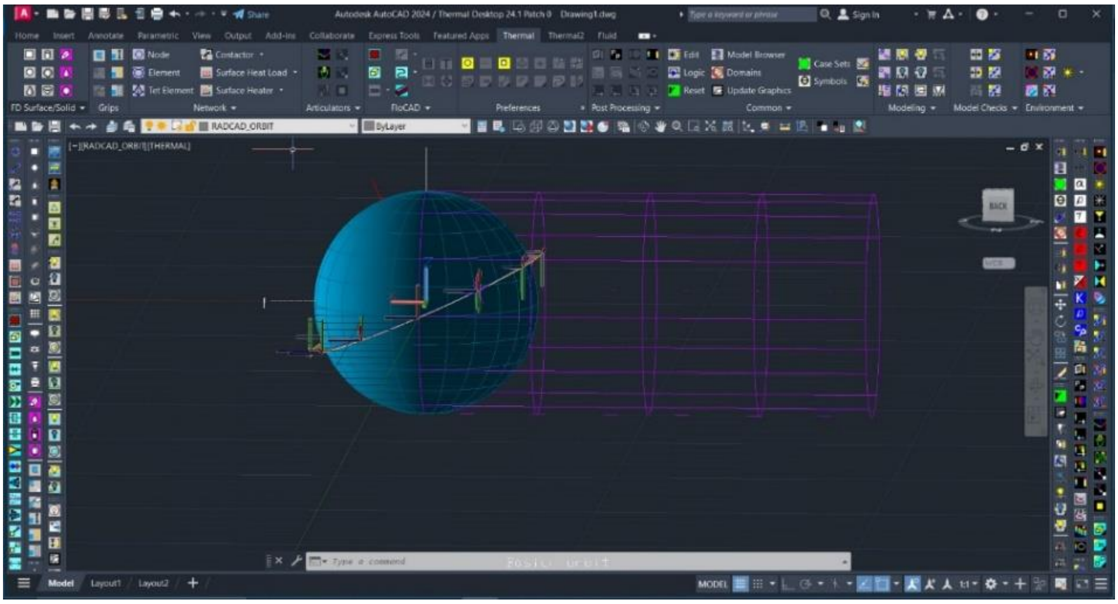

Fig.6. Shooting mode at $\beta = 27^\circ$.

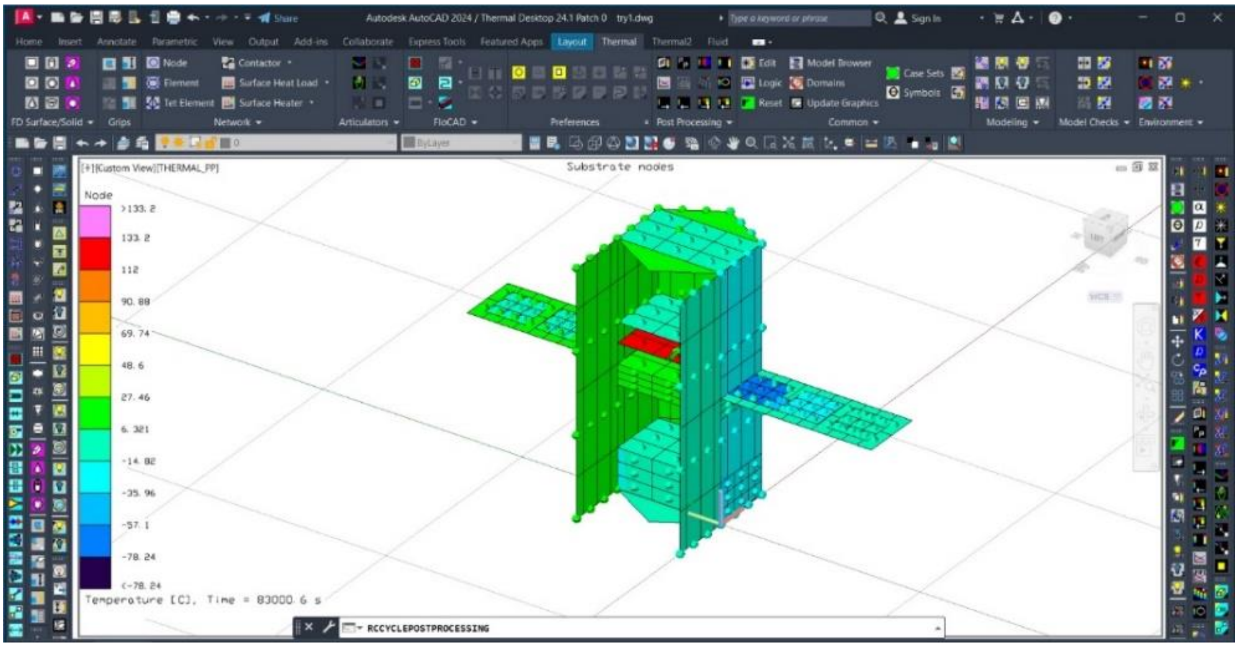

Fig.7. The satellite drawing after being thermally analyzed in the cold case.

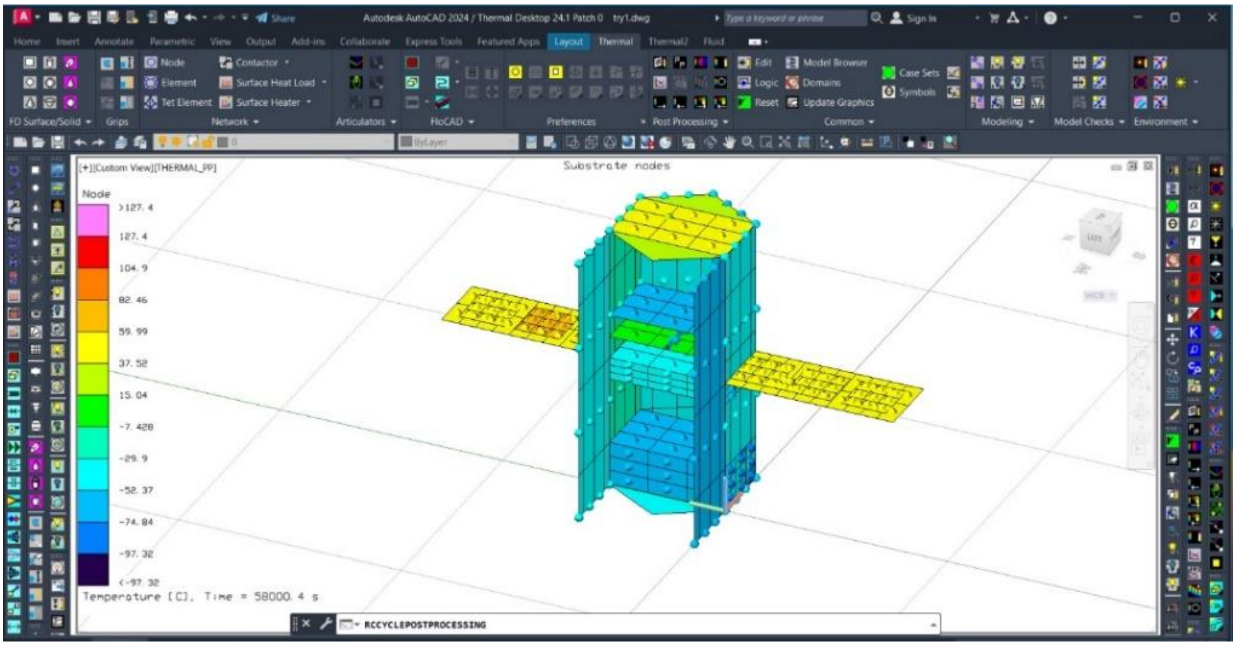

Fig.8. The satellite drawing after being thermally analyzed in the hot case.

Table 4: Temperature Results for the main satellite components in the hot and cold scenarios with 4 nodes analysis.

Component	Temperature (ºC)	
	Hot Scenario	Cold Scenario
Batteries	from 23.8 to 27.5	from -0.5 to 4.1
Electronic components and sensors	from 36.5 to 39.6	from -11.3 to -7.7
Solar panels	from 48.2 to 53.6	from -9.3 to -5.2
Camera	from 33.1 to 37.4	from -0.5 to 2.2
Antennas (Bluetooth module)	from 46.1 to 52.8	from -4.7 to 1.5
Sun Sensors	from 44.1 to 47.6	from -7.6 to -2.2
Main Structure	from 21.2 to 25.1	from -16.1 to -9.7
Magnetometer	from 32.4 to 37.6	from -5.6 to -1.7

Table 5: Temperature results for the main satellite components in the hot and cold scenarios with 40 nodes analysis.

Component	Temperature (ºC)	
	Hot Scenario	Cold Scenario
Batteries	from 23.8 to 27.5	from -0.5 to 4.1
Electronic components and sensors	from 36.5 to 39.6	from -11.3 to -7.7
Solar panels	from 48.2 to 53.6	from -9.3 to -5.2
Camera	from 33.1 to 37.4	from -0.5 to 2.2
Antennas (Bluetooth module)	from 46.1 to 52.8	from -4.7 to 1.5
Sun Sensors	from 44.1 to 47.6	from -7.6 to -2.2
Main Structure	from 21.2 to 25.1	from -16.1 to -9.7
Magnetometer	from 32.4 to 37.6	from -5.6 to -1.7

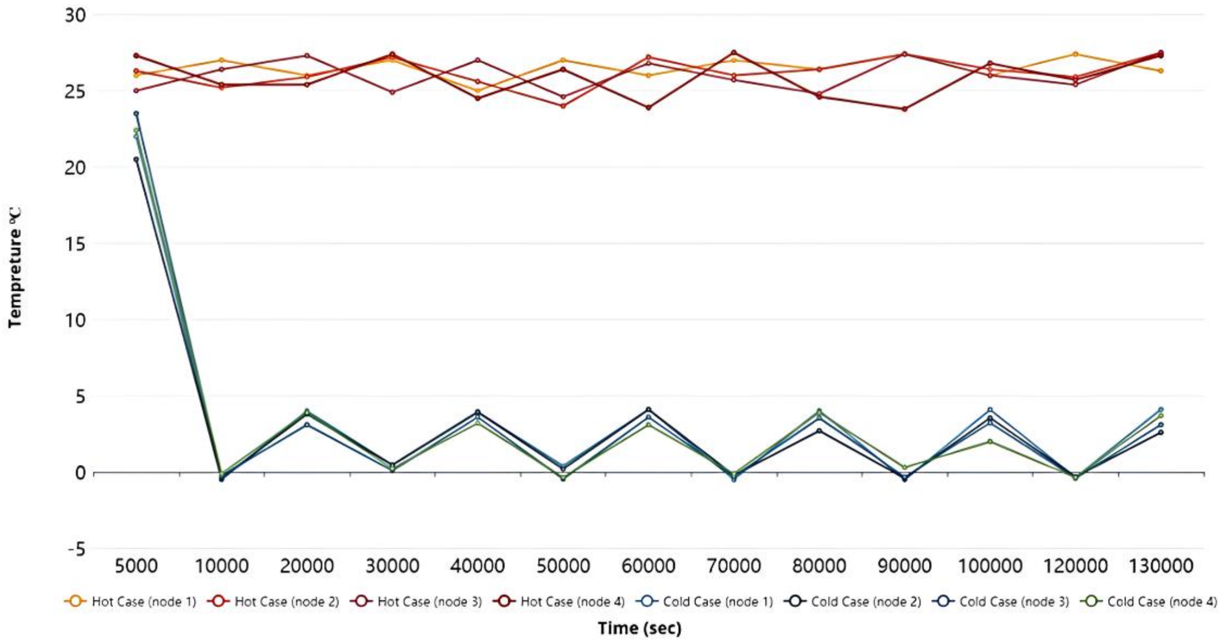

Fig. 9. Temperature curve of the battery in the hot and the cold conditions (4 node analyses).

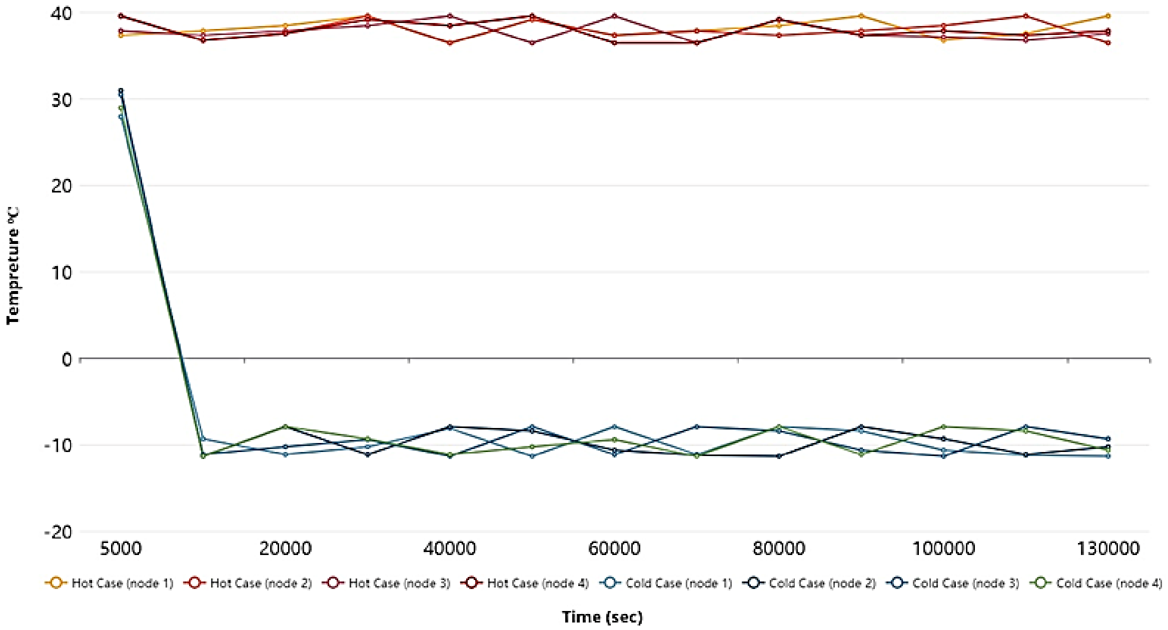

Fig. 10. Temperature curve of electronic components and sensors in hot and cold conditions (4 node analyses).

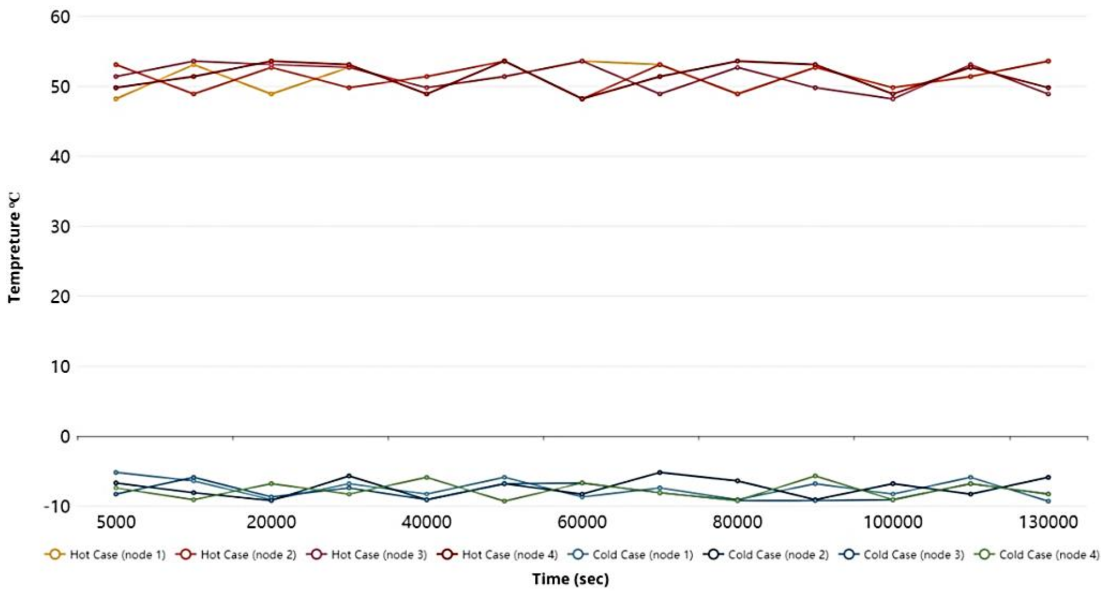

Fig. 11. Temperature curve of solar panels in the hot and the cold conditions (4 node analyses).

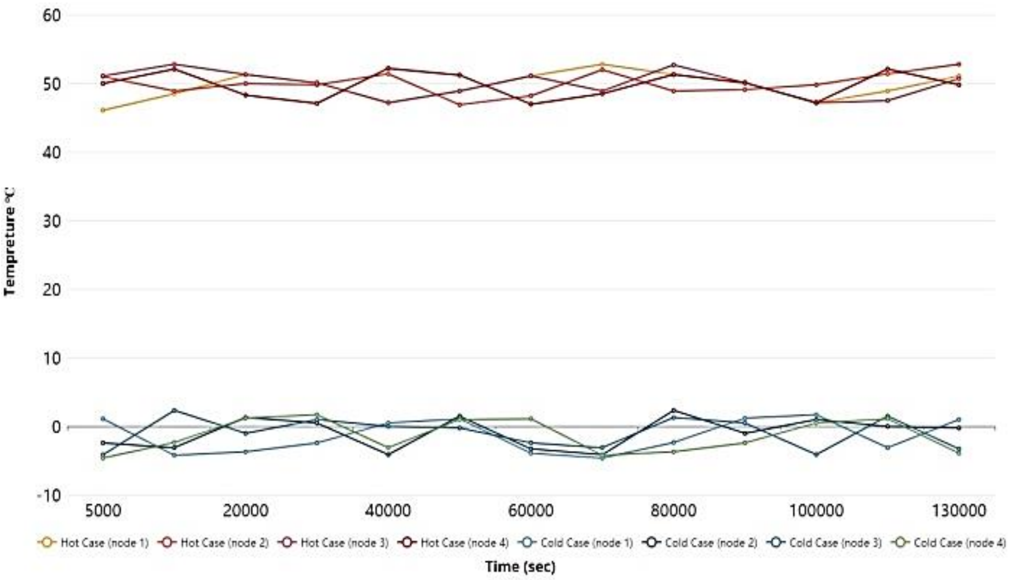

Fig. 12. Temperature curve of the antennas in the hot and the cold conditions (4 node analyses).

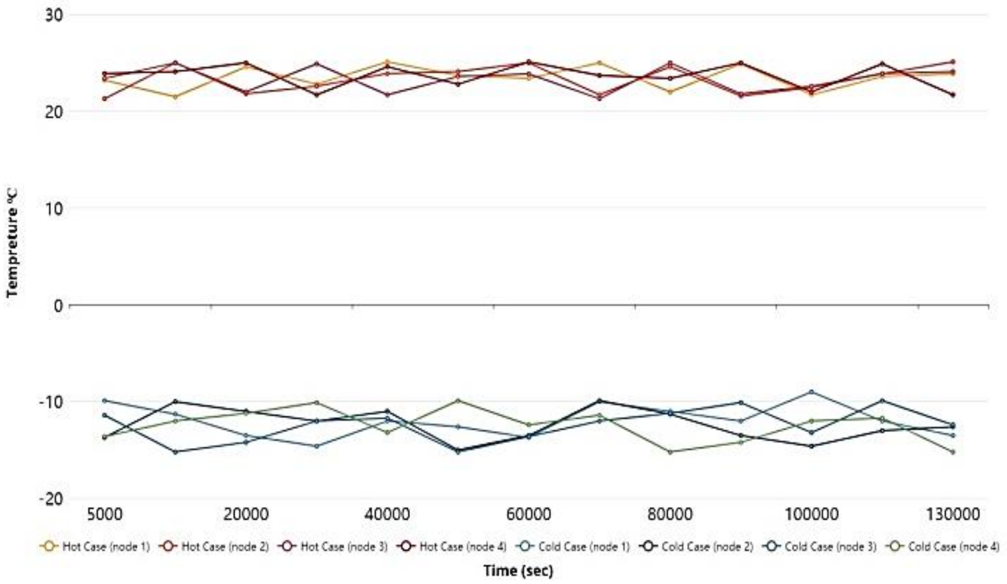

Fig. 13. Temperature curve of the main structure in the hot and the cold conditions (4 node analyses).

Table 6: Comparison between High operational limit temperature and the results in the hot scenario

Component	High operational limit (°C)	Simulation results (°C)
Battery	T_{max}= 28	From 23.8 to 27.5
Electronic components	T_{max}= 40	From 36.5 to 39.6
Sun sensors	T_{max}= 50	From 44.1 to 47.6

According to the table, the temperature of the components does not surpass the operating limit in the hot scenario, though it is near it. If the satellite operates in an environment where temperatures frequently approach these upper limits, the electronic components may experience reduced efficiency or premature wear. In order to address this, additional cooling measures might be necessary, such as optimizing radiator placement or increasing radiator surface area to improve heat dissipation.

4.2.2. Cold scenario: The battery, electronic components, and camera are close to their lower temperature limits. This could lead to some issues, like in the hot scenario.

Table 7:Comparison between low operational limit temperature and the results in the Cold scenario

Component	Lower operational limit (°C)	Simulation results (°C)
Battery	T_{min}= -2	From -0.5 to 4.1
Electronic components	T_{min}= -7	From -11.3 to -7.7
Camera	T_{min}= 0	From -0.5 to 2.2

Therefore, it was necessary to install a radiator and a heater and to calculate the radiator's surface area and the power of the heater to raise the temperature of the components and the subsystems and make them operate at the optimal temperature.

4.3. Design parameters:

4.3.1. Radiators area:

The radiator area can be calculated through the following equation [24, 25]:

$$\dot{Q}_s \; As \; Frad + \; \dot{Q}_E \; \varepsilon \; Frad + \dot{Q}_{sb} \; \varepsilon \; Frad + \dot{Q}_{diss} - \varepsilon \, \sigma \, T^4 \, Frad = 0 \qquad (12)$$

Where:

$$\dot{Q}_s = \dot{Q}_{solar} + \dot{Q}_{albedo} \qquad (13)$$

4.3.2 Heaters power:

The power of the heater can be calculated through the following equation:

$$\dot{Q}_{diss-min} + \; \dot{Q}_{heater} - \; \varepsilon \, \sigma \, T^4 \, Frad = 0 \qquad (14)$$

4.3.3 Optimum values:

Radiator Area ($m^{2)}$	Power of Heaters (w)
0.5871	40

5. Validation

To ensure the accuracy and reliability of the thermal model developed for the Space Sight MED 2025 satellite, a comprehensive validation was performed by comparing the results with those from multiple similar studies. Validation is a critical aspect of any thermal design process, as it confirms that the computational thermal analysis (CTA) reflects the real-world behavior of satellite components under various thermal conditions. The current study focuses on two extreme scenarios: the worst-case hot and worst-case cold conditions encountered by the satellite in low Earth orbit (LEO). While the thermal simulations demonstrate that the satellite's components remain within operational temperature ranges, further validation is necessary to confirm the robustness of these results. This validation process compares the key thermal parameters—such as radiator size, heater power, and component temperatures—with findings from similar studies in small satellite thermal design. The following subsections detail these comparisons, highlighting similarities and differences in results and offering insights into the reasons behind any observed discrepancies. By validating the model against multiple sources, we can assess the reliability of the design and determine whether the current thermal control system is sufficient to maintain satellite performance in extreme hot and cold conditions.

5.1 Sundu and Döner (2020)

This section includes a validation of a research study on detailed thermal design and control of an observation satellite in low earth orbit published in December 2020 by Sundu and Döner [28]. A satellite underwent design and modeling using Systema Thermica v.4.8.P1 software employing the Monte-Carlo ray tracing technique. The analysis encompassed two extreme environmental scenarios: intense heat and severe cold. During the hot scenario, the focus was mostly on assessing radiators' dimensions, temperatures, and positioning across satellite panels. The following Figures represent the main research satellite drawing of a thermal model on thermic and our validation drawing on a thermal desktop.

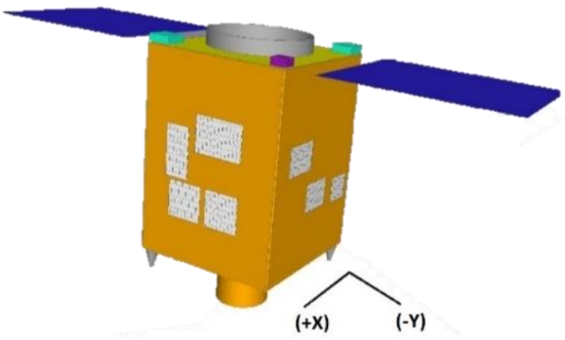

Fig. 14: The Research model on Thermica

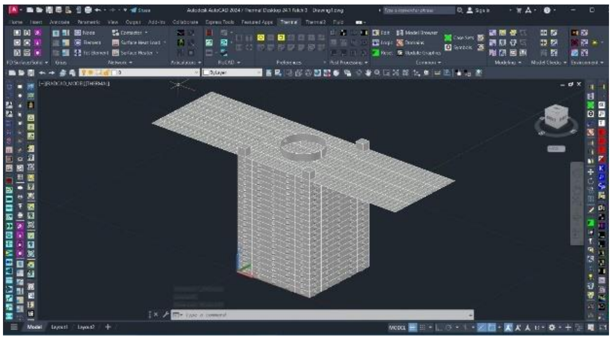

Fig. 15: Our model on thermal desktop

The following tables describe the satellite components' temperature ranges, the satellite's orbital parameters, and the hot and cold cases we use in our software validation. After running the case and performing thermal analysis using Thermal Desktop software, incorporating all parameters used in the original research, we compared our thermal analysis results with those from Sundu and Döner's study. We found a similarity and closeness between the results of up to 90%, validating our approach and confirming the reliability of the Thermal Desktop for thermal analysis and simulation of new satellite launches for subsequent thermal testing. Notice that in the Sundu and Döner study, they found that the battery temperature in a cold case was dangerous**,** ranging from (-5.7 to -14.6) **therefore,** they decided to add two heaters to raise the temperature of the temperatures after that approach in the cold case ranging from (+2 °C to +11.38 °C) and this proves the importance of heaters in the satellite like mentioned before.

Table 8:Operating temperature ranges of the satellite components

Component	Current Study (Space Sight MED 2025)	Sundu and Döner (2020)
Batteries	-2 to +28	0 to +30
Electronic Components	-7 to +40	-20 to +50
Solar Panels	-100 to +110	-100 to +100
Camera	0 to +50	------------
Antennas	-70 to +100	-80 to +100
Magnetometer	-20 to +50	-20 to +50
Sun Sensor	-20 to +50	-20 to +50

Table 9: Operating parameters for the satellite.

Parameter	Current Study	Sundu and Döner (2020)
Orbit Type	Sun-Synchronous	Sun-Synchronous
Revolution	10 Rev	8 Rev
Altitude (km)	820	840
Solar Time	22:30:00	22:30:00
Launch Year	2025	2022

Table 10: Parameters for the hot and cold cases.

Parameter	Current study	Sundu and Döner
Solar Flux (W/m²)	1367 (Hot) / 1326 (Cold)	1414 ±5 (Hot) /1317 ±5 (Cold)
Albedo Factor	0.35 (Hot) / 0.20 (Cold)	0.35 (Hot) / 0.2 (Cold)
Earth Temperature (K)	252.4 (Hot) / 248 (Cold)	252.4 (Hot) / 248 (Cold)
Earth I.R. (W/m²)	258 (Hot) / 258 (Cold)	258 (Hot) / 216 (Cold)
Beta Angle (β)	27 (Hot) / 22 (Cold)	23.59 (Hot) /17.02 (Cold)
Space Temp	4 k	

Table 11: Results of the comparison between the research best case and our study.

Component	Current Study (Hot)	Sundu and Döner (Hot)	Current Study (Cold)	Sundu and Döner (Cold)
Batteries (°C)	23.8 to 27.5	26.78 to 31.15	-0.5 to 4.1	-5.7 to -14.6
Electronic Components (°C)	36.5 to 39.6	35.1 to 40.2	-11.3 to -7.7	-20 to +40
Solar Panels (°C)	48.2 to 53.6	46.8 to 55.5	-9.3 to -5.2	-10 to +55
Camera (°C)	33.1 to 37.4	---------------	-0.5 to 2.2	---------------
Antenna	46.1 to 52.8	---------------	-4.7 to 1.5	---------------

6. Conclusion

This study was dedicated to the design of a remote sensing satellite for low Earth orbit (LEO), with a particular emphasis on specific thermal operating conditions. It aims to address a knowledge gap by developing a comprehensive thermal analysis and thermal control model, which includes various simulations to evaluate two critical scenarios impacting satellite design. Thermal analyses are crucial for optimizing the placement and size of radiators. The satellite's high-emissivity material enables effective operation in deep space, potentially resulting in exceptionally low equipment temperatures. The analyses cover two extreme scenarios: high and low sun flux conditions. The thermal control system design may be either passive or active; however, this study adopts a passive system to conserve power and ensure effective thermal control. The research demonstrates the impact of radiators and heaters on the satellite's thermal performance, with the thermal control system designed to maintain component temperatures within permissible ranges. The hot scenario focuses on the areas, temperatures, and locations of radiators on the satellite panels. In contrast, in the cold scenario, the power and operating conditions of heaters are evaluated. The satellite is equipped with five heaters, each with a power rating of 8 watts, totaling 40 watts. This study provides a detailed examination of thermal design and satellite control, integrating the effects of radiators and heaters. The major findings of this study that could help in the following studies are:

- The required radiator optimum area is 0.5871 m^2.
- The required heater power is 40 w.
- The electronic equipment's operating temperature range should be −7°C to +40°C.
- The battery's operating temperature range should be between - 2°C and +28°C due to its high sensitivity to temperature changes.
- The thermistor controls the heaters automatically to control the desired battery temperature.
- Optimizing the radiator area is crucial for the hot scenario, while considering the duty cycle of the heaters is essential for the cold scenario.
- The study results showed that the thermal control measures can guarantee that the devices operate within the allowable temperature range.
- The developed numerical model can be a reliable tool in the thermal design of the new communication satellites.

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