Passive thermal control design and analysis of a university-class satellite

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Abstract
This paper describes the passive thermal control analysis and design for a small satellite in low Earth orbit. The main objective of the thermal control system is to guarantee the proper operation against the harsh environment in space. The European Student Earth Orbiter satellite was chosen to carry out this study. The paper introduces an alternative means for the thermal control system to be passive by using tapes, coatings, radiators, and multi-layer insulation applied to the satellite to control radiation heat exchange between the satellite and its environment. For this purpose, a finite-difference model was developed using a commercial software package. Results obtained from the simulations were introduced, analyzed, and partially verified for both extreme hot and cold cases.
The results show that all the components inside the satellite, structural, and solar panels were within their temperature limits. The most critical components in the hot case are the battery and gyro box with temperature safety margins of 1.83 °C and 2.47 °C, respectively. The most critical components in the cold case are reaction wheel 2 and uCAM with temperature safety margins of 4.62 °C and 4.73 °C, respectively. The battery on panel 6 has a temperature safety margin of 6.64 °C.

Keywords University-class satellite · Passive thermal control · Thermal desktop package · Hot and cold cases

Abbreviations
ADCS Attitude determination and control system
ESA European space agency
ESEO European student earth orbiter
FDM Finite difference method
FEM Finite element method
IR Infrared
LET Linear energy transfer
LEO Low earth orbit
LMP Langmuir plasma diagnostic probe
LTAN Local time of ascending node
MLI Multi-layer Insulation
NASA National aeronautics and space administration
SFL Space flight laboratory
TCS Thermal control subsystem
WCC Worst-case cold
WCH Worst-case hot

Symbols
Ai Nodal area [m²]
dx The distance between two adjacent nodes
Fij The view factor between nodes i and j
k The thermal conductivity of the material
Kij Conductive heat exchange factor between nodes i and j [W K⁻¹]
m,CI Thermal mass of node I [J K⁻¹]
Q Amount of heat transferred rate [W]
Rij Radiative heat exchange factor between nodes i and j [W K⁻⁴]
T Temperature [°C or K]
t Time [s or hr]
α Absorptivity
ε Emissivity
σ Stefan–Boltzmann constant [W m⁻² K⁻⁴]

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Introduction

University-class satellites are designed by university students for the specific purpose of student training. Many satellites have been flown since the first 70 s [1, 2]. The process of thermal control for a satellite involves controlling the energy entering and leaving the satellite to ensure that the equipment of the satellite remains within an acceptable temperature range. Thus, the first step in the thermal control system design lifecycle is to define the values of the external heat fluxes based on the orbital parameters and establish the temperature specifications in which the satellite will be operated during its lifetime [3]. External and internal heat loads on a satellite differ over some range, depending on the time of launch, exact orbit details, and natural variations in the solar output and Earth’s atmospheric conditions.

Small satellite thermal control design, modeling, and analysis may be carried out by either analytical or software. Due to the widespread use of these software tools based on numerical methods, analytical approaches for satellite thermal analysis are now hardly ever used. Nevertheless, analytical studies highlight the physics of the problem and are essential at an early stage of the thermal design when the mission and structure are not yet completely defined [4]. At the beginning of spacecraft thermal control development, some attempts were made to face the problem of the thermal design of a spacecraft analytically [5–7]. Analytical solutions can only be found for simple geometric scenarios that are not often representative of real satellite design situations.

Preliminary thermal analysis has been carried out using an in-house thermal simulation software tool to estimate the temperature that the satellite will meet quickly and accurately [8–10]. Recent complex numerical algorithms were developed and incorporated for satellite thermal problems in commercial software [11]. These software packages employ “lumped-parameter” models that describe the spacecraft as a discrete network of nodes, with one energy balance equation per node [12]. Predicting the thermal behavior of small-sized satellites is critical due to the small space and mass for their thermal control which is often desired in the space industry [13, 14]. Performing thermal analysis of a small-sized satellite with different categories was studied. Finite difference method (FDM) was used to simulate the thermal behavior on the PiCPoT sat. by [13]. Bulut et al. [15] studied the effect of different proportions of solar cell and painted aluminum on CubeSat faces, while FDM is used to estimate the temperature on the faces of the FalconSat-2 satellite [16]. The finite element method (FEM) used ABAQUS–MATLAB to assess the thermal behavior of the FASTRC nanosatellite [17]. Commercial software was also used to validate the obtained results. ESATAN-TMS software was used by Reiss [18]. Also, Thermal Desktop software was used to validate the results obtained by Richmond et al. [19]. Table 1 shows a summary of some universities’ activities in small satellite thermal control analysis and design. The table sums up the main features for each satellite such as university name, method of thermal control, and software used in the analysis.

From the above literature, Thermal design may be active or passive temperature control systems. The active thermal control devices include pumped loop systems, heaters, shape memory alloy (SMA), and louvers [33]. It is complicated to

| No | University | Country   | Satellite name       | Thermal Control System type                        | Software used    | References |
|----|------------|-----------|----------------------|---------------------------------------------------|------------------|------------|
| 1  | Applied Sciences Aachen | Germany   | Compass-1 (2003)     | Passive                                           | ANSYS            | [20]       |
| 2  | Liège University          | Belgium   | OUFTI-1 (2008)       | Passive with an electric heater for the battery   | ESATAN-TMS      | [21]       |
| 3  | San Jose State University | USA       | A CubeSat (2009)     | Passive                                           | Thermal Desktop | [22]       |
| 4  | Istanbul Technical University | Turkey     | Turksat-3U (2010)    | Passive                                           | Therm-XL        | [23]       |
| 5  | The Pennsylvania State University | USA       | OSIRIS-3U (2012)    | Passive                                           | COMSOL           | [24]       |
| 6  | Politecnico di Milano     | Italy     | ESEO (2012)          | Passive with an electric heater for the battery   | ESATAN-TMS      | [25]       |
| 7  | National Institute of Space Research | Brazil   | Amazonia-1 (2014)    | Passive means with heaters regulated by thermistors | Thermal Desktop | [26]       |
| 8  | Toronto University, Canada | Canada   | CanX-4 (2014)        | Passive Active                                    | Siemens’ NX 8   | [27–29]    |
| 9  | Von Karman Institute      | Belgium   | QARMAN (2015)        | Passive                                           | ESATAN-TMS      | [30]       |
| 10 | Delft University of Technology | Netherlands | Delfi (2015)      | Passive                                           | ESATAN-TMS      | [31]       |
| 11 | Missouri University       | USA       | MR sat (2018)        | Passive                                           | Thermal Desktop | [32]       |
exploit active thermal control devices with small satellites [34]. Passive thermal control system uses the conduction and radiation properties of materials to control the satellite temperature. Besides, it does not need a supplementary power source that saves the satellite power [35]. Very low cost of passive thermal control devices is achieved [36]. So, the passive method is the foremost suitable solution for the thermal control system of small satellites.

The European Student Earth Orbiter (ESEO) satellite was chosen to carry out this study. It is a low earth orbit (LEO) micro-satellite mission. The thermal control subsystem (TCS) of ESEO was carried out by [25]. It included active and passive thermal control elements and was performed using the ESATAN-TMS software package. This study will introduce an alternative means for the thermal control system of ESEO to be passive by partially modifying the arrangement of internal components on each panel and using tapes, coatings, radiators, and multi-layer insulation (MLI) applied to the satellite to control radiation heat exchange between the satellite and its environment. A detailed thermal model for ESEO satellite has been created using Thermal Desktop software [37]. The external fluxes absorbed by the satellite predicted by Thermal Desktop were introduced and compared with that predicted ESATAN-TMS software package. Satellite components operating temperatures were introduced under both hot and cold cases as the worst operating regime conditions.

The paper is organized as follows: First, the selected satellite for study, ESEO is described; then, the thermal analysis model based on a nodal lumped parameter method is elaborated; finally, results, discussions, and conclusions are given.

**Satellite’s configuration**

ESEO [25] has a cuboid shape with six structural panels and three solar panels of which two are deployable and one fixed. The main dimensions are within a cuboid of 967 × 750 × 680 mm, and the total mass of the satellite is less than 100 kg. The main features of the satellite are:

- Orbit: Sun-synchronous, 520 km altitude, 98.48° inclination, and Local Time of Ascending Node (LTAN) 10:30.
- Structure: Aluminum and honeycomb structure.
- Power: Solar panels, 180 W (Peak) 100 W (average).
- Battery: Lithium-Ion battery 190 Wh.
- Stabilization: 3 axes stabilized.
- Mission’s life: 4.5 years.

Figure 1 A shows the internal view of ESEO satellite adapted from [25], while Fig. 1B illustrates the arrangement of the internal components with the new relative distribution. This internal view was created as a resource in developing the model in this paper. The satellite equipment and their functions are given in Table A1

**Passive thermal control system modeling**

The analysis starts with gathering enough information about satellite equipment nominal operation temperature ranges and predicted heat dissipation. Thermal boundary conditions for each mission phase must be identified, including spacecraft altitude, orbital parameters, and orientation relative to the Sun and Earth. In the present work, the model was built using the Thermal Desktop package.

**Internal component rearrangement**

ESEO thermal control system was initially designed as passive and active thermal control, and thermal analysis was performed using ESATAN-TMS software package [25]. The satellite has been partially modified by utilizing internal components rearrangement and controlling external radiation exchange by managing the exterior thermo-optical properties. Rearrangements are made such that minor changes are done to keep on the satellite configuration design which is based on the general process for configuring a satellite [38]. This means that all satellite components are redistributed such that the components on each structural panel are the same as the previously investigated satellite [25]. The relative position of each component to the others is iteratively changed to meet all temperature requirements when a passive thermal control system instead of an active thermal control system was used.

The new arrangement of the components on each panel is based on the following considerations. There are two high heat dissipation equipment mounted on panel 1 (+ X) (TMTC main and Gyro Box). They dissipate 68.04 W in a hot case in addition to the heat generated from mounting the solar panel on the external side of this structure panel. The two highly dissipating equipment have to be separated and make a thermal path to radiate the excess heat to the space. So two radiation areas (Radiators) are added to the adjacent panels (panels 2 and 5). No changes have been done to the equipment locations on Panel 2 but the MLI was replaced with Teflon Aluminized 1-mm radiator to increase the heat transfer between the spacecraft and the space. On Panel 3, The TMTC redundant equipment has been moved away from the adjacent hot panel 1 to avoid hot spot generation. The locations of OBDH and PEB on panel 4 have been changed to increase the heat transfer to panel 6 and to decrease the heat transfer to panel 3. The brilliant aluminum coating was replaced by MLI to decrease the heat transfer between the spacecraft and space. No changes have been done for
equipment location on panel 5 but MLI was replaced by Aeroglaze A276 white paint coating to increase the heat transfer between the spacecraft and space. On Panel 6, The TMTC main and the battery have been moved away from the adjacent hot panel 1 to avoid hot spot generation. Most of the panels were covered with MLI to avoid overcooling the battery. There are no changes in the thermal control of the solar panels.

After many trials of components arrangement with different insulators, radiators, and their thermophysical properties, the final distribution of the internal components on different structure panels is shown in Fig. 1 B and Table A2.
Geometry creation

The first step in model creation is defining the external geometry. The spacecraft geometry consists of a cuboid structure (six structure panels) and three solar panels (one fixed and two deployable panels). The external solar and structural panels were designed by creating nine Thermal Desktop rectangles to represent the satellite’s shell and the solar panels.

Aluminum 2024 was used for panels number one, four, and five (in the directions +X, -X, and -Y, respectively). For design reasons, the aluminum panels have a thickness of 20.6 mm. Honeycomb panels were used for panel number two, three, and six (in the directions +Y, +Z, and -Z, respectively) and the three solar panels. The body or equipment panels have a shell thickness of 0.3 mm and a core thickness of 20 mm with a total thickness of 20.6 mm. The solar panels have a shell thickness of 0.3 mm and a core thickness of 13 mm with a total thickness of 13.6 mm. Nine nodes were defined for each panel, coming to a total of 81 nodes for the external structural and solar panels. The node is designated by two digits; the first is for the panel number, and the second is for the node number. The MLI was modeled as 36 nodes.

The second step is defining the internal geometry that represents the equipment. To create a thermal model of the internal equipment in the Thermal Desktop, all equipments were represented as cylindrical or box shapes. Each equipment has a thickness of 5 mm.

Six nodes were defined for each internal component coming to a total of 126 nodes. Each component node is designated by three digits; the first is for the panel, followed by the component number on the panel, and the third is the node number as shown in Table A2. The Thermal Desktop model has a total of 243 nodes. There are three types of nodes that can be used in the model: diffusion nodes, arithmetic nodes, and boundary nodes. The satellite is represented by 207 diffusion nodes and 36 arithmetic ones. Some experience is needed to determine the suitable number of nodes for each element (nodes sensitivity analysis). In general, more nodes lead to higher resolution in the results. However, large numbers of nodes increase the complexity of the thermal model and the time required to build and run the model.

Thermal energy balance

The thermal modeling is based on a nodal or lumped parameter method. In this method, the satellite is divided into a number of regions, assumed isothermal, which are called nodes. These nodes exchange heat among each other by conduction and radiation. The external nodes exchange heat with the environment via radiation. The temperature of each node is the result of these interactions. The heat balance equation for node $i$ coupled with nodes $j$ through $N$ can be written as Eq. (1) [39, 40].

$$m_i C \frac{dT_i}{dt} = \dot{Q}_{\text{external},i} + \dot{Q}_i - \sum_{j=1}^{n} K_{ij} (T_i - T_j) - \sum_{j=1}^{n} R_{ij} (T_i^4 - T_j^4)$$

where $m_i C$: the thermal mass [J K$^{-1}$].

$\dot{Q}_i$: the internal heat dissipation [W] is the total heat dissipated by the satellite equipment [W] calculated by summation of the operating components during the considered missions as shown in Table A2.

$K_{ij}$: conductive heat exchange factor between nodes $i$ and $j$ [W K$^{-1}$].

$R_{ij}$: radiative heat exchange factor between nodes $i$ and $j$ [W K$^{-4}$].

$\sigma$: Stefan–Boltzmann constant [W m$^{-2}$ K$^{-4}$].

$T_i$ and $T_j$: the temperatures of nodes $i$ and $j$, respectively [K].

The term $\dot{Q}_c$ is the emitted heat to space [W] given by:

$$\dot{Q}_c = \sigma \varepsilon_A S T_i^4$$

The term $\dot{Q}_{\text{external},i}$ is external loads (solar, albedo, and planetary heat rate) [W], given by Eq. (3) [40].

$$\dot{Q}_{\text{external},i} = \dot{Q}_{\text{solar}} + \dot{Q}_{\text{Albedo}} + \dot{Q}_{\text{Earth}}$$

The solar radiation equation is

$$\dot{Q}_{\text{solar}} = A_p \alpha S$$

where $A_p$ is the projected area, $\alpha$ is the absorptivity of external panels, and $S$ is the solar constant (Solar flux). Albedo is described by:

$$\dot{Q}_{\text{Albedo}} = A_p F_{S-E} \varepsilon_A f S \cos \theta$$

where $F_{S-E}$ is the view factor from the satellite to the Earth, $f$ is the albedo factor, and $\theta$ is the angle between the satellite position and the zenith.

Earth’s infrared radiation is:

$$\dot{Q}_{\text{Earth}} = A_p F_{S-E} \varepsilon G$$

where $\varepsilon$ is the emittance of external surfaces and $G$ is the Earth’s radiation flux.

Different types of conductance exist between various nodes such as through-thickness conductance, inner-shell conductors, conductance between different components, conductance between the three solar panels, and between the central solar panel and structural panels to which it is attached. The conductive heat exchange factors are defined as:
The radiative conductance exists between all internal components, different sides of each component, and between each component and internal structural walls. The radiative heat exchange factors are defined as:

\[ R_{ij} = A_i F_{i-j} \varepsilon_{ij} \]  

where,

\[ k \] the thermal conductivity of the material [W m\(^{-1}\) K\(^{-1}\)].
\[ A_i \] the nodal area [m\(^2\)].
\[ d_x \] the distance between two adjacent nodes [m].
\[ F_{i-j} \] the view factor between nodes i and j by knowing the optical properties of all components.
\[ \varepsilon_{ij} \] the emissivity between nodes i and j.

**Boundary and operating conditions**

The design philosophy is to analyze the two extreme cases defined as:

- **Worst-Case Hot (WCH)** represents the operational mode in which maximum external heat loads (albedo: 0.35; Earth radiation: 258 W m\(^{-2}\); solar radiation: 1418 W m\(^{-2}\)) [25] and maximum internal heat dissipation (176.86 W) [25] as shown in Table A2. The satellite is pointing toward the Sun (the x-axis faces the Sun, and the y-axis faces the north celestial pole); then, its orientation changed to nadir for imaging Earth according to mission requirements (the z-axis faces the Earth, and the y-axis follows the velocity vector).
- **Worst-Case Cold (WCC)** represents the nominal operational mode in which minimum external heat loads (albedo: 0.25; Earth radiation: 208 W m\(^{-2}\); solar radiation: 1326 W m\(^{-2}\)) [25], minimum internal heat dissipation (60.12 W) [25] as shown in Table A2. The satellite is pointing toward the Sun (the x-axis faces the Sun, and the y-axis faces the north celestial pole).

Each internal equipment has a heat capacity \( C_p \) of 921 J kg\(^{-1}\) K\(^{-1}\), and thermal conductivity of \( k = 155 \text{ W/m.K} \) which approximates all equipment to aluminum [25]. Conductive heat exchange between the internal components and the mounting panels is controlled by applying HALA TGF-C0500-SI as a thermal filler with thermal conductivity of 1.5 W m\(^{-1}\) K\(^{-1}\) [25] with a thickness of 0.5 mm. The conductive heat exchange between structural panels is controlled by using thermal filler Epotek H74 with thermal conductivity of 1.3 W m\(^{-1}\) K\(^{-1}\) [32] and thickness of 0.2 mm. Table 2 shows the different thermal fillers with their thickness for both old and new designs.

All external heat loads and internal heat dissipation considered in this work follow the same scenario of [25] including the internal heat dissipation of the battery during charge and discharge (zero heat dissipation as clear in Table A2) to achieve the same base for comparison. Karam [39] reported that there are many difficulties in characterizing actual heat dissipation as it varies with temperature, perturbations in consumed power, eclipse times, state of charge/discharge, and charge efficiency, which often varies from one cell to another in the same batch.

The 5 °C margin is commonly used by many aerospace companies [28]. An informal survey of NASA and commercial satellite programs (Boeing, Lockheed Martin, and Space Systems Loral) showed that 5 °C was the most common margin used, although significantly different margins were used on some programs [3].

The values of the temperature limits for all components except the battery are used according to reference [25] as shown in Table 2. For the battery, there are a lot of discrepancies regarding the operating temperature limit; The author of [25] mentioned three types of batteries (Li-ion, Ni–Cd, and Ni–H) with different operating temperature limits. According to NASA report [42] regarding the state of the art in small spacecraft technology, lithium-based batteries are the most commonly used in portable electronic devices because of their rechargeability, low weight, and high energy, and have become ubiquitous on spacecraft missions. After surveying many battery data sheets for different manufacturers BST BAT-110 (Berlin Space Technology) was chosen because it has the most suitable operating range which is − 20 °C to 40 °C during charging and discharging [41].

The optical properties of the satellite external surfaces for both old and new designs are presented in Table 3.

All equipment and the internal sides of the structural panels have the optical properties of polished aluminum with an emissivity of 0.05 and absorptivity of 0.15. These values are the same for the old [25] and the new design.

To provide a reasonable analysis time, results for WCC were presented during nine orbits to reduce the run time. Nine orbits are sufficient because the steady-state profile occurs after the six orbits. While results for WCH were presented during 23 orbits because the satellite orientation was changed from Sun pointing to nadir pointing for taking images within three consecutive orbits (orbit 11 to 13). In the following section, the WCH and WCC simulation results are presented and discussed to prove that the passive thermal control system meets the requirements.
Table 2  Thermal filler, thickness, and operating temperature range for satellite components

| Component                  | Filler Type                  | Thickness/mm | Operating temperature range°C [25] |
|----------------------------|------------------------------|--------------|-----------------------------------|
|                            | Old Design [25]              | New Design   | Old Design [25]                   | New Design | Min  | Max  |
| Panel 1 (+ X)              | Not Applied                  | Epotek H74  | –                                 | 0.2        | –30  | 50   |
| Gyro box                   | Alfatec Softtherm 86/20      | HALA TGF-C0500-SI | 5 | 0.5 | –40 | 40 |
| AMSAT box                  | HALA TGF-C0500-SI            |              | 2                                 | 0.5        | –60  | 65   |
| Panel 2 (+ Y)              | Not Applied                  | Epotek H74  | –                                 | 0.2        | –30  | 50   |
| uCAM                       | HALA TGF-C0500-SI            |              | 2                                 | 0.5        | –20  | 55   |
| Reaction Wheel             | HALA TGF-C0500-SI            |              | 2                                 | 0.5        | –20  | 45   |
| Magneto-Torquer + Y        | HALA TGF-C0500-SI            |              | 2                                 | 0.5        | –30  | 45   |
| Panel 3 (+ Z)              | Not Applied                  | Epotek H74  | –                                 | 0.2        | –30  | 50   |
| TMTC redundant             | HALA TGF-C0500-SI            |              | 2                                 | 0.5        | –25  | 60   |
| LMP                        | HALA TGF-C0500-SI            |              | 2                                 | 0.5        | –25  | 60   |
| Tri-Tel S                  | HALA TGF-C0500-SI            |              | 2                                 | 0.5        | –40  | 40   |
| Magnetometer 1             | HALA TGF-C0500-SI            |              | 2                                 | 0.5        | –20  | 65   |
| Magnetometer 2             | HALA TGF-C0500-SI            |              | 2                                 | 0.5        | –20  | 65   |
| Panel 4 (- X)              | Not Applied                  | Epotek H74  | –                                 | 0.2        | –30  | 50   |
| EPS PEB                    | HALA TGF-C0500-SI            |              | 2                                 | 0.5        | –20  | 40   |
| OBDH                       | HALA TGF-C0500-SI            |              | 2                                 | 0.5        | –20  | 40   |
| Star Tracker               | HALA TGF-C0500-SI            |              | 2                                 | 0.5        | –20  | 50   |
| Panel 5 (- Y)              | Not Applied                  | Epotek H74  | –                                 | 0.2        | –30  | 50   |
| Reaction Wheel 1           | HALA TGF-C2000-SI            |              | 0.5                               | 0.5        | –20  | 45   |
| Reaction Wheel 2           | HALA TGF-C2000-SI            |              | 0.5                               | 0.5        | –20  | 45   |
| Reaction Wheel 3           | HALA TGF-C2000-SI            |              | 0.5                               | 0.5        | –20  | 45   |
| Reaction Wheel 4           | HALA TGF-C2000-SI            |              | 0.5                               | 0.5        | –20  | 45   |
| Magneto-Torquer - Y        | HALA TGF-C0500-SI            |              | 2                                 | 0.5        | –30  | 45   |
| Panel 6 (- Z)              | Not Applied                  | Epotek H74  | –                                 | 0.2        | –30  | 50   |
| TMTC box                   | HALA TGF-C0500-SI            |              | 2                                 | 0.5        | –25  | 120  |
| EPS battery                | Alfatec Softtherm 86/2086/20 | HALA TGF-C0500-SI | 5 | 0.5 | –20[41] | 40[41] |
| Magneto-Torquer - Z        | HALA TGF-C0500-SI            |              | 2                                 | 0.5        | –30  | 65   |
| Solar panel (+ X)          | Not Applied                  | –             | –                                 | –           | 90   | 115  |
| Solar panel (+ Z)          | Not Applied                  | –             | –                                 | –           | 90   | 115  |
| Solar panel (- Z)          | Not Applied                  | –             | –                                 | –           | 90   | 115  |

Table 3  Satellite external surface’s optical properties

| Material    | Panel Type                  | Absorptivity $\alpha$ | Emissivity $\varepsilon$ | References |
|-------------|-----------------------------|------------------------|---------------------------|------------|
| MLI         | Panels 1, 2, 3, 5 and 50% of panel 6 | 0.55                   | 0.78                      | [25]       |
| Brilliant Aluminum | Panel 4                    | 0.3                    | 0.31                      | [25]       |
| AZW-LA-II   | Not applied                 | 0.09                   | 0.91                      | [25]       |
| Aeroglaze A276 white paint | Panel 2               | 0.26                   | 0.88                      | [3]        |
| Teflon Aluminized 1 mm | Panel 5                     | 0.14                   | 0.6                       | [32]       |
| Silver Teflon | Solar panels Front side     | 0.08                   | 0.78                      | [25]       |
| Solar cells  | Solar panels Front side     | 0.92                   | 0.85                      | [25]       |
| AMJ-750-LSBU | Solar panels Back side      | 0.76                   | 0.81                      | [25]       |

Once a full thermal model has been defined and initial conditions are given, a steady-state and transient solution can be found for each node over some time. The temperatures have been calculated considering variations in external heat loads and equipment heat dissipation profiles. The convergence criterion was considered when the temperature variation between two consecutive iterations is less than 0.01 °C.
Results and discussion

Single-mode verification

The single-mode analysis consists in having distinctive dissipated powers with time in both pointing directions. The boundary conditions were constant, and non-chained radiative cases were studied.

The external heat flux (Solar, albedo, and planetary IR) along one orbit impinging the external faces (six structures and three solar panels) for 81 nodes at Sun pointing and nadir pointing modes of operation are calculated by Thermal Desktop. The results are compared with the corresponding results obtained by ESATAN-TMS analyses [25]. The behavior of the heat fluxes on the satellite is strongly influenced by the attitude dynamics along the orbit. Regarding direct solar radiation, if a face points toward the Sun, the opposite face is “in eclipse.” For the albedo and the IR, the behavior is less intuitive.

Node 10 located on the solar panel + X and node 50 located on structural panel + Y are presented here as a sample of the results obtained. Figure 2 illustrates the time evolution of the heat flux impinging the external faces of the solar panel + X along one orbit at Sun pointing (left) and nadir pointing (right) modes of operation,

![External heat fluxes on solar panel + X as predicted by ESATAN-TMS and Thermal Desktop (node 10)](image)

(a) Solar heat/Sun pointing

(b) Albedo heat/Sun pointing

(c) IR heat/Sun pointing

(d) Solar heat/Nadir pointing

(e) Albedo heat/Nadir pointing

(f) IR heat/Sun pointing

Fig. 2 External heat fluxes on solar panel + X as predicted by ESATAN-TMS and Thermal Desktop (node 10)
respectively. When solar panel + X is facing the Sun (Fig. 2A (left)), the solar flux is maximum, while it tends to be zero when pointing to nadir as shown in Fig. 2D (right). The albedo is dependent on Sun flux. IR depends on the view factor between the satellite and the Earth. External fluxes of Node 50 located on the structural panel + Y are shown in Fig. 3 as a sample of the structural panel. It is found that no significant changes in external fluxes have been recorded among all nodes of the same surfaces calculated from both software.

**Hot and cold cases results**

**Hot case**

For the hot, transient thermal analysis of the Thermal Desktop model was run for a time of 23 orbit periods (95 min per one orbit). This is an adequate amount of time for the satellite temperature to accomplish steady-state profile conditions. The repeated oscillation in the temperature for all figures is due to the orbital variation of entering and leaving the Earth’s shadow. The temperature of solar panels, structural panels, and all internal satellite components were examined.

![Graphs showing thermal analysis results for different cases](image)

**Fig. 3**  External heat fluxes on structural panel + Y as predicted by ESATAN-TMS and Thermal Desktop (node 50)
The results of the three solar panels (+X, +Z, and –Z) for nine nodes are given in Fig. 4A, B, C. The results show that all the panels are within their required temperature limits. For the solar panel (+X), it is noticed that the temperature profile is quite similar for nodes from 1 to 6, and they are at a higher temperature of about 9 °C to 19 °C above nodes 7, 8, and 9. This is related to the arrangement of both the nodes and the internal components on the panel. For the solar panels (+Z and –Z), all nodes have similar temperature profiles. The solar panel +X has a maximum temperature of around 78.7 °C with a safety margin of 36.3 °C below the maximum allowable operating temperature (115 °C), while solar panels +Z and –Z have an equal average maximum temperature of around 57.22 °C and 56.51 °C, respectively, with a margin of 57.78 °C and 58.49 °C, respectively, below the maximum allowable operating temperature.

The maximum heat input is received by the solar panel +X because this panel is fixed on the structural panel +X and receives heat flux dissipated from the internal components of 68.04 W from AMST and Gyro in addition to external heat flux. The difference in heat input received by the panel -Z and +X is caused by the change in surface area and view factors.

The transient temperature profile for nine nodes over the six structural panels is shown in Fig. 4. Also, all the structural panels are within their required temperature limits. The maximum temperature attained is 40.54 °C which is located at node 3 on panel +X (Fig. 4D) which is slightly higher than node 6 on panel –Y (Fig. 4H) and node 9 on panel –Z (Fig. 4I). The other panels +Y (Fig. 4E), +Z (Fig. 4F), and –X (Fig. 4G) have a maximum temperature of about 35.77 °C to 37.2 °C. Panels +Y, +Z, and –X have the lowest maximum temperature due to the low external heat flux calculated in Sect. 4.1, while panel +X has the maximum temperature due to high external heat flux and high internal heat dissipation of internal components.

For internal components as shown in Fig. 5, the maximum temperature is approximately less or equal to the maximum temperature of the panel supporting these components. The results show that all the components are within their required temperature limits. For example, in Fig. 5, the predicted AMSAT and Gyro temperatures analysis show that Gyro temperature levels at 37.53 °C and AMSAT temperature

![Fig. 4](image-url)
Fig. 5  Hot case temperature variation (including margin) on internal components
levels at 37.68 °C as maximum temperatures with temperature margins of 2.47 °C and 27.32 °C, respectively.

Figures 5G, H demonstrate the temperature variation for six nodes of the most critical components and battery and gyro box, respectively, to ensure the validity of temperature limits with the new design. The maximum temperature of the battery attained is between 37.83 °C (for node 2) and 38.17 °C (for node 3) with a minimum safety margin of 1.83 °C. For Gyro box, the maximum temperature ranges between 32.65 °C (for node 4) and 37.53 °C (for node 3) with a minimum safety margin of 2.47 °C. The maximum temperature listed in Table 4 and the temperature profile presented for all internal components in Fig. 5 (A to F) correspond to the node which has the maximum temperature for each. (Fig 6 and 7)

The extreme hot cases in this study are considered very severe heat loading so it is not a nominal mode of operation. The temperature profiles in normal operating conditions for both battery and Gyro box are shown in Appendix B Figs 8 and 9. In these figures, the maximum operating temperature of gyro box and battery is 24.1 °C and 15.29 °C which are far from the maximum operating limit. The low safety margins of the battery and gyro box do not represent a defect in the concept of using a passive thermal control system because

| Component          | Maximum Predicted Temperature/°C | Uncertainty Margin/°C | Maximum Temperature with Margin/°C | Upper Operating Limit/°C From Table 2 | Temperature Safety Margin/°C |
|--------------------|----------------------------------|-----------------------|------------------------------------|---------------------------------------|-----------------------------|
|                    | Old Des [25]                     | New Des               | Old Des                             |                                       |                             |
| Des                | New                              | Old Des               |                                     |                                       |                             |
| Panel 1(+ X)       | 22.96                            | 35.54                 | +5                                  | 27.96                                 | 40.54                       | 22.04                       | 9.46                        |
| Gyro box           | 26.71                            | 32.53                 | +5                                  | 31.71                                 | 37.53                       | 40                         | 8.29                        | 2.47                        |
| AMSAT box          | 36.78                            | 32.68                 | +5                                  | 41.78                                 | 37.68                       | 65                         | 23.22                       | 27.32                       |
| Panel 2(+ Y)       | 26.96                            | 30.77                 | +5                                  | 31.96                                 | 35.77                       | 50                         | 18.04                       | 14.23                       |
| uCAM               | 26.67                            | 21.35                 | +5                                  | 31.67                                 | 26.35                       | 55                         | 23.04                       | 28.65                       |
| Reaction Wheel     | 26.93                            | 30.79                 | +5                                  | 31.93                                 | 35.79                       | 45                         | 13.07                       | 9.21                        |
| Magneto-Torquer+ Y | 29.55                            | 23.62                 | +5                                  | 34.55                                 | 28.62                       | 45                         | 10.45                       | 16.38                       |
| Panel 3 (+ Z)      | 24.65                            | 31.1                  | +5                                  | 29.65                                 | 36.1                        | 50                         | 20.35                       | 13.9                        |
| TMTC redundant     | 22.94                            | 27.63                 | +5                                  | 27.94                                 | 32.63                       | 60                         | 32.06                       | 27.37                       |
| LMP                | 22.14                            | 22.65                 | +5                                  | 27.14                                 | 27.65                       | 60                         | 32.86                       | 32.35                       |
| Tri-Tel S          | 22.13                            | 27.21                 | +5                                  | 27.13                                 | 32.21                       | 40                         | 12.87                       | 7.79                        |
| Magnetometer 1     | 24.97                            | 31.23                 | +5                                  | 29.97                                 | 36.23                       | 65                         | 35.03                       | 28.77                       |
| Magnetometer 2     | 25.04                            | 31.59                 | +5                                  | 30.04                                 | 36.59                       | 65                         | 34.96                       | 28.41                       |
| Panel 4 (-X)       | 34.87                            | 32.2                  | +5                                  | 39.87                                 | 37.2                        | 50                         | 10.13                       | 12.8                        |
| EPS PEB            | 35.88                            | 19.85                 | +5                                  | 40.88                                 | 24.85                       | 40                         | -0.88                       | 15.15                       |
| OB DH              | 39.54                            | 30.1                  | +5                                  | 44.54                                 | 35.1                        | 40                         | -4.54                       | 4.9                         |
| Star Tracker       | 29.26                            | 21.83                 | +5                                  | 34.26                                 | 26.83                       | 50                         | 15.74                       | 23.17                       |
| Panel 5 (-Y)       | 39.75                            | 34.91                 | +5                                  | 44.75                                 | 39.91                       | 50                         | 5.25                        | 10.09                       |
| Reaction Wheel 1   | 42.55                            | 31.15                 | +5                                  | 47.55                                 | 36.15                       | 45                         | -2.55                       | 8.85                        |
| Reaction Wheel 2   | 42.57                            | 31.17                 | +5                                  | 47.57                                 | 36.17                       | 45                         | -2.57                       | 8.83                        |
| Reaction Wheel 3   | 43.16                            | 34.86                 | +5                                  | 48.16                                 | 39.86                       | 45                         | -3.16                       | 5.14                        |
| Reaction Wheel 4   | 42.56                            | 32.23                 | +5                                  | 47.56                                 | 37.23                       | 45                         | -2.56                       | 7.77                        |
| Magneto-Torquer -Y| 40.04                            | 31.92                 | +5                                  | 45.04                                 | 36.92                       | 45                         | -0.04                       | 8.08                        |
| Panel 6 (-Z)       | 33.29                            | 35.17                 | +5                                  | 38.29                                 | 40.17                       | 50                         | 11.71                       | 9.83                        |
| TMTC box           | 34.37                            | 31.7                  | +5                                  | 39.37                                 | 36.7                        | 120                        | 80.63                       | 83.3                        |
| EPS battery        | 29.55                            | 33.17                 | +5                                  | 34.55                                 | 38.17                       | 40                         | 5.45                        | 1.83                        |
| Magneto-Torquer -Z | 29.55                            | 31.2                  | +5                                  | 34.55                                 | 36.2                        | 65                         | 30.45                       | 28.8                        |
| Solar panel (+ X)  | 59.82                            | 73.7                  | +5                                  | 64.82                                 | 78.7                        | 115                        | 50.18                       | 36.3                        |
| Solar panel (+ Z)  | 47.86                            | 52.22                 | +5                                  | 52.86                                 | 57.22                       | 115                        | 62.14                       | 57.78                       |
| Solar panel (-Z)   | 51.4                             | 51.51                 | +5                                  | 56.4                                  | 56.51                       | 115                        | 58.6                        | 58.49                       |
these narrow safety margins can be increased through increasing radiator surface area or any other passive tool which is a passive thermal control system component for heat rejection. Also, the larger radiator surface area compensates for the accuracy of predicted results due to assuming zero battery heat dissipation. Moreover, according to [42], there are advanced components that have a wider operating temperature range.

A comparison of the present work and [25] based on the maximum temperature limit given in Table 2 and a margin of 5 are demonstrated in Table 4, while the present work has met the maximum temperature limit for all components. In the old design [25], the upper-temperature limit is not satisfied for many components shaded in Table 4.

**Cold case**

For the cold case, it is found that a time of nine orbit periods is enough time for the satellite temperature to reach steady-state profile conditions. The temperature of solar panels, structural panels, and all internal satellite components were examined. The minimum temperature shown in Table 5 and the temperature profile presented for all internal components in Fig. 6(A–F) correspond to the node which has a minimum temperature for each.

Figures 6 A, B, and C shows the temperature profile of the three solar panels (+X, +Z, and –Z) for nine nodes. The minimum allowable operating temperature limit is -90 °C. The results show that all the panels are within their required temperature limits. For the solar panel (+X), it is noticed that the temperature profile is quite similar for nodes from 1 to 6, and they are at a higher temperature of about 10 °C to 20 °C above nodes 7, 8, and 9. For the solar panels (+Z and –Z), all nodes have a similar temperature profile as found in hot case analysis. The solar panels +X has a minimum temperature of – 31.95 °C with a safety margin of 58.05 °C above the minimum allowable operating temperature, while solar panels +Z and –Z have a minimum temperature of around – 54.4 °C and – 54.11 °C, respectively, with a margin of 35.6 and 35.89 °C above the minimum allowable operating temperature.

The transient temperature profile for nine nodes over the six structural panels is shown in Fig. 6. Also, all the structural panels are within their required temperature limits. The minimum temperature attained ranges from – 14.77 °C to – 17.1 °C for panels 6 and 2, respectively at all nodes.
Fig. 7 Cold case temperature variation (including margin) on internal components
For internal components as shown in Fig. 7, the minimum temperature is approximately higher or equal to the minimum temperature of the panel supporting these components. The results show that all the components are within their required temperature limits.

In the literature, the most critical component is the battery because it can work only in a small temperature range [13]. In this work, the battery shows a temperature safety margin of 6.64 °C, although the heat dissipation is assumed to be zero. The temperature safety margin would be increased if the heat dissipation was assumed nonzero.

Figure 7G and H demonstrates the temperature variation for six nodes of reaction wheel 2 and uCAM, respectively (which have the lowest temperature safety margin), to ensure the validity of temperature limits with the new design. The minimum temperature of the reaction wheel 2 attained is between −15.12 °C (for node 4) and −15.38 °C (for node 2).

For the uCAM, the minimum temperature ranges between −14.62 °C (for node 4) and −15.27 °C (for node 5).

A comparison of the present work and old design based on the minimum temperature limit given in Table 2 and a margin of 5 are shown in Table 5, while the present work has met the minimum temperature limit for all components; in the old design, the lower temperature limit is not satisfied for many components shaded in Table 5.

### Table 5 Cold case results summary

| Component                  | Minimum Predicted Temperature/°C | Uncertainty Margin/°C | Minimum Temperature with Margin/°C | Lower Operating Limit/°C From Table 2 | Temperature Safety Margin/°C |
|----------------------------|----------------------------------|-----------------------|------------------------------------|--------------------------------------|-------------------------------|
|                            | Old Des [24] New Des             |                       | Old Des [24] New Des               |                                      |                               |
| Panel 1 (+x)               | −9.67                            | −11.77                | −14.67                             | −16.77                               | −30                           | 15.33                         | 13.23                         |
| Gyro box                   | −8.74                            | −11.12                | −13.74                             | −16.12                               | −40                           | 26.26                         | 23.88                         |
| AMSAT box                  | −9.37                            | −10.1                 | −14.37                             | −15.1                                | −40                           | 2.63                          | 24.9                          |
| Panel 2 (+Y)               | −14.07                           | −12.1                 | −19.07                             | −17.1                                | −30                           | 10.93                         | 12.9                          |
| uCAM                       | −14.03                           | −10.27                | −19.03                             | −15.27                               | −20                           | 0.97                          | 4.73                          |
| Reaction Wheel             | −14.06                           | −8.83                 | −19.06                             | −13.83                               | −20                           | 0.94                          | 6.17                          |
| MagNeto-Torquer + Y        | −13.99                           | −11.62                | −18.99                             | −16.62                               | −30                           | 11.01                         | 13.38                         |
| Panel 3 (+Z)               | −14.46                           | −11.82                | −19.46                             | −16.82                               | −30                           | 10.54                         | 13.18                         |
| TMTC redundant             | −13.48                           | −8.46                 | −18.48                             | −13.46                               | −25                           | 6.52                          | 11.54                         |
| LMP                        | −14.23                           | −11.73                | −19.24                             | −16.73                               | −25                           | 5.76                          | 8.27                          |
| Tri-Tel S                  | −14.24                           | −10.9                 | −19.24                             | −15.9                                | −40                           | 20.76                         | 24.1                          |
| Magneto-Meter 1            | −14.11                           | −9.67                 | −19.11                             | −14.67                               | −20                           | 0.89                          | 5.33                          |
| Magneto-Meter 2            | −13.94                           | −9.38                 | −18.94                             | −14.38                               | −20                           | 1.06                          | 5.62                          |
| Panel 4 (-X)               | −13.45                           | −10.22                | −18.45                             | −15.22                               | −30                           | 11.55                         | 14.78                         |
| EPS PEB                    | −13.18                           | −9.86                 | −18.18                             | −14.86                               | −20                           | 1.82                          | 5.14                          |
| OBDH                       | −12.84                           | −6.39                 | −17.84                             | −11.39                               | −20                           | 2.16                          | 8.61                          |
| Star Tracker               | −10.83                           | −7.25                 | −15.83                             | −12.25                               | −20                           | 4.17                          | 7.75                          |
| Panel 5 (-Y)               | −13.45                           | −10.39                | −18.45                             | −15.39                               | −30                           | 11.55                         | 14.61                         |
| Reaction Wheel 1           | −30.94                           | −10.02                | −35.94                             | −15.02                               | −20                           | −15.94                        | 4.98                          |
| Reaction Wheel 2           | −30.93                           | −10.38                | −35.93                             | −15.38                               | −20                           | −15.93                        | 4.62                          |
| Reaction Wheel 3           | −30.98                           | −9.97                 | −35.98                             | −14.97                               | −20                           | −15.98                        | 5.03                          |
| Reaction Wheel 4           | −30.96                           | −8.87                 | −35.96                             | −13.87                               | −20                           | −15.96                        | 6.13                          |
| MagNeto-Torquer -Y         | −31.17                           | −9.99                 | −36.17                             | −14.99                               | −30                           | −16.96                        | 15.01                         |
| Panel 6 (-Z)               | −17.26                           | −9.77                 | −22.26                             | −14.77                               | −30                           | 7.74                          | 16.23                         |
| TMTC box                   | −17.03                           | −8.46                 | −22.03                             | −13.46                               | −25                           | 2.97                          | 15.54                         |
| EPS battery                | −17.23                           | −8.36                 | −22.23                             | −13.36                               | −0.00                         | −20                           | 6.64                          |
| MagNeto-Torquer -Z         | −17.19                           | −8.94                 | −22.19                             | −13.94                               | −30                           | 7.81                          | 16.06                         |
| Solar panel (+ X)          | −33.68                           | −26.95                | −38.68                             | −31.95                               | −90                           | 51.32                         | 58.05                         |
| Solar panel (+ Z)          | 35.91                            | −49.4                 | −40.91                             | −54.4                                 | −90                           | 49.09                         | 35.6                          |
| Solar panel (-Z)           | −38.48                           | −49.11                | −43.48                             | −54.11                                | −90                           | 46.52                         | 35.89                         |
Conclusions

A detailed thermal model for ESEO satellite has been created using Thermal Desktop software. Equipment rearrangement, emissivity, absorptivity, and MLI placement are the main parameters that can be varied to change the temperature distribution. Specific conclusions can be summarized as:

- The passive thermal control system was able to meet requirements and maintain component temperatures and panels within their design limits.
- The most critical components in the hot case are the battery and gyro box with a temperature safety margin of 1.83 °C and 2.47 °C, respectively. The temperature safety margin can be increased by increasing radiator surface area and passive thermal control tools needed for more heat rejection.
- In the cold case, the reaction wheel 2 on panel 5 with a temperature safety margin of 4.63 °C and the uCAM on panel 2 with a temperature safety margin of 4.73 °C have the lowest temperature safety margins. The battery on panel 6 has a temperature safety margin of 6.64 °C.
- The new battery used in this work is 3 kg mass [35], while a 7.98 kg battery was used in the old design [25] which means a reduction of 5 kg of the added load on the satellite.
- The safety margins in the present work are based on the temperature operating range of the same components used in the old design. Based on the state of the art concerning small satellites, there are many components with a wider operating range that enable using passive thermal control systems with wider temperature safety margins.

Finally, thermal vacuum tests should be conducted in a vacuum chamber where the satellite (or equipment) is under vacuum and is subjected to the worst hot and cold conditions including adequate margins.

Appendix 1 ESEO Internal components data

See Table 6 and 7

| No | Equipment | System | Function |
|----|-----------|--------|----------|
| 1  | AMSAT     | Payload| The primary purpose of the AMSAT payload is to provide downlink telemetry that can be easily received by schools and colleges for educational purposes |
| 2  | Tridimensional Telescope dosimeter (TRI-TEL) | Payload | TRI-TEL is used to measure: linear energy transfer spectra absorbed dose, equivalent dose |
| 3  | Langmuir plasma diagnostic probe (LMP) | Payload | LMP is used to measure: Electron density, Electron temperature |
| 4  | Micro camera (uCAM) | Payload | Taking images in the visible part of the spectrum, to be used for educational purposes |
| 5  | Telemetry and Telecommand system (TMTC) and Telemetry and Telecommand Antenna (TMTC Antenna) | Communication system | A communication channel between satellite and ground control stations for receiving commands and transmitting telemetry and payload data |
| 6  | Electric Power System control unit (EPS-PEB) and Battery | Electric power system | Generating, storing, and distributing power to all spacecraft equipment |
| 7  | Reaction Wheel, Magneto-Torquer, Magnetometer, Star Tracker, and Gyro | Attitude determination and control system | Determining angles and angular rates of the satellite with respect to the initial coordinate system, Maintaining three-axis stabilization, Performing maneuvers according to mission needs, Technology demonstration of new equipment |
| 8  | On-Board data Handling (OBDH) | On-Board data Handling system | Managing and controlling onboard systems after receiving commands from the control station and gathering telemetry information from all systems |
Table 7  Hot and cold cases internal equipment heat dissipation

| Component          | Panel | Node numbers | Dissipated heat hot case (W) | Dissipated heat cold case (W) |
|--------------------|-------|--------------|------------------------------|------------------------------|
| AMSAT box          | 1     | 111–116      | 54.84                        | 0                            |
| Gyro box           | 121–126| 13.2         |                              | 0                            |
| uCAM               | 2     | 211–216      | 0                            | 0                            |
| Reaction Wheel     | 221–226| 0            |                              | 0                            |
| Magneto-Torquer + Y | 231–236| 2.16         | 1.08                         |
| TMTC redundant     | 3     | 311–316      | 0                            | 0                            |
| LMP                | 321–326| 0            |                              | 0                            |
| TRITELE S          | 331–336| 0            |                              | 0                            |
| Magnetometer 1     | 341–346| 1.44         | 1.44                         |
| Magnetometer 2     | 351–356| 1.44         | 1.44                         |
| EPS PEB            | 4     | 411–416      | 12                           | 12                           |
| OBDH               | 421–426| 30           | 30                           |
| StarTracker        | 431–436| 0            | 0                            |
| Reaction Wheel 1   | 5     | 511–516      | 6                            | 0                            |
| Reaction Wheel 2   | 521–526| 6            | 0                            |
| Reaction Wheel 3   | 531–536| 6            | 0                            |
| Reaction Wheel 4   | 541–546| 6            | 0                            |
| Magneto-Torquer-Y  | 551–556| 2.16         | 1.08                         |
| TMTC box           | 6     | 611–616      | 33.6                         | 12                           |
| EPS Battery        | 621–626| 0            | 0                            |
| Magneto-Torquer-Z  | 631–636| 2.16         | 1.08                         |
| Total              |       |              | 177.58                       | 60.12                        |

Appendix 2 Nominal operational phase

See Figs. 8 and 9

**Fig. 8**  Temperature profile of gyro box on the nominal operational phase

**Fig. 9**  Temperature profile of the battery on the nominal operational phase
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