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Optimizing Space Telescopes' Thermal Performance through Uncertainty Analysis: Identification of Critical Parameters and Shaping Test Strategy Development

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Abstract: The integration of uncertainty analysis methodologies allows for improving design efficiency, particularly in the context of instruments that demand precise pointing accuracy, such as space telescopes. Focusing on the VINIS Earth observation telescope developed by the Instituto de Astrofísica de Canarias (IAC), this paper reports an uncertainty analysis on a thermal model aimed at improving cost savings in the future testing phases. The primary objective was to identify critical parameters impacting thermal performance and reduce overdesign. Employing the Statistical Error Analysis (SEA) method across several operational scenarios, the research identifies key factors, including the Earth's infrared temperature and albedo, and the spacecraft's attitude and environmental conditions, as the variables with major influences on the system's thermal performance. Ultimately, the findings suggest that uncertainty-based analysis is a potent tool for guiding thermal control system design in space platforms, promoting efficiency and reliability. This methodology not only provides a framework for optimizing thermal design and testing in space missions but also ensures that instruments like the VINIS telescope maintain optimal operating temperatures in diverse space environments, thereby increasing mission robustness and enabling precise resource allocation.

Keywords: uncertainty; SEA; telescope; design; efficiency

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1. Introduction

1.1. The Relevance of Thermal Testing in Spacecraft Instruments

In aerospace engineering, the tolerance for error is extremely limited, requiring rigorous analysis. This is particularly important in spacecraft development, which is constrained by weight, space availability, and high launch costs [1]. The opportunity to correct design flaws once a satellite is in orbit is minimal, highlighting the importance of avoiding errors at the design and manufacturing phases [2]. The primary strategy to mitigate these risks is error prevention, which is especially challenging in system elements which require high accuracy.

The importance of thermal testing in this context cannot be overstated. Given the harsh space conditions, spacecraft instruments must be designed to operate reliably within a range of thermal environments. These conditions vary widely, from the intense cold of shadowed space to the severe heat when exposed directly to the sun. Thermal testing, therefore, plays a pivotal role in spacecraft development. It serves as a critical check against the theoretical models used in the design phase, offering a practical assessment of how spacecraft instruments will perform under the thermal conditions they will face in space. This testing phase enables engineers to identify and address potential thermal performance issues, thereby reducing the risk of failure and the costly prospects of in-orbit adjustments.

Moreover, the evolving landscape of space exploration demands ever-increasing levels of precision in spacecraft instrumentation, especially for missions involving Earth observation, planetary exploration, and deep space scientific research. Instruments like the VINIS Earth observation telescope, developed by the Instituto de Astrofísica de Canarias (IAC), exemplify the need for such precision. These missions depend not only on the accurate collection of data but also on the reliability of instruments to operate within expected thermal parameters.

It is within this context that the integration of uncertainty analysis methodologies emerges as a key strategy for enhancing design efficiency. By conducting a thorough uncertainty analysis on the thermal model, engineers can identify critical parameters that impact thermal performance. This approach not only aids in reducing overdesign but also contributes to cost savings in future testing phases. Thus, uncertainty-based analysis is not merely a theoretical exercise; it is a practical tool that guides the design of thermal control systems, ensuring spacecraft instruments can withstand the variable conditions of space. This methodology enhances mission robustness, enables precise resource allocation, and, ultimately, secures the success of space missions.

This paper is organized as follows. Section 1 outlines the importance of thermal testing in spacecraft design due to the strict constraints in aerospace engineering and introduces uncertainty calculation as a tool for thermal analysis. Section 2 details the methods for uncertainty calculation applied to spacecraft thermal control. The results in Section 3 present insights into thermal performance and the impact of uncertainties, leading to Section 4's discussion on the key thermal drivers. The paper concludes in Section 5, emphasizing the role of uncertainty analysis in enhancing the design and reliability of spacecraft thermal control systems.

1.2. Uncertainty Calculation

In complex system design, the use of mathematical models is essential. They are crucial for initial system trade-off analyses, design refinement, and performance evaluation, aligning with the system objectives. The accuracy and efficiency of these models in representing the physical system and predicting behavior within their application domain are critical, necessitating thorough validation [3].

The fidelity of models in mirroring reality depends on several factors. These include the unknown parameters, the limitations in capturing certain phenomena, and the challenges in accounting for all possible configurations [4–7]. Parameters, typically defined under ideal or constrained test conditions, may not always represent the real system accurately. Engineers often introduce equivalent effective parameters to manage the geometric complexities and interactions between components, a task that grows more complex with increasing system scale [8].

Recognizing and integrating the inherent uncertainties in the numerical model outcomes is essential throughout all the analysis stages. This integration significantly influences decision-making in design and project management, particularly in the early phases where approximately 85% of the project's lifecycle costs are determined [9]. Addressing uncertainties related to manufacturing, material properties, positioning, mounting, environmental conditions, and modelling processes is crucial for ensuring robustness, reliability, and safety of the systems.

The framework of Uncertainty Quantification (UQ) is applicable in various fields, which ranges from deterministic models based on physical laws to models for complex socio-economic phenomena (like the efficiency of sustainability policies in the European Union [10]), groundwater modelling [11], ocean dynamics [12], remote sensing [13], and aircraft design [14]. This approach increases the likelihood of mission success and assists in efficient resource utilization and risk mitigation. Despite its benefits, UQ is not widely implemented in the design of space missions. The diversity of methods presented in the specialized literature can sometimes make this analysis challenging.

Uncertainty analysis is often conducted alongside sensitivity analysis, yet these two concepts have different focuses, and their distinction is often blurred in the existing literature. Sensitivity analysis evaluates the effects of variations in input parameters on the outputs, while uncertainty analysis encompasses the assessment of all possible outcomes and their associated probabilities.

Methods for sensitivity analysis are classified based on the characteristics of the mathematical model, such as nonlinearities or the effects of simultaneous parameter variations, and how they influence the results of uncertainty analysis. These methods fall into three primary categories: screening methods, local sensitivity analysis, and global sensitivity analysis [15]. Screening methods prioritize parameters by importance without detailed quantification. Local methods focus on uncertainties close to the nominal solution but may overlook significant effects. Global methods cover the entire range of parameter validity, capturing important model characteristics, including nonlinearities and wide parameter validity intervals.

Another way to categorize these methods is based on the type of information sought from the analysis [16]. This includes screening methods, importance measurements (which compare statistical values of parameters derived from outputs to those of input parameters), and techniques for deeper exploration of sensitivities (providing comprehensive knowledge of the model's behavior in parameter space).

Uncertainties in modeling are classified as either random, arising from the inherent unpredictability of natural phenomena, or epistemic, resulting from gaps in information during system modeling [17]. Random uncertainties are represented using probability distributions and require expert knowledge to develop representative distributions for the parameters involved [18]. Epistemic uncertainties are further divided into phenomenological uncertainties, linked to unknown information in innovative projects, and model-associated uncertainties, originating from the limitations in the precision of the mathematical model [19].

1.3. Application of Uncertainty Calculation in the Aerospace Domain

Uncertainty significantly influences aerospace designs, whose impact can be either advantageous or detrimental to the system performance. Assessing and understanding the extent and impact of this uncertainty is essential. Therefore, uncertainty analysis is a useful tool in aerospace engineering for risk management. By quantifying uncertainties in system components and processes, engineers can more effectively predict and mitigate potential failures, enhancing the safety, reliability, and effectiveness of space missions. This approach requires a comprehensive understanding of how different uncertainties interact within the overall system [20,21].

UQ in aerospace engineering is important not only for design and manufacturing improvement but also for the planning and developing of testing campaigns. By identifying the system elements most susceptible to uncertainty and which have a higher impact on performance, engineers can focus their testing strategies on these critical aspects, improving testing efficiency and the overall reliability of the system. This process represents an integration of theoretical analysis, empirical data, and practical experience, evolving continuously with new insights and contributing to the development of robust and resilient aerospace systems.

1.4. Application of Uncertainty Calculation in Spacecraft Thermal Analysis

A two-phase methodology is commonly used in the process of thermal control and design for space systems [22–24]. Initially, engineers establish scenarios that represent worst-case design conditions, combining the most challenging environmental factors (such as solar irradiance or planetary infrared radiation) with demanding operational conditions (like internal heat dissipation and the degradation of material and optical properties).

Following the analysis of these scenarios, predetermined design margins, also known as uncertainty margins, are applied to the results. These margins are designed to address uncertainties in parameters during the initial analysis.

The most common practice in thermal design is to adhere to predefined margins, determined from statistical analyses of temperature predictions versus actual measurements from several spacecraft operations once in orbit. These margins, reflecting the deviation between predicted and actual temperatures, have not seen significant updates since the last revision by NASA in 1994 [25], though more recent studies [26–30] suggest the need for mission-specific margins, considering their unique nature.

The application of uncertainty analysis in thermal control provides an alternative to the traditional fixed-margin approach. It employs the results of uncertainty assessments to establish design margins. This methodology is broadly categorized into two types of methods: One-At-a-Time (OAT) and stochastic methods. OAT approaches, exemplified by Statistical Error Analysis (SEA), offer simplicity and speed at the cost of model simplification. In contrast, stochastic methods like Monte Carlo Simulation (MCS), involving hundreds of solves of the complete thermal model, yield results closer to the actual thermal performance but also bring longer computation times and a lack of detailed insights into how each parameter individually contributes to the overall uncertainty.

In terms of data availability for uncertainty parameters in thermal systems, there is a significant lack of information. The probability distributions associated with these parameters, often assumed to be Gaussian normal, may vary significantly across different project phases. In the initial stages, distributions with higher uncertainty, such as uniform or triangular distributions, are more commonly assigned due to undefined parameter values [31,32]. However, as the project progresses and specific choices are made (e.g., selecting a particular type of paint for a radiator), the distribution may shift towards a normal distribution due to random variations between samples.

1.5. Research Objectives

The primary objective of this research was to assess the effectiveness of uncertainty analysis methodologies for identifying design drivers and allowing for a more efficient test campaign planning. The research focused on a conceptual design of a satellite platform capable of accommodating the VINIS Earth observation telescope, an initiative of the IAC. The study sought to apply the methodology to identify the thermal parameters that mostly influence the system's performance. This approach is intended to enhance the design process, ensuring the telescope operates optimally in its intended environment. A critical aspect of this objective is to mitigate the risk of overdesign by avoiding the implementation of unnecessary margins or to identify points in the design where those predefined margins could be insufficient, which might be even worse. To achieve this main objective, the following secondary objectives have been outlined:

- Development of a conceptual thermal model for a platform capable of supporting the VINIS instrument.
- Conduct an analysis of the expected thermal environment that the VINIS instrument will encounter. This analysis will be based on the platform as defined in the previous objective, ensuring a comprehensive understanding of the thermal challenges and requirements in the operational context.
- Design and propose a passive protection system for the VINIS instrument. The aim of this system is to maintain the instrument's temperature within a controlled range of -10 °C to +30 °C, thereby ensuring optimal performance and longevity under varying space conditions.

2. Materials and Methods

2.1. Uncertainty Calculation Methods Applied to the Thermal Domain

There is no standardized method for calculating uncertainties for space thermal analysis. However, as mentioned in the introduction, there are three prevalent methods generally adopted: the application of pre-established margins, OAT methods, and stochastic methods.

2.1.1. Fixed Margins

The most employed approach in space thermal design is the use of fixed margins, which are based on statistical analyses that compare outcomes from mathematical models with actual flight data [33–37]. This technique is implemented from the start of a project and continues throughout the design phase. However, these safety factors, often based on engineering judgment and applied to worst-case scenario results, lack a reliable quantification method, leading to ambiguity. Although they are intended to add conservatism, these factors can inadvertently lead to a false sense of safety. Furthermore, basing system designs on such margins can result in overdesign, incurring unnecessary expenses, especially in large missions.

2.1.2. OAT Methods

Among OAT methods, SEA is a conventional approach, originating from the methods of Kline and McKlintock in 1953 for the statistical analysis of experimental samples [38]. SEA computes uncertainties by multiplying sensitivity coefficients $\partial T_i / \partial x_k$ (temperature derivatives of parameters) by parameter uncertainties at a specified confidence level. The final uncertainty is obtained from the contributions' Root Sum Square (RSS). Given the uncertainty values w_{xk} for the x_k parameters for a defined level of confidence σ_n, the uncertainty of each of the T_i temperatures can be expressed as follows:

$$w_{Ti} = \left[\left(\frac{\partial T(x_1, \ldots, x_k)}{\partial x_1} w_{x1} \right)^2 + \ldots + \left(\frac{\partial T(x_1, \ldots, x_k)}{\partial x_k} w_{xk} \right)^2 \right]^{1/2} \tag{1}$$

Despite its simplicity and suitability for initial approximations, SEA has limitations, including its assumption of linear models, statistical independence, and normal distribution of parameters. It aligns with procedures endorsed by ESA per their ECSS, but recent standards do not provide methods for uncertainty calculation.

2.1.3. Stochastic Methods

Recent advances in computational resources have promoted the adoption of stochastic methods such as MCS for uncertainty analysis assessment in mathematical models [39]. Unlike other methods, MCS does not depend on oversimplified assumptions. Nevertheless, it requires examining probability distribution data for each parameter uncertainty. These data, which can be found in several sources [40–43], usually presume uniform or normal distributions. In scenarios where specific data are not available, uniform distributions are used to represent an equal likelihood of all values within the defined range.

2.2. Spacecraft Thermal Control

2.2.1. Thermal Environment

In adherence to the specifications laid out by the IAC for the VINIS instrument, the thermal analyses are conducted in a predefined orbital scenario. This orbit scenario, consistent across all cases, is a Sun-Synchronous Orbit (SSO) at an altitude of 550 km, with an inclination of 97.7° and a Local Time of Ascending Node (LTAN) at 11:00 AM (Right Ascension of Ascending Node (RAAN) = 30°). The primary distinction between the hot and cold orbit scenarios lies in the Earth–Sun distance: for the cold cases, it is set at Earth's aphelion (1.52×10^6 km), and for the hot cases, at the perihelion (1.47×10^6 km). In an SSO, the spacecraft experiences key factors that significantly affect its thermal environment. Notably, the spacecraft faces periodic eclipse events, leading to cyclic thermal conditions due to the lack of direct solar radiation, which requires a thermal control system capable of effectively dissipating heat when exposed to the sun and retaining it during eclipses. The orbit's polar nature also subjects the spacecraft to varying thermal conditions at different latitudes, influenced by Earth's albedo and infrared radiation. This demands a thermal control system that is both robust and adaptable, which is able to handle a range of thermal inputs.

The thermal environment must maintain a temperature range of $-20/+40$ °C at the platform level and $-10/+30$ °C for the telescope, including the baffle and optical bench. For specific components like the Back End Electronics (BEE) and Focal Plane Assembly (FPA), the maximum allowable temperatures exceed these ranges, reaching up to 65 °C.

2.2.2. Thermal Model

A comprehensive systems engineering analysis was conducted to determine the most suitable platform to allocate the VINIS telescope. An initial assessment indicated that while it is feasible to find platforms with a payload mass capacity of 20 kg, it is challenging to find one that offers a volume compatible with VINIS and the desired EELV Secondary Payload Adapter (ESPA) size. A critical aspect of the platform design is maintaining the telescope's Earth orientation to prevent freezing, which may occur if the satellite loses attitude control. This issue potentially needs a protective cover for the telescope, thus increasing the complexity of the design.

After evaluating up to three configurations with their corresponding preliminary thermal models in the initial project stage, it was concluded that the detailed thermal response of the telescope would be assessed using a platform comprising a prismatic square structure made of sandwich panels. This structure includes a service module at the rear side of the telescope frame. The entire structure would be enveloped in a Multi-Layer Insulation (MLI) blanket, providing thermal stability, and equipped with a thermal radiator. Additionally, it would feature two deployable solar panels capable of being oriented on a perpendicular axis to two platform external faces, as shown in Figure 1. While the inclusion of deployable solar panels adds technical complexity, this configuration allows for maximized energy extraction with minimum size.

The platform's structure is primarily made of sandwich panels with aluminum core and CFRP skins for their advantageous thermo-mechanical properties. The telescope assembly, instead, is designed based on the iso-thermal and iso-static mounting principles, ensuring thermal stability and uniform temperature distribution. The structure which surrounds both the Primary (M1) and Secondary (M2) metallic mirrors is made of the same aluminum material. Additionally, aluminum 6061-T6 is used in other components, such as the radiator and antenna.

In terms of thermo-optical properties, the complete platform is wrapped in MLI blankets, with Kapton on the outer layer and VDA on the inner. Optical elements, including mirrors, receive a reflective silver coating to enhance their performance, while solar panels are modeled with a gallium arsenide surface finish with absorptance depending on the panel's efficiency. The employment of black paint across most of the elements serves dual purposes: thermal control and stray light mitigation within the telescope. Conversely, white paint is applied to the radiators and antennas to reflect heat.

Figures 1–3 provide an overview of the Geometrical Mathematical Model (GMM) across three levels of simplification, setting the stage for the subsequent presentation of results. The three levels of simplification begin with the integration of the VINIS platform and telescope assembly. The focus then shifts to the telescope assembly, examining components like the baffle and mounting panels. The most detailed level centers on the VINIS telescope itself.

As for the Thermal Mathematical Model (TMM), there are several points which also deserve to be emphasized. The connection between the electronics and the radiator was modeled through a linear conductor of 0.4 W/K in both cases. After adjusting the TMM, it was concluded that the radiator should have dimensions of 0.3 m $\times$ 0.3 m. Regarding the insert-type joints on the sandwich panels, they were computed accounting for (i) the contact conductance between the insert and any external surface, (ii) the through-conductance of the potting material, and (iii) the contact between potting and the honeycomb core. These calculations led to a linear conductor in between the telescope–platform electronic box–vertical optical bench of 0.004 W/K. As for the connection of the BEE and FPA to their respective supports, these were carried out through a contact conductance of 300 W/m^{2}K. Finally, it was made a capacitance adjustment according to a VINIS CAD model.

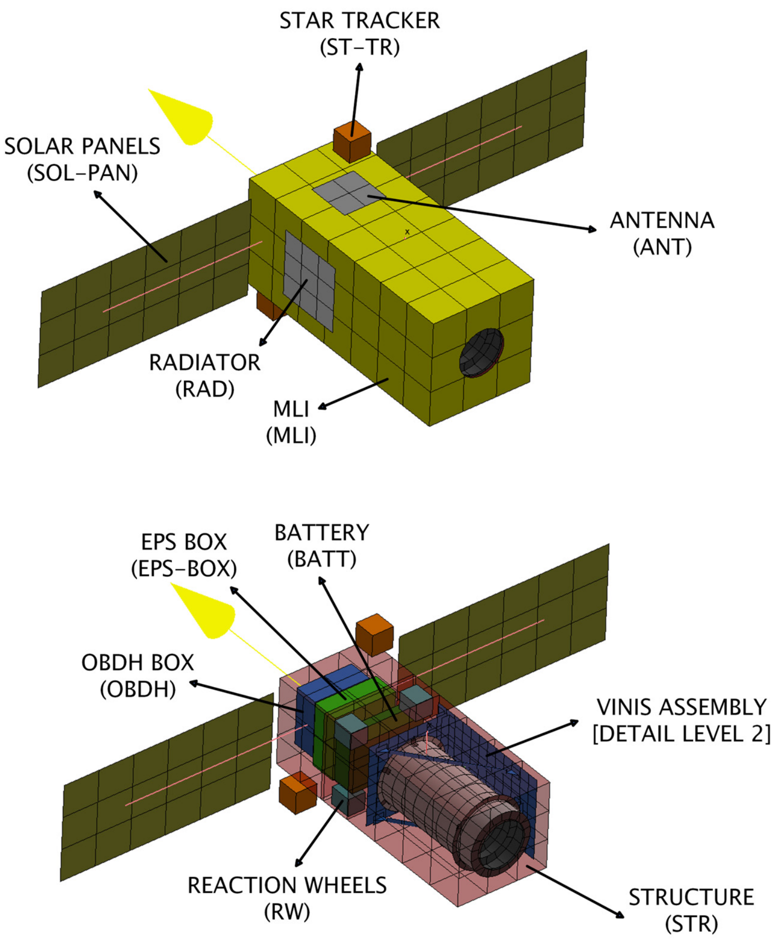

Figure 1. Elements included in the VINIS platform (first level of detail).

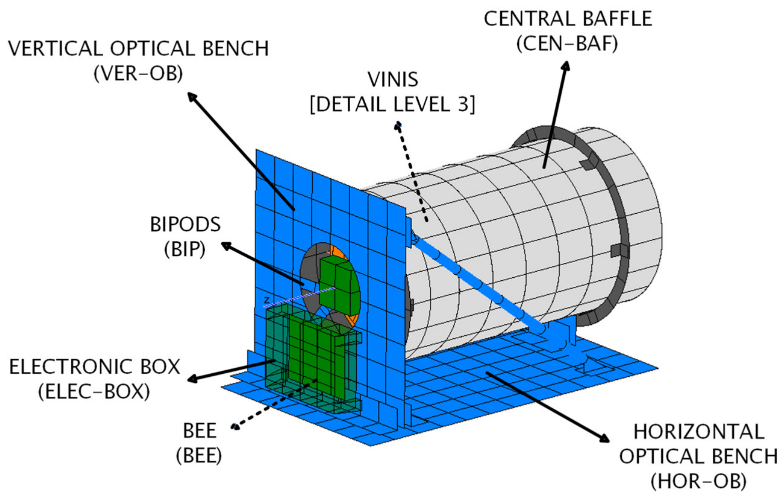

Figure 2. Elements included in the VINIS telescope assembly (second level of detail).

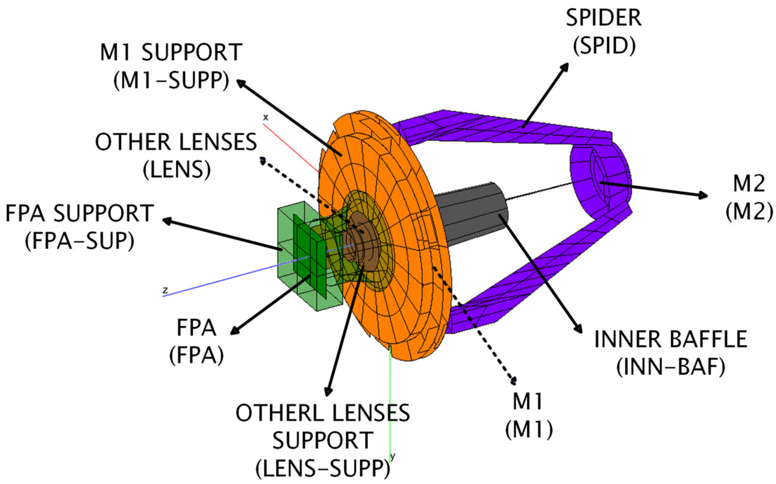

Figure 3. Elements included in VINIS telescope (third level of detail).

2.2.3. Thermal Cases

The analysis cases were derived from exploring several thermal scenarios, focusing on the effects of different operational modes and spacecraft attitudes. The spacecraft's operational modes include the following:

- Sun Pointing. Used for powering subsystems and recharging batteries. The solar panels are aligned perpendicularly to the Sun, while the telescope points towards nadir to avoid excessively cold temperatures.
- Science. The telescope is directed towards Earth for observations, with solar panels optimized for maximum sun exposure.
- Communications. Here, the spacecraft's antenna is oriented towards Earth, specifically focusing on the Canary Islands. This mode's positioning is subject to change in the early design stages due to limited information.
- Off-pointing. Activated during subsystem failure, directing the telescope away from Earth to minimize thermal impact.

The study also delves into the internal heat dissipation of the satellite, acknowledging the high design margins typical of preliminary project stages. These margins are set at ±10% of the nominal value for components like the Electrical Power System (EPS), On Board Data Handling (OBDH), reaction wheels, and instrument components (BEE and FPA), aiming to avoid overdesign.

To assess the thermal effectiveness of these configurations, four thermal cases are examined: Consecutive Imaging Case (CIC), Hot Operational Case (HOC), Cold Operational Case (COC), and Cold Non-Operational Case (CNOC), each with unique operational modes and power dissipation profiles. Key aspects are presented in Tables 1–3 and include the following:

- CIC. Follows a descending Sun-Synchronous Orbit (SSO), emerging from an eclipse over the North Pole, and includes three science measurements and a communication window over the Canary Islands.
- HOC. Combines ground contact and scientific operations under continuous sunlight.
- COC. Entails multiple Sun Pointing orbits followed by scientific measurements after emerging from an eclipse.
- CNOC. Keeps an off-pointing mode throughout the orbit with constant heat dissipation from the EPS and OBDH subsystems.

Table 1. Operation modes and total power dissipation under the CIC scenario.

Operational Mode and Attitude	% Orbit Time	Total Power Dissipation [W]
Sun Pointing 1	25.0	16.5
Science Pointing	5.3	16.5
Science Imaging 1	1.0	33.5
Science Post-Processing 1	2.6	22.5
Science Imaging 2	1.1	33.5
Science Post-Processing 2	2.6	22.5
Science Imaging 3	1.1	33.5
Science Post-Processing 3	1.7	22.5
Comms Pointing	4.4	16.5
Comms Data Link	2.5	26.5.
Sun Pointing 2	52.8	16.5

Table 2. Operation modes and total power dissipation under the COC scenario.

Operational Mode and Attitude	% Orbit Time	Total Power Dissipation [W]
Sun Pointing 1	68.7	14.85
Science Pointing	5.5	14.85
Science Imaging	1.1	30.25
Science Post-Processing	4.9	20.25
Sun Pointing 2	19.8	14.85

Table 3. Operation modes and total power dissipation under the HOC scenario.

Operational Mode and Attitude	% Orbit Time	Total Power Dissipation [W]
Sun Pointing 1	10.8	18.15
Comms Pointing	4.9	18.15
Comms Data Link	6.4	18.15
Science Pointing	6.2	18.15
Science Imaging	1.0	36.75
Science Post-Processing	4.3	24.75
Sun Pointing 2	66.4	18.15

3. Results

3.1. Thermal Results (Baseline)

During the evaluation of the results, an investigation was conducted on the evolution of maximum and minimum temperatures, average temperatures, temperature slopes, and gradients within parts. It was demonstrated that the incorporation of MLI and a radiator as passive control measures generally ensured a satisfactory satellite performance.

For the computation of the CIC results, the dissipation profile was based on averages between the HOC and COC. This approach provides a comprehensive understanding of the expected orbital conditions under a representative scenario. Given the high frequency of science operations, as indicated in Table 1, this scenario resembles a variant of the HOC. In this context, a more pronounced thermal gradient within the telescope was observed, presumably due to increased mean dissipations from continuous operations. Nonetheless, all components met the operational temperature ranges within the nominal operation profile.

In the HOC, a local thermal gradient of approximately 30 °C (Figure 4) was observed in the outermost part of the central baffle, particularly towards the end of the science phase. The evolution (in green) and temporal variation (blue) of this gradient during the orbit can be seen in Figure 5. This local effect, induced by direct solar radiation during polar observations, has the potential to adversely affect optical performance by elevating the temperature of the central baffle beyond established limits. Although passive control measures may not suffice to mitigate these effects, adjusting the satellite's attitude could be an effective strategy.

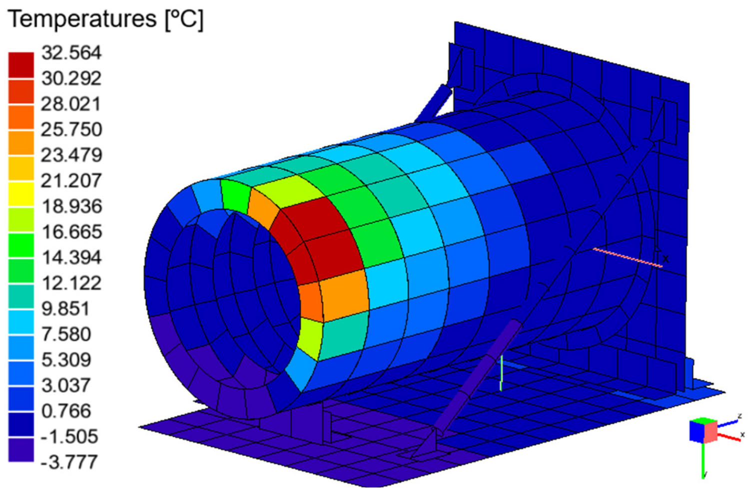

Figure 4. Baffle local thermal gradient under the HOC.

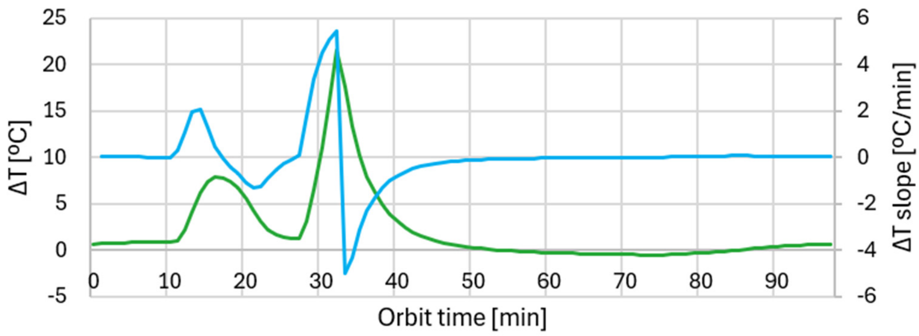

Figure 5. Variation of the temperature gradient (green curve) and temperature gradient slope (blue curve) on the main baffle under the HOC.

The COC analysis identified significant thermal gradients, particularly at the end of the science imaging phase. These gradients, predominantly orthogonal to the observation direction, were observed mainly on the main baffle and the horizontal optical bench. Additionally, a through-thickness temperature gradient was noted on the vertical optical bench, primarily arising from the temperature disparity between the cold outer space and the heat dissipation of electronic components. Nevertheless, the study also highlighted that the use of the same material across the telescope assembly, including the M1, M2, and spider, effectively minimized thermal gradients.

Finally, during the CNOC, numerous subsystems failed to meet temperature requirements. Passive control measures proved inadequate in elevating the low temperatures affecting the instrument, needing the inclusion of active thermal control mechanisms, such as heaters.

3.2. Uncertainty Analysis

The uncertainty analysis was performed by applying the SEA method. Although it presents some limitations, it is an excellent tool for a first approximation. In this way, the uncertainty associated with the parameters with a random nature was calculated. Additionally, a modeling uncertainty was considered. The typical value in uncorrelated models ranges between 2 to 5 °C. Due to the level of detail of the model, the design phase, and the type of geometry and MLI considered, a 3 °C uncertainty was added to the calculated margins. For example, if $w = 11.5$ °C was the calculated uncertainty, $w = 14.5$ °C was the considered uncertainty value. The values for the uncertainty of the different parameters were obtained from [44] and were for a 2σ confidence level (95.4%

confidence interval). Table 4 presents the different types of parameters. In total, the analysis encompassed the evaluation of up to 104 different parameters.

Table 4. Main input parameters, symbols, and uncertainty applied.

Parameter Type	Symbol	Uncertainty Applied
IR emissivity	ε_i	5%
Solar absorptance	α_i	5%
Sun temperature	T_S	21 K
Earth temperature	T_E	16 K
Earth albedo	a	0.1
Heat dissipation	Q_i	20%
Thermal capacitance	C_i	7.5%
Thermal conductivity (general)	k_i	10%
Thermal conductivity (composite)	$k_i,\ i = CFRP/Honeycomb$	30%
Contact coefficients	h_i	100%
Linear conductor	GL_i	100%
MLI efficiency	MLI_{EFF}	50%

The findings for the absolute minimum and maximum temperatures, along with their corresponding uncertainty margins across three scenarios, are presented in Tables 5–7. The maximum and minimum temperatures correspond to the ones reached by the satellite element, regardless of the orbit moment and whether they correspond to the same thermal node or not. Emphasis is placed on the results corresponding to the VINIS telescope assembly (components of the second level of detail, Figure 2). This focus is driven by the study's objective, which is to devise passive methods to maintain the temperature of the telescope's surrounding structure within the necessary operational range.

In the last part of the uncertainty analysis, a results decomposition from all three scenarios was performed. In this way, a physical understanding of the problem was attained, and all the relevant parameters to be tracked in future stages of the design were identified. Among the 104 parameters assessed, only 18 accounted for over 99% of the total uncertainty within any section of the telescope or its assembly. Furthermore, out of these 18 critical parameters (detailed in Table 8), 6 were associated with local phenomena, with the other 12 being the drivers of the overall thermal behavior.

Table 5. CIC scenario, absolute minimum and maximum temperature for each element along the orbit, for the VINIS telescope assembly (temperatures in °C) and SEA method.

	T_{min}	T_{max}	w_{min}	w_{max}	$T_{min}+w_{min}$	$T_{max}+w_{max}$	T_{min_req}	T_{max_req}
BIP	15.3	17.3	11.2	11.3	4.1	28.6	−10.0	30.0
CEN-BAF	0.5	16.9	10.1	11.2	−9.6	28.1	−10.0	30.0
ELEC-BOX	21.2	21.8	11.3	11.3	9.9	33.1	−20.0	65.0
BEE	24.0	29.9	11.2	11.6	12.8	41.5	−20.0	65.0
VER-OB	17.2	18.4	11.3	11.3	5.9	29.7	−10.0	30.0
HOR-OB	6.9	17.6	10.6	11.4	−3.7	29.0	−20.0	40.0

Table 6. HOC scenario, absolute minimum and maximum temperature for each element along the orbit, for the VINIS telescope assembly (temperatures in °C) and SEA method.

	T_{min}	T_{max}	w_{min}	w_{max}	$T_{min}+w_{min}$	$T_{max}+w_{max}$	T_{min_req}	T_{max_req}
BIP	16.2	17.7	11.6	11.6	4.6	29.3	−10.0	30.0
CEN-BAF	3.6	55.5	10.9	19.8	−7.3	75.3	−10.0	30.0
ELEC-BOX	20.2	20.6	11.6	11.6	8.6	32.2	−20.0	65.0
BEE	21.7	25.2	11.5	11.5	10.2	36.7	−20.0	65.0
VER-OB	17.1	18.6	11.6	11.7	5.5	30.3	−10.0	30.0
HOR-OB	10.2	18.7	11.3	11.8	−1.1	30.5	−20.0	40.0

Table 7. COC scenario, absolute minimum and maximum temperature for each element along the orbit, for the VINIS telescope assembly (temperatures in °C) and SEA method.

	T_{min}	T_{max}	w_{min}	w_{max}	T_{min}+w_{min}	T_{max}+w_{max}	T_{min_req}	T_{max_req}
BIP	2.4	4.0	10.5	10.6	−8.1	14.6	−10.0	30.0
CEN-BAF	−9.4	4.0	9.8	10.6	−19.2	14.6	−10.0	30.0
ELEC-BOX	6.5	6.7	10.6	10.6	−4.1	17.3	−20.0	65.0
BEE	7.8	10.7	10.5	10.5	−2.7	21.2	−20.0	65.0
VER-OB	3.3	4.9	10.6	10.6	−7.3	15.5	−10.0	30.0
HOR-OB	−3.2	5.1	10.1	10.7	−13.3	15.8	−20.0	40.0

Table 8. Principal contributors to thermal uncertainty.

Group	Symbol	Name
Optical properties	$\alpha_{BLACK-V}$	VINIS black paint solar absorptance (telescope)
Optical properties	ε_{KAPT-S}	Satellite Kapton IR emissivity (MLI)
Optical properties	α_{KAPT-S}	Satellite Kapton solar absorptance (MLI)
Optical properties	$\varepsilon_{WHITE-S}$	Satellite white paint IR emissivity (radiators)
Environment	T_E	Earth temperature
Environment	a	Earth albedo
Heat dissipation	Q_{BEE}	BEE heat dissipation
Heat dissipation	Q_{EPS}	EPS heat dissipation
Heat dissipation	Q_{FPA}	FPA heat dissipation
Heat dissipation	Q_{OBDH}	OBDH heat dissipation
Heat dissipation	Q_{RW}	RW heat dissipation
Thermal capacitance	$C_{BEE-BOX}$	BEE structure thermal capacitance
Thermal capacitance	$C_{BEE-PCB}$	BEE PCB thermal capacitance
Contact coefficient	h_{FPA}	FPA thermal contact coefficient
Linear conductor	GL_{INS}	Honeycomb insert linear conductor
Linear conductor	$GL_{RAD-EPS}$	EPS to radiator linear conductor
Linear conductor	$GL_{RAD-OBDH}$	OBDH to radiator linear conductor
MLI efficiency	MLI_{EFF}	MLI effective emittance

The analysis detailed below evaluates the specific impact of uncertainty from each parameter, quantifying it as a percentage of the overall temperature uncertainty. This evaluation covers all components comprising the VINIS telescope assembly, as depicted in Figure 2. Consequently, every segment of the pie chart illustrates the contributions to the RSS of Equation (1), with each expressed as a percentage of w_{Ti}^2.

Figure 6 provides a detailed overview of each parameter's contribution to the total thermal uncertainty, highlighting the contributions to the CIC scenario and minimum temperature (T_{min}) conditions. Generally, these contributions do not significantly differ from other scenarios and maximum temperature (T_{max}) conditions. Nevertheless, an exception occurs to the CEN-BAF in the HOC scenario, which exhibits a substantial difference; these findings are compiled in Figure 7.

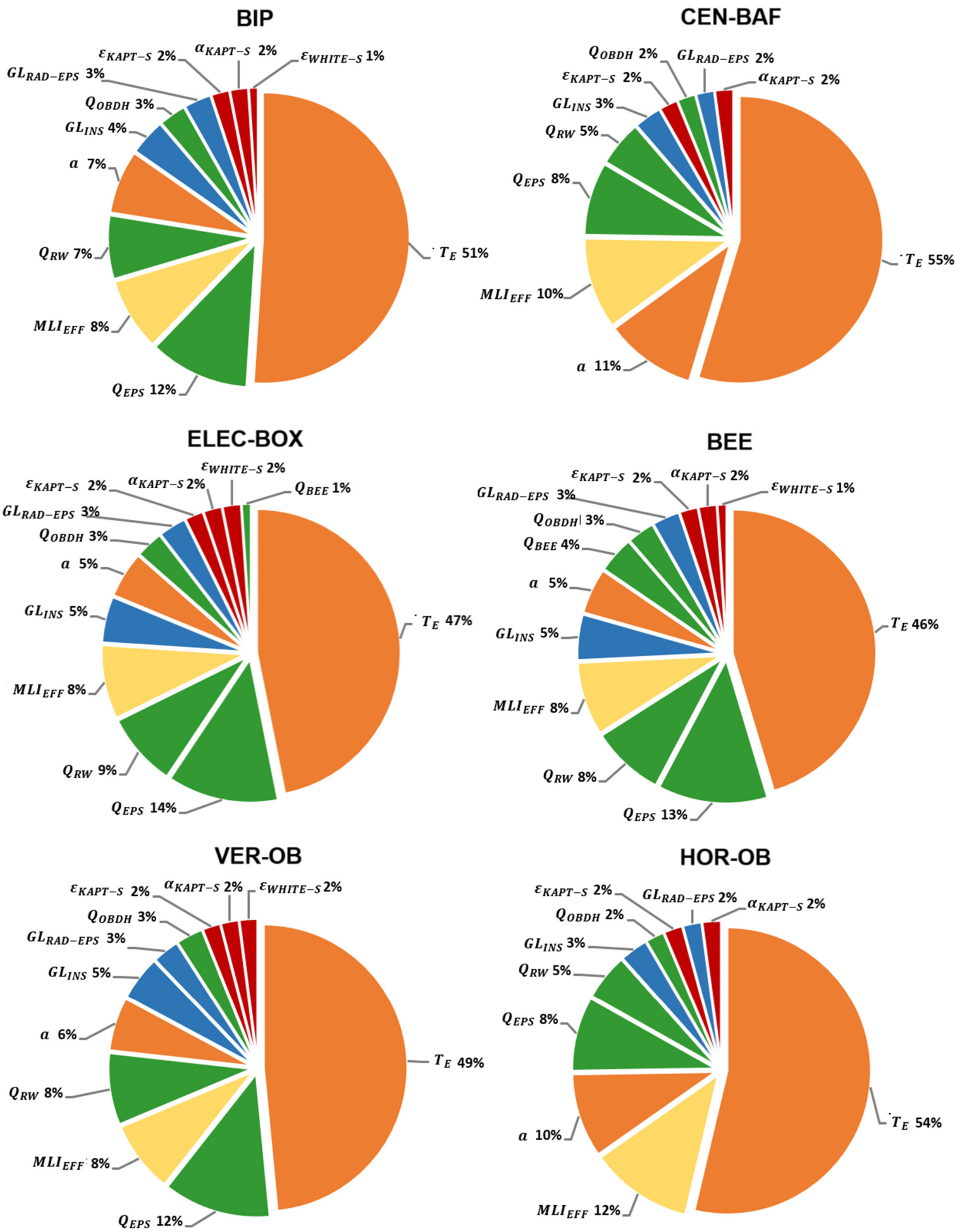

Figure 6. Breakdown of primary factors contributing to the thermal uncertainty of each of the VINIS telescope assembly components (second level of detail). CIC case and minimum temperature (T_{min}) results. Color coding is used to differentiate parameter groups: optical properties in red, environmental parameters in orange, heat dissipation in green, linear conductors in blue, and MLI efficiency in yellow.

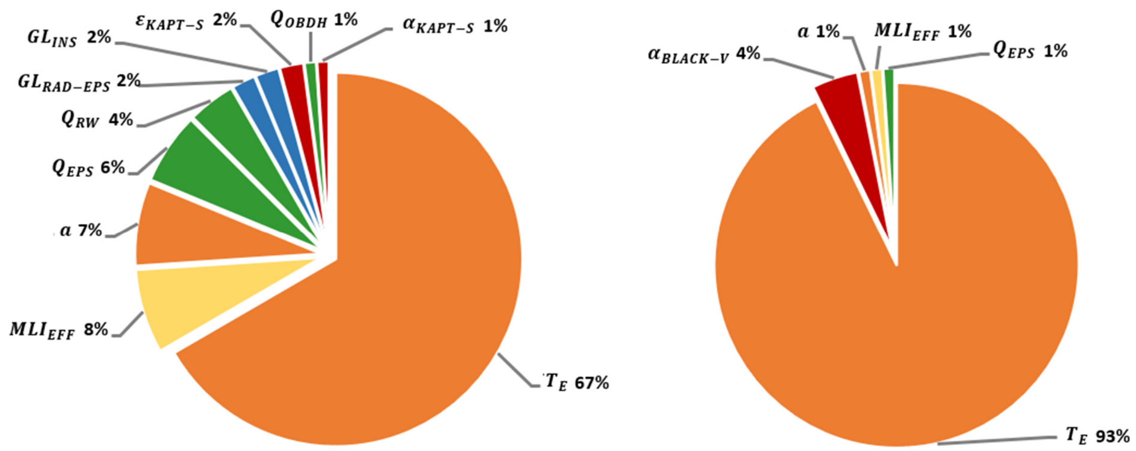

Figure 7. Breakdown of primary factors contributing to the thermal uncertainty of each of the CEN-BAF and CIC cases, for both the minimum temperature (T_{min}, **left**) and maximum temperature (T_{max}, **right**) results. Color coding is used to differentiate parameter groups: optical properties in red, environmental parameters in orange, heat dissipation in green, linear conductors in blue, and MLI efficiency in yellow.

4. Discussion

4.1. Evaluation of the Uncertainty Results

The results from Tables 5–7 show the predicted temperatures as a result of applying the margins to the calculated temperatures and the thermal requirements to compare if the results are within the allowable limits.

Concerning the telescope assembly, it is noted that the environmental temperatures generally remain within the required range for all scenarios, except for the telescope baffle (CEN-BAF). The baffle's temperature deviations are largely attributed to the extreme orientations adopted during the imaging of Earth's poles in both hot and cold cases. This indicates that, firstly, temperature control within the telescope assembly is achievable through precise pointing strategies, and secondly, a careful planning of telescope pointing operations is essential to prevent achieving temperatures outside the required range, which could negatively impact optical performance. Moreover, the highest and lowest temperatures typically occur at the most external sections of the telescope. Radiative heat transfer tends to mitigate these temperature gradients, suggesting that these variations may ultimately be within the limits.

Lastly, it is noteworthy that the uncertainty associated with the baffle's maximum temperature in the HOC is nearly twice as large as that in the other scenarios. This underscores the thermal challenges posed by the direct influx of solar radiation into the telescope, emphasizing the need for effective thermal management strategies to counteract such effects.

A comparative analysis of the uncertainty margins calculated using the SEA method with the ± 10 K margin proposed by the ECSS for a Phase B study [44] reveals that, except for the w_{max} at the central baffle (CEN-BAF), the margins are generally close to the recommended limits. This trend holds true for the telescope components (third level of detail, Figure 3). However, for the VINIS platform parts (first level of detail, Figure 1), the calculated uncertainties exceed the recommended range in some cases.

4.2. Main Thermal Drivers

Upon analyzing the uncertainty decomposition, it becomes evident that the Earth's IR temperature stands as the predominant source of uncertainty in all scenarios, with albedo also contributing significantly to most cases. Such implications could be anticipated due to the low satellite's altitude, as well as its attitude, exposing it to a wide spectrum of IR temperatures and albedo changes. These fluctuations stem from the Earth's varied surface features, including oceans, forests, and cloud-covered regions. Thus, these elements of uncertainty are inherent to the satellite's operation and cannot be acted upon, but the design can accommodate this uncertainty in the optical performance budget. There are other sources of uncertainty which are elements of the design of the satellite, and these should be the next focus of attention.

Furthermore, the platform's thermal design parameters emerge as crucial factors influencing the VINIS's thermal performance. The parameters that are the main sources of uncertainty in this regard regulate the main heat paths that drive the thermal behavior. They can be seen in Figure 8 and are the following:

1. The service module's heat dissipation represents the major source of controllable uncertainty in the problem (Q_{EPS}, Q_{RW}, Q_{OBDH})
2. The heat flux through the MLI, influenced by the MLI's efficiency and the thermo-optical properties of its outer layer (MLI_{EFF}, ε_{KAPT-S}, α_{KAPT-S}).
3. The heat path through the radiator, including the conductive couplings to it, and the IR emissivity of its white paint coating ($GL_{RAD-EPS}$, $GL_{RAD-OBH}$, $\varepsilon_{WHITE-S}$).

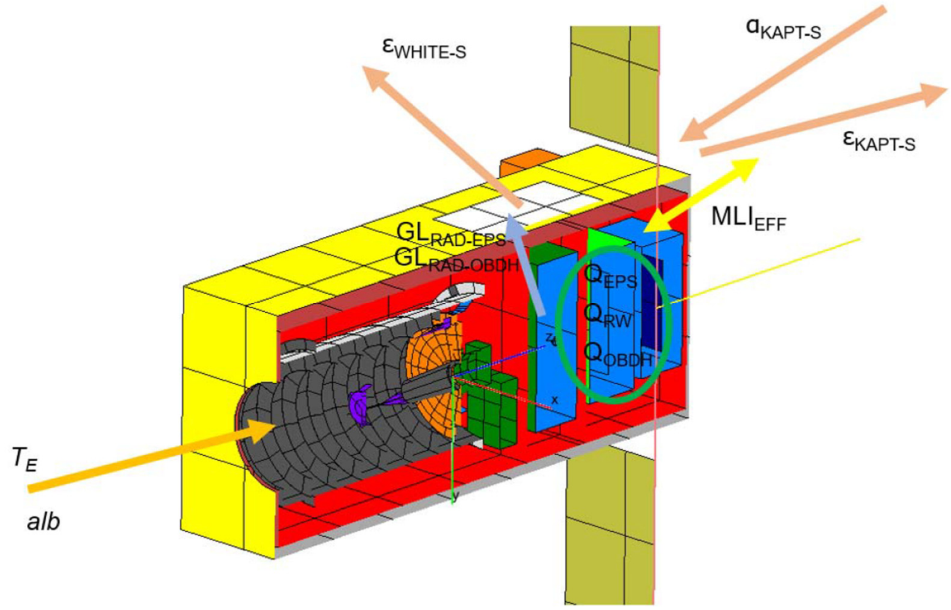

Figure 8. Main contributors to the thermal uncertainty of the VINIS thermal model.

Keeping these parameters under check and reducing their uncertainty as early in the project as possible will ensure that the thermal design is reliable and robust. This can be achieved by tailoring the engineering test program.

Other parameters, such as the inserts' conductive coupling, also contribute to the total uncertainty. Nevertheless, its implications are challenging to quantify due to their presence in most of the platform's conductive heat paths. Additionally, certain parameters may become significant in the detailed thermal analysis of specific components, such as the FPA.

4.3. Proposed Thermal Testing Model

The benefits of adopting an uncertainty-based analysis methodology will be demonstrated during the testing process. By identifying the key thermal drivers through this analysis, the test campaign can be streamlined, focusing on elements that have the greatest impact on the final design. This targeted approach leads to a more efficient and cost-effective testing strategy. It eliminates the need for the extensive testing of every component, allowing for a more focused allocation of attention and resources towards critical aspects that dictate the satellite's performance. Such an approach not only simplifies the development process but also enhances the effectiveness of thermal testing, ensuring a more reliable and robust satellite design.

Considering the uncertainty analysis findings, a proposed approach to the design process is outlined as follows:

1. Prioritize the detailed identification of heat dissipation values early in the design process, as these will significantly influence the temperature levels within the satellite, aside from the environmental and platform design factors.
2. During the development of the Structural and Thermal Model (STM), it is essential for engineers to pay special attention to the MLI. Since its performance has significant implications, the MLI employed in the STM should closely mirror that of the final design in materials, thickness, size, and openings. This alignment will help in minimizing the uncertainty associated with both its effectiveness and optical properties.
3. The STM will allow for retrieving high-resolution temperature measurements from specific points to correlate with the inserted conductive couplings, ensuring accurate thermal modeling.
4. It would be beneficial to treat the thermal straps for radiators as a degree of freedom, allowing for modifications during testing. These straps should be incorporated into the tests, yet with the flexibility to make modifications. This approach facilitates the fine-tuning of the satellite's operating temperature to achieve optimal performance, once other non-tunable parameters with large uncertainties, like the MLI effective emittance, are determined.
5. Moreover, engineers could consider a cost-effective Thermal Vacuum Chamber (TVAC) STM test that ensures the representativeness of these critical elements. Focus on the representativeness of the MLI should be the key, and considerations of the straps as per point 4 should apply. Other elements in the design may not need to be so representative, allowing for two things:
    i. Less expensive hardware/less engineering hours employed in other elements deemed to not be critical.
    ii. Leaving some elements of the design open when other subsystems still need some iterations (for example, if there are some doubts on which inserts to use in some areas or similar).

These elements do not dominate the thermal behavior and, therefore, allow for flexibility without significantly affecting the results.

This methodology diverges from traditional approaches by providing a quantitative assessment of the impact of uncertainties on thermal performance. It effectively identifies and evaluates critical thermal drivers, guiding the development of thermal management strategies. Offering a structured method for prioritizing design and testing efforts, it introduces an innovative perspective to thermal testing planning, thus improving the thermal control system's efficiency and reliability.

Furthermore, the suggested thermal testing model is a novel approach that leverages uncertainty analysis to streamline the testing process. Concentrating on key thermal drivers allows for a more targeted and cost-efficient design optimization process, ensuring crucial uncertainties are addressed promptly to enhance the overall robustness of the design.

5. Conclusions

This study on the VINIS space telescope underscores the significant advantages of incorporating an uncertainty-based analysis methodology into the satellite design process. This methodology is instrumental in identifying the key thermal drivers, streamlining the testing campaign to focus on elements that greatly influence the final design. Such a targeted approach not only makes the testing strategy more efficient and cost-effective but also eliminates the need for the exhaustive testing of every component. By concentrating efforts and resources on the critical aspects that dictate satellite performance, the development process is simplified, and the effectiveness of thermal testing is enhanced, resulting in a more reliable and robust satellite design.

Additionally, the findings from the uncertainty analysis provide valuable insights for the design process. Key recommendations include the early identification of heat dissipation values, which significantly influence internal temperature levels, and the need for a careful consideration of the MLI during the development of the STM. The performance of the MLI, closely mimicking that of the final design, is crucial, and high-resolution temperature measurements from the STM are vital for accurate thermal modeling. Flexibility in adjusting thermal straps for radiators during testing is recommended, allowing for the fine-tuning of the satellite's operating temperature. A targeted TVAC test on the STM should focus on these critical elements, ensuring the representativeness of the MLI and thermal straps, while allowing for some design elements to remain adaptable for future iterations.

As secondary conclusions drawn from the thermal behavior analysis, the study presents the following points:

- The assessment of four operational scenarios (CIC, HOC, COC, CNOC) validated the effectiveness of passive thermal control strategies in maintaining the telescope within its optimal operational temperature range, except for minor deviations under extreme pointing conditions.
- A temperature gradient in the baffle appears to be an inherent challenge that passive methods alone may not overcome. Accurate pointing is critical to ensure that the satellite's baffle temperatures remain within the required limits. Evaluating the maximum permissible thermal gradient for correct optical performance and adjusting operational profiles may be advantageous.
- Frequent scientific observations, as in the scenario, could produce significant temperature gradients, potentially needing a limit on operational frequency to prevent performance degradation.

These secondary conclusions, derived from the detailed thermal analysis, complement the primary insights gained through the uncertainty analysis, contributing to a comprehensive understanding of the design and operational challenges of the satellite.

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