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The THESEUS Space Mission and the Infrared Telescope Calibration Unit

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ABSTRACT

The Transient High-Energy Sky and Early Universe Surveyor (THESEUS) is an ESA M7 mission concept currently in Phase A, designed to exploit gamma-ray bursts to probe the early Universe while advancing multi-messenger and time-domain astrophysics. To achieve its ambitious goals, THESEUS will combine wide-band x-ray and gamma-ray monitors with an onboard InfraRed Telescope (IRT), providing autonomous arcsecond-scale localisation and high-precision redshift determination of near-infrared counterparts to high-energy transients. Achieving this precision requires a well-characterised detector response enabled by an internal Calibration Unit. The unit will ensure accurate calibration of the detector throughout the mission's 4-year nominal lifetime—and potentially beyond—using near-infrared LEDs as internal illumination sources. We highlight THESEUS science cases relevant for the Calibration Unit performance, discuss key challenges in the LED selection process and present the current status of the optical and mechanical design concept enabling a spatially uniform and temporally stable detector illumination within a structure that ensures long-term durability.

1 | Introduction

Gamma-ray bursts (GRBs) are brief flashes of gamma rays produced by the collapse of massive stars or the mergers of compact objects. Their prompt emission ranks among the most luminous events in the Universe, while their afterglows are detectable across the electromagnetic spectrum. Because they remain visible to the highest redshifts and have simple, bright spectra, GRBs are powerful probes of the early Universe, providing unique insights into star formation, chemical enrichment and the state of the intergalactic medium (Gehrels et al. 2009; Kumar and Zhang 2015).

The Transient High-Energy Sky and Early Universe Surveyor (THESEUS; Amati et al. 2018, 2021) is a proposed ESA M7-class space mission currently in Phase A, designed to make a decisive leap in our understanding of the early Universe, GRBs and the transient high-energy sky. By combining wide-field x-ray and gamma-ray detection with an on-board InfraRed Telescope (IRT), THESEUS will detect and localise high-energy transients and, in many cases, determine their redshifts on board. The mission is designed to exploit high-redshift GRBs as probes of the cosmic dawn, the epoch of reionisation and early galaxy evolution.

Over its nominal 4-year mission, THESEUS will address three overarching science themes: (1) tracing the cosmic dawn, (2) exploring the transient sky and (3) enabling multi-messenger astrophysics. See details in the THESEUS Assessment Study

Report (Yellow Book; ESA/SCI(2021)2; THESEUS Study Team 2021).

The mission's reference payload (Amati et al. 2018, 2021) consists of three scientific instruments: the Soft X-ray Imager (SXI) providing the initial triggers for many events, the X-/Gamma-ray Imaging Spectrometer (XGIS) offering broad spectral coverage of GRB prompt emission and the InfraRed Telescope (IRT) enabling precise localisation and redshift determination.

This paper highlights IRT-relevant science cases, describes the instrument's on-board capabilities and presents the Calibration Unit, focusing on the key challenges in its development and the current status of its optical and mechanical design.

2 | Theseus Science Cases

A central aim of modern astrophysics is to understand how the first stars, black holes and galaxies formed and evolved during the first billion years, encompassing the epoch of reionisation and early chemical enrichment. THESEUS is expected to detect 40–50 GRBs at $z > 6$ over its nominal mission, providing a unique sample to address key questions about star formation, faint galaxies, chemical enrichment, the transparency of galaxies to ionising radiation and the signatures of the first stellar populations (Amati et al. 2018; Racz et al. 2023; Tanvir et al. 2021). In the following, we highlight selected science cases where on-board NIR observations play a central role.

Global star-formation history from the GRB rate. At high redshift, galaxy surveys are incomplete and biased against faint or dust-obscured systems. GRBs trace massive star formation and provide an alternative probe of the cosmic star-formation rate density; THESEUS will establish the GRB redshift distribution at $z \gtrsim 5.5$ with unprecedented completeness (Kistler et al. 2009; Robertson and Ellis 2012).

Revealing faint galaxies via GRB hosts. GRBs act as beacons to galaxies that are too faint for direct detection, allowing their redshifts and environments to be studied independently of host luminosity. THESEUS will constrain the faint end of the galaxy luminosity function and assess the contribution of undetected galaxies to reionisation (Salvaterra et al. 2013; Tanvir et al. 2012).

Build-up of metals, molecules and dust. GRB afterglows provide bright continua for absorption spectroscopy. A large THESEUS sample at $z > 6$ will enable measurements of metallicity, dust extinction and molecular content, tracing early chemical enrichment and star formation conditions (Fynbo et al. 2009; Prochaska et al. 2007).

Lyman-continuum escape fraction. The escape fraction of ionising photons, f_{esc}, is a key parameter in reionisation models. GRB afterglow spectroscopy provides a direct probe via neutral hydrogen measurements, enabling THESEUS to place statistical constraints on f_{esc} across the reionisation epoch (Finkelstein 2019; Wise et al. 2014).

Reionisation and Population III stars. High-redshift GRB afterglows probe the neutral intergalactic medium through the Ly α damping wing and may reveal abundance patterns indicative of extremely metal-poor progenitors. THESEUS will test the role of massive stars in reionisation and search for signatures of Population III star formation (Bromm and Loeb 2006; Totani et al. 2014).

A key element enabling these studies is the on-board IRT, providing rapid localisation and autonomous redshift determination through NIR imaging and spectroscopy. Precise position and redshift measurements are essential for placing GRBs in their correct cosmological context and this precision critically depends on the long-term stability and calibration of the IRT detector, enabled by the Calibration Unit.

3 | The Infrared Telescope (IRT)

The IRT is a 0.7 m off-axis Korsch telescope with a $15' \times 15'$ field of view, imaging in five NIR filters (I, Z, Y, J, H) and slit-less spectroscopy at $R \sim 400$ across 0.8–1.6 μm. It is central to the THESEUS mission, as it provides the capability to localise transients to arcsecond precision and to determine their redshifts on board (Amati et al. 2018, 2021).

Upon triggers from the SXI or XGIS, the spacecraft autonomously slews to the event and initiates an observing sequence with the IRT. Imaging ensures accurate localisation of the afterglow, while spectroscopy allows identification of spectral breaks such as the Ly α cutoff, enabling rapid redshift estimation (ESA THESEUS Study Team 2021). This autonomy is essential for capturing high-redshift GRBs, as their afterglows fade rapidly and may be inaccessible to ground-based follow-up due to visibility or weather constraints. This ensures that THESEUS can independently achieve its science objectives, while also providing rapid, high-quality targets for follow-up with facilities such as JWST, ELTs and ATHENA (Amati et al. 2021).

The IRT will be capable of arcsecond-scale localisation and redshift determination with ˜10% precision from photometry and $< 1\%$ accuracy from spectroscopy. This level of precision requires the detector response to be characterised to a high degree, enabled by the Calibration Unit.

4 | IRT Calibration Unit—The Hungarian Contribution

4.1 | Baseline Concept

The IRT Calibration Unit, developed by the University of Debrecen in collaboration with Admatis Ltd., is designed to ensure accurate and stable NIR calibration throughout the mission. It provides spatially uniform detector illumination with high temporal stability, enabling long-term monitoring of the IRT detector's response. By doing so, the Calibration Unit guarantees that localisation, photometry and spectroscopy of GRB afterglows remain reliable over the full mission lifetime (Amati et al. 2021; ESA THESEUS Study Team 2021).

The baseline concept places the Calibration Unit inside the closed IRT camera cavity, off-axis, with no moving parts required to switch between calibration and science modes (Figure 1).

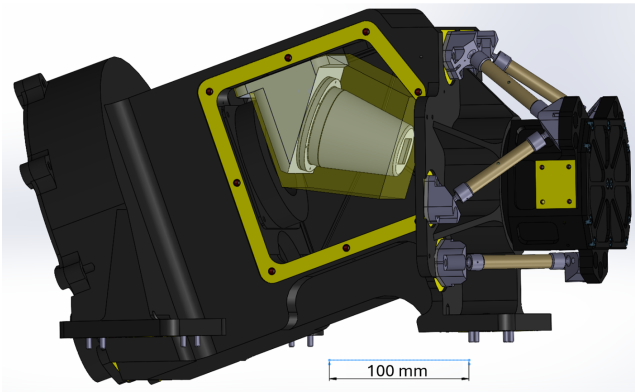

FIGURE 1 | Concept of the Calibration Unit inside the IRT Camera cavity. The yellow bounding box around the unit is the allocated volume for the assembly.

This design minimises mechanical complexity while maintaining a stable and repeatable illumination of the detector. Key system-level challenges include achieving sub-percent spatial uniformity within tight volume and alignment constraints and ensuring robustness under the mechanical, thermal and radiation conditions encountered in space.

Importantly, THESEUS's approach of the IRT Calibration Unit finds precedent in Euclid's Near-Infrared Spectrometer and Photometer (NISP) Calibration Unit (NI-CU), which is the first astronomical calibration lamp based on LEDs to be operated in space (Hormuth et al. 2025). This heritage illustrates the feasibility and scientific utility of LED-based calibration systems for space-borne NIR instruments, while highlighting the opportunity for THESEUS to expand the method's applicability in transient astrophysics.

4.2 | LED Selection, Challenges and Solutions

At the heart of the Calibration Unit are NIR LEDs, serving as stable illumination sources across the required bands. Their selection builds on the successful heritage of NI-CU, while addressing the specific wavelength coverage and operational requirements of THESEUS.

Euclid employs LEDs at five independent NIR channels covering the wavelength range from 940 to 1890 nm, operating at cryogenic temperatures around 135 K (typically within the 130–140 K range). The LEDs are implemented in hermetic TO-18 metal-can packages using Kovar two-pin headers with glass windows, providing mechanical robustness, low outgassing and compatibility with repeated cryogenic thermal cycling. NI-CU provides large-scale illumination non-uniformity below approximately 10%–12% across the detector plane and small-scale uniformity better than 0.1% on millimetre scales, with temporal flux drift below 0.2% over a 1200 s interval after stabilisation. Each LED is designed for an operational lifetime exceeding 800 h under repeated on/off cycling (Hormuth et al. 2025).

In contrast, THESEUS IRT CU requires full coverage of the I, Z, Y, J and H bands over a partially overlapping but shifted wavelength range spanning 731–1785 nm, see Figure 2.

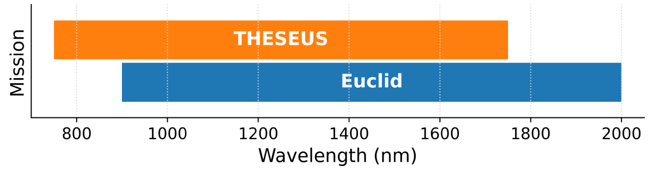

FIGURE 2 | Comparison of the wavelength coverage of the Euclid NISP and THESEUS IRT calibration units.

The IRT LEDs will operate across a wide thermal range from -120°C to $+50^{\circ}$C, with a long-term flux stability ($\pm$10%), lifetime exceeding 3000 h and more than 1000 on/off cycles. In addition, the calibration LEDs must be compatible with the applicable radiation environment and withstand the mechanical loads associated with launch and in-orbit operation, as defined in the mission requirements (ESA THESEUS Study Team 2021).

To address these requirements, a dedicated Phase A LED market research activity was performed, accounting for the THESEUS wavelength range and operational constraints. The objective was to identify NIR LED technologies that satisfy the spectral and packaging requirements of the Calibration Unit and that are suitable for subsequent space qualification.

The market survey confirmed the availability of multiple NIR LED devices covering the full THESEUS spectral range, either as bare semiconductor dies or as hermetically packaged TO-CAN components. Based on the proven NI-CU concept, a hermetic TO-18 metal-can package with a glass window has been adopted as the baseline solution for THESEUS. Several potential manufacturers were identified whose LED products meet the baseline requirements in terms of wavelength coverage and packaging feasibility, including Epigap, Thorlabs, TechLED, InPhenix, Hamamatsu and Superlum. These devices form a well-defined candidate pool for further evaluation in Phase B.

In addition to LED die and device suppliers, a dedicated activity was initiated to identify bare-die assembly partners, recognising that a uniform TO-18 package may need to be produced independently of the LED manufacturer. This approach enables tighter control over materials, assembly processes, and quality, and directly follows the successful NI-CU strategy. Potential packaging and assembly partners identified during Phase A include Epigap, First Sensor Lewicki and Alter Technology. These organisations have demonstrated experience in hermetic optoelectronic packaging, cryogenic-compatible die attach, sealing and screening, and will be considered during Phase B for prototype assembly.

4.3 | Optical Design

The Calibration Unit includes two redundant calibration source LEDs for each of the five wavelength bands, resulting in a total of ten LEDs. The optical design builds on the heritage of the NI-CU, which is also positioned off-axis. This configuration leads to non-perpendicular illumination of the detector surface, making the achievement of spatial uniformity challenging. The adopted solution is to direct the LEDs onto a diffuse surface, which is angled to provide the lowest flux gradient in the direction of the detector plane centre (Figure 3).

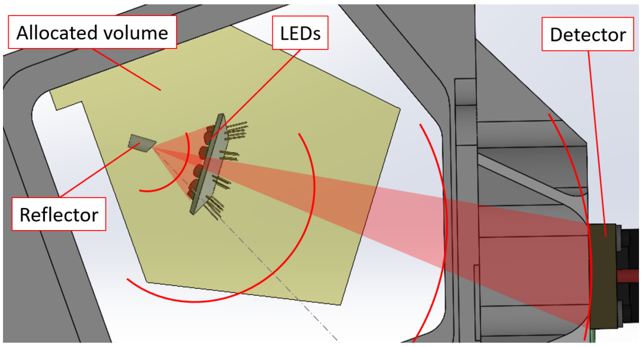

FIGURE 3 | Schematics of the optical system: LEDs directed towards a tilted dispersive reflector, which reflects with the lowest gradient in the direction of the detector plane.

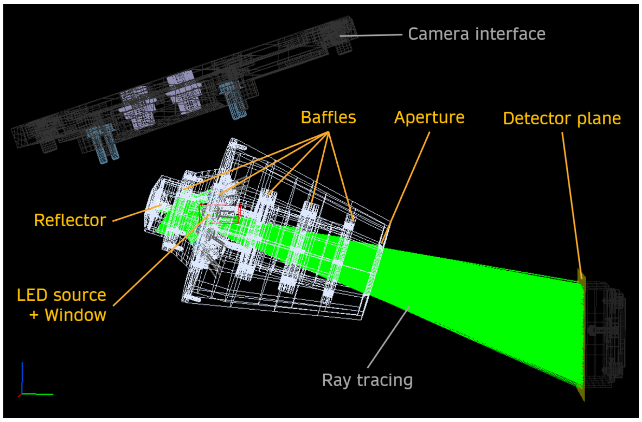

FIGURE 4 | Ray tracing simulation in the optical model's first iteration with the included optical elements in yellow.

Besides the high uniformity, the requirements for the Calibration Unit also include a sharp illumination cut-off at the detector edges to minimise straylight. We achieve this with a series of baffles inside the unit, followed by an aperture cut in the housing. The optical model was built up with the elements: (1) LED light source, (2) TO-18 LED package with a planar Schott BK7 glass window, (3) Spectralon diffuse reflector, (4) a series of five baffles and (5) aperture (Figures 4 and 5).

Low-resolution ray-tracing simulations show a well-aligned illumination field at the detector plane with the rays dispersed uniformly. The well-defined edges of the illumination pattern indicate a sharp cutoff. High-resolution simulations will quantify the inhomogeneity level and the cutoff distance, providing feedback for the next iteration of the optical design.

4.4 | Mechanical Design

The challenge of the mechanical design lies in accommodating all optical components within the limited volume and mass budget, providing space for electronics and harnessing, while ensuring structural rigidity and efficient thermal conduction.

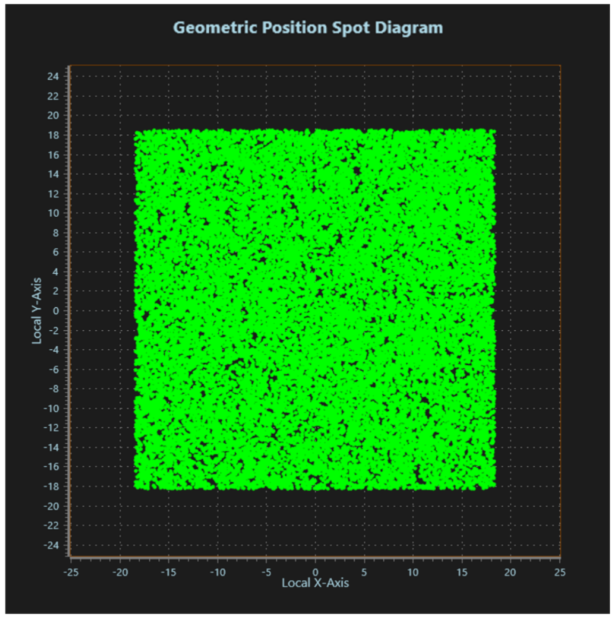

FIGURE 5 | Geometric positions spot diagram at the detector plane for the ray tracing simulation. A well-aligned illumination pattern with sharp edges and uniform random dispersion.

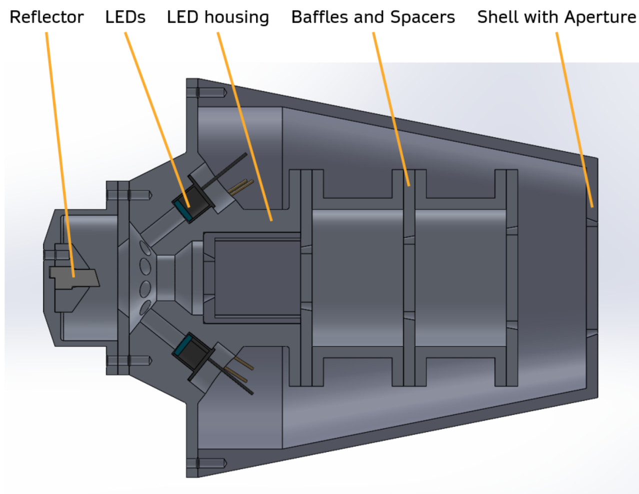

FIGURE 6 | Section of the mechanical design's first iteration with the main components highlighted.

Building on the NI-CU heritage and in compliance with the IRT material requirements, the LEDs are embedded in an aluminium housing that also integrates the reflector mount. The optical assembly is completed by a stack of baffles with spacers and a top shell providing structural closure and incorporating the aperture. Figure 6 shows a section for the first design iteration of the Calibration Unit assembly.

The design will undergo further iterations once high-resolution optical simulations guide the next update of the optical design. So far, the design utilises the allocated volume efficiently and has a mass of roughly a third of the net mass budget, leaving room for the addition of electronics parts and the structural element for mounting to the camera housing.

5 | Summary

THESEUS will provide a transformative view of the high-redshift Universe, advancing gamma-ray burst studies, early-Universe star formation research and multi-messenger astrophysics. By detecting tens of GRBs at $z > 6$, it will map the cosmic star-formation history, reveal faint galaxy populations and constrain the role of massive stars in reionisation. The on-board IRT, supported by the Hungarian-led Calibration Unit, will ensure reliable NIR measurements and secure the mission's full scientific return.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Amati, L., P. O'Brien, D. Götz, et al. 2018. "The THESEUS Space Mission Concept: Science Case, Design, and Expected Performances." *Advances in Space Research* 62: 191–244.

Amati, L., P. O'Brien, D. Götz, et al. 2021. "The THESEUS Space Mission: Science Goals, Requirements, and Mission Concept." *Experimental Astronomy* 52: 183–218.

Bromm, V., and A. Loeb. 2006. "High-Redshift Gamma-Ray Bursts From Population Iii Progenitors." *Astrophysical Journal* 642: 382–388.

ESA THESEUS Study Team. 2021. *Yellow Book. Technical Report ESA/SCI(2021)2*. European Space Agency.

Finkelstein, S. L. 2019. "Observational Searches for Star-Forming Galaxies at $z > 6$." *Annual Review of Astronomy and Astrophysics* 57: 157–205.

Fynbo, J. P. U., P. Jakobsson, J. X. Prochaska, et al. 2009. "Low Metallicity and High Escape Fraction as Progenitors of the First Stars? Constraints From GRB Afterglows." *Astrophysical Journal Supplement Series* 185: 526–573.

Gehrels, N., E. Ramirez-Ruiz, and D. B. Fox. 2009. "Gamma-Ray Bursts in the Swift Era." *Annual Review of Astronomy and Astrophysics* 47: 567–617.

Hormuth, F., K. Jahnke, M. Schirmer, et al. 2025. "Euclid. IV. The Nisp Calibration Unit." *Astronomy & Astrophysics* 697: A4.

Kistler, M. D., H. Yüksel, J. F. Beacom, A. M. Hopkins, and J. S. B. Wyithe. 2009. "The Star Formation Rate in the Reionization Era as Indicated by Gamma-Ray Bursts." *Astrophysical Journal* 705: L104–L108.

Kumar, P., and B. Zhang. 2015. "The Physics of Gamma-Ray Bursts and Relativistic Jets." *Physics Reports* 561: 1–109.

Prochaska, J. X., H.-W. Chen, and J. S. Bloom. 2007. "Dissecting a Gamma-Ray Burst: Ands and Dampness of the Circumburst Medium." *Astrophysical Journal* 668: 1–14.

Racz, I. I., L. G. Balazs, and I. Horvath. 2023. "Redshift Dependence of GRBs' Observed Parameters." *Contributions of the Astronomical Observatory Skalnate Pleso* 53, no. 4: 115–126.

Robertson, B. E., and R. S. Ellis. 2012. "Connecting the Gamma Ray Burst Rate and the Cosmic Star Formation History: Implications for Reionization and Galaxy Evolution." *Astrophysical Journal* 744: 95.

Salvaterra, R., E. Bissaldi, G. Ghirlanda, et al. 2013. "Evidence for Luminosity Evolution of Long Gamma-Ray Bursts in Swift Data." *Monthly Notices of the Royal Astronomical Society* 429: 2407–2414.

Tanvir, N. R., L. Amati, P. T. O'Brien, et al. 2021. "Exploration of the High-Redshift Universe Enabled by Theseus." *Experimental Astronomy* 52: 219–243.

Tanvir, N. R., A. J. Levan, A. S. Fruchter, et al. 2012. "Star Formation in the Early Universe: High-Redshift GRB Hosts." *Astrophysical Journal* 754: 46.

Totani, T., K. Aoki, M. Hattori, N. Kawai, D. Yonetoku, and K. Abe. 2014. "Population III Gamma-Ray Bursts and Cosmology." *Publications of the Astronomical Society of Japan* 66: 63.

Wise, J. H., V. G. Demchenko, M. T. Halicek, et al. 2014. "The Birth of a Galaxy—II. The Role of Radiation Pressure." *Monthly Notices of the Royal Astronomical Society* 442: 2560–2579.