

OGSE For Calibration and Characterization of the EnVision VenSpec-H Instrument

J. Pimentão^{1*}, Raquel Henriques¹, Daniela Nunes¹, Dylan du Preez¹, Ricardo Santos¹, Eddy Neefs²,
Justin Erwin², Pierluigi Foglia Manzillo³

¹*Lusospace, Lisbon, Lisbon, Portugal*

²*Royal Belgian Institute for Space Aeronomy, BIRA-IASB, Ringlaan 3, 1180, Brussels, Belgium*

³ *European Space Research & Technology Centre (ESA-ESTEC), 2200 Noordwijk, The Netherlands*

ABSTRACT

EnVision is an upcoming European Space Agency mission dedicated to the study of Venus, aiming to investigate its atmosphere, surface, and interior through a comprehensive suite of scientific instruments. One of these instruments is VenSpec-H, a high-resolution near-infrared spectrometer designed to observe Venus in both dayside and nightside conditions, imposing demanding requirements on its ground calibration and characterization campaign.

In this context, LusoSpace is responsible for the design, development, integration, alignment, and verification of the Optical Ground Support Equipment (OGSE) supporting the spectral, radiometric, and polarization characterization of the VenSpec-H instrument.

The instrument operates across multiple near-infrared spectral bands (1165–1180 nm, 1370–1390 nm, 1720–1750 nm, 2340–2480 nm), with a field of view of 7° (spectral) by 0.2° (spatial) and an entrance aperture of 14,5 x 20,5 mm.

The OGSE is designed to operate with the instrument installed inside a thermal-vacuum chamber, while the optical source assembly remains outside the chamber and illuminates the instrument through an infrared-transparent window. This configuration introduces significant constraints on radiometric performance, field-of-view coverage, spectral fidelity, alignment, and environmental stability.

To address the complexity of the requirements, the proposed OGSE combines multiple dedicated optical sources in a single modular architecture. A high-temperature extended-area blackbody is used for radiometric calibration and detector response characterization, providing the required radiance levels together with high spatial uniformity and temporal stability. A narrow spectral source subsystem, based on multiple DFB laser sources and support optics, enables spectral calibration and instrument spectral response function characterization across the full set of VenSpec-H science bands. In addition, a small scanning bright source, based on a high-temperature micro blackbody mounted on precision XY translation stages, is used for field-of-view mapping, boresight determination, and straylight-related measurements. A polarization characterization capability is also implemented by means of a rotatable linear polarizer integrated in the radiometric source path.

The OGSE architecture is further supported by dedicated EGSE, automation, and monitoring capabilities, enabling standalone or remote operation, scripted test execution, source stability monitoring, and efficient interfacing with the instrument test environment. To minimize atmospheric absorption features in the near-infrared, the optical path is enclosed and continuously purged with nitrogen.

This paper presents the design drivers, optical architecture and verification approach adopted for the EnVision VenSpec-H OGSE, highlighting the technical solutions implemented to meet the stringent calibration requirements of a high-performance planetary spectrometer.

Keywords: Space Instruments, Optical Ground Support Equipment (OGSE), EnVision, Venus.

*jpimentao@lusospace.com, www.lusospace.com

1. INTRODUCTION

Venus and Earth are often regarded as planetary twins due to their comparable size, bulk composition, and position within the inner Solar System. Despite these similarities, the two planets followed radically different evolutionary paths. While Earth evolved into a habitable planet with stable oceans and a temperate climate, Venus developed an extremely dense CO₂-rich atmosphere, surface temperatures exceeding 730 K, and pressures around 92 bar. Understanding how two planets with apparently similar initial conditions evolved into such contrasting worlds remains one of the major unresolved questions in planetary science and has become increasingly relevant in the context of terrestrial exoplanet studies. [ESA - Envision factsheet - https://www.esa.int/Science_Exploration/Space_Science/Envision]

Following the scientific achievements of missions such as *Venus Express*, *Magellan* and *Akatsuki*, numerous questions concerning the geological evolution, atmospheric chemistry and present-day activity of Venus remain unanswered. Recent observations have provided increasing evidence that Venus may still be geologically active, with indications of recent volcanic eruptions, localized surface changes and temporal variations in atmospheric trace gases. These observations strongly suggest that the planet should no longer be considered a geologically dormant body, highlighting the need for a mission capable of simultaneously investigating its interior, surface and atmosphere as a coupled system.

The European Space Agency's EnVision mission has been conceived to address these fundamental scientific questions through the first comprehensive investigation of Venus from its inner core to its upper atmosphere. Rather than studying the individual components of the planet independently, EnVision is designed to characterise the physical and chemical interactions between the interior, surface and atmosphere, providing a holistic understanding of the processes responsible for the planet's past and present evolution. The mission will investigate Venus' geological history, present-day tectonic and volcanic activity, atmospheric dynamics, climate evolution, and the mechanisms that may have driven the transition from a potentially habitable planet to the extreme environment observed today. [ESA - Envision factsheet]

To accomplish these objectives, EnVision carries a complementary payload composed of radar instruments, radio science experiments and three spectrometers forming the VenSpec suite: VenSpec-U, VenSpec-M and VenSpec-H. Together, these instruments provide synergistic observations spanning ultraviolet, visible, infrared and microwave wavelengths, enabling simultaneous investigations of atmospheric composition, surface mineralogy, subsurface structure and geological processes. This multi-instrument approach is essential for correlating atmospheric measurements with surface and subsurface observations, particularly when searching for signatures of active volcanism and surface-atmosphere interactions. (Colin F. Wilson et al. 2024)

Among these instruments, VenSpec-H (Venus Spectrometer – High Resolution) is dedicated to high spectral resolution observations in the near-infrared spectral range between approximately 1.15 μm and 2.5 μm . Building upon the successful heritage of the SOIR instrument onboard *Venus Express* and the NOMAD spectrometers developed for the ExoMars Trace Gas Orbiter, VenSpec-H adopts similar high-resolution spectroscopic principles while introducing a fundamentally different observation concept based on nadir viewing. This observation geometry enables measurements beneath the Venusian cloud deck during the nightside, while also allowing daytime observations of the atmosphere above the cloud tops, considerably extending the accessible scientific targets compared with previous infrared spectrometers. [E.Neef et al, 2025]

The primary scientific objective of VenSpec-H is the detection and quantification of trace gases associated with volcanic activity and surface-atmosphere exchange processes, including SO₂, H₂O and HDO [J. Helbert et al, 2019]. By monitoring both their spatial distribution and temporal variability, the instrument will provide key information on active volcanic plumes, atmospheric circulation and the chemical evolution of the lower atmosphere. Combined with observations from VenSpec-M and VenSAR, these measurements will enable the correlation of atmospheric gas abundances with thermal anomalies, surface emissivity and geological features, providing an unprecedented capability to identify ongoing geological activity on Venus [J. Helbert et al, 2019].

Achieving these ambitious scientific objectives requires an extensive pre-flight calibration campaign capable of accurately characterising the radiometric, spectral, geometric and polarimetric performance of the instrument under representative operational conditions. Unlike conventional laboratory calibration systems, the VenSpec-H Optical Ground Support Equipment (OGSE) must operate with the instrument installed inside a thermal-vacuum chamber while all optical sources remain external to the chamber, illuminating the instrument through an infrared-transparent window. This configuration introduces significant challenges related to radiometric performance, field-of-view coverage, spectral fidelity, optical alignment and environmental stability. Consequently, the development of a dedicated multi-source OGSE becomes a key enabling element for the successful calibration and scientific exploitation of the VenSpec-H instrument. The present paper describes the design philosophy, optical architecture and verification approach adopted for this calibration system, developed by LusoSpace to support the EnVision calibration campaign.

2. CALIBRATION CHALLENGES

The scientific objectives of VenSpec-H translate into a demanding set of calibration and characterization activities. The instrument is designed to perform high-resolution near-infrared observations of Venus in both dayside and nightside conditions, with the nightside measurements exploiting selected atmospheric transparency windows to investigate the near-surface atmosphere. The scientific requirements therefore extend beyond the conventional characterization of a spectrometer and include accurate radiometric, spectral, geometric and polarization calibration over the complete operational wavelength range [Robert et al., 2024; Neefs et al., 2025].

The calibration approach also benefits from the heritage of previous planetary infrared spectrometers. In particular, the NOMAD instrument on board the ExoMars Trace Gas Orbiter required an extensive ground calibration campaign covering detector characterization, illumination patterns, boresight determination, instrument line shape and radiometric response. Its LNO channel, which performs nadir observations in the infrared, provides particularly relevant heritage for the calibration of VenSpec-H [Thomas et al., 2022a]. The VenSpec-H calibration requirements, however, introduce additional constraints associated with its specific spectral bands, observation geometry and thermal-vacuum test configuration.

The diversity of calibration and characterization activities required for VenSpec-H is summarized in Table 1. Each activity imposes different requirements on the optical stimulus, making the use of a single calibration source impractical.

Table 1 - Main VenSpec-H calibration and characterization functions and associated OGSE performance drivers.

Calibration / characterization function	Required stimulus	Main OGSE performance drivers	OGSE subsystem
Radiometric calibration	Extended, uniform broadband source	Radiance, uniformity, temporal stability	Extended-area blackbody
Spectral calibration	Narrow spectral lines	Wavelength accuracy, spectral radiance, stability	DFB laser sources
ISRF characterization	Narrow spectral lines	Linewidth, wavelength stability, SNR	DFB laser sources
Detector response	Extended broadband source	Radiometric stability, repeatability	Extended-area blackbody
FOV mapping	Small bright source	Source size, position accuracy, stability	Micro-blackbody + XY stages
Boresight determination	Small bright source	Position knowledge, repeatability	Micro-blackbody + XY stages
Straylight characterization	Scanning bright source	Radiance, spatial control, stability	Micro-blackbody + XY stages
Polarization characterization	Polarized source	Polarization purity, angular accuracy	Rotatable polarizer + Extended-area blackbody

The calibration activities listed in Table 1 span substantially different radiometric, spectral and spatial requirements. As a consequence, a single optical source cannot provide the complete set of stimuli required for the VenSpec-H calibration campaign. The OGSE must instead combine complementary sources within a common and accurately controlled optical architecture.

2.1 Radiometric and signal-to-noise requirements

VenSpec-H is designed to measure molecular footprint associated with the Venusian atmosphere, including the ones relevant to the investigation of volcanic activity and surface-atmosphere interactions. On the nightside, selected near-infrared transparency windows provide access to radiation originating from below the main cloud deck, enabling observations of the lower atmosphere that are not possible at wavelengths strongly absorbed by the clouds [Robert et al., 2024; Neefs et al., 2025].

These measurements can involve relatively weak radiometric signals. The scientific requirements consequently impose stringent signal-to-noise performance on the instrument, particularly for the detection and quantification of minor atmospheric constituents. The radiometric calibration must therefore establish the instrument response with sufficient accuracy and stability

to ensure that variations in the measured signal can be attributed to the observed scene rather than to uncertainties in the instrument response [Robert et al., 2024].

The four VenSpec-H spectral bands cover approximately 1165–1180 nm, 1370–1390 nm, 1720–1750 nm and 2340–2480 nm. They address complementary scientific objectives and correspond to different atmospheric transmission and radiometric regimes [Robert et al., 2024; Neefs et al., 2025]. The calibration system must consequently provide adequate radiometric margin over the complete spectral range while maintaining a stable and accurately characterized output.

For the OGSE, this requirement leads to the use of an extended-area blackbody as the primary radiometric source. The source must provide sufficiently high and accurately known radiance, together with high spatial uniformity over the instrument field of view and excellent temporal stability. These characteristics are essential because the source constitutes the reference against which the radiometric response of VenSpec-H is established.

The same source must also support detector response characterization. Variations in source output during a measurement sequence must remain sufficiently small compared with the signal variations being characterized. The stability and repeatability of the extended-area blackbody therefore become direct contributors to the calibration uncertainty budget.

Temporal stability is equally important, since variations in source output during an acquisition sequence would be indistinguishable from changes in instrument response. The calibration source must therefore provide a stable and repeatable radiometric reference over the duration of the measurements.

The required radiance is driven by the signal-to-noise performance of VenSpec-H. In particular, the weak signals available through the Venusian infrared windows make the available photon flux a critical parameter. The OGSE must consequently provide sufficient radiometric margin to enable the instrument response to be characterized with significantly better accuracy than would be possible at marginal signal levels.

The same considerations apply to the characterization of detector response and linearity. The OGSE must be capable of generating repeatable illumination conditions over a suitable radiometric range, allowing detector response to be distinguished from variations in the calibration source. The resulting source performance therefore directly contributes to the uncertainty budget of the instrument calibration.

2.2 Spectral calibration and ISRF characterization

The high spectral resolution of VenSpec-H is central to its scientific objectives. The instrument employs an echelle grating-based spectrometer and operates between approximately 1.15 and 2.5 μm , with the spectral bands selected to target molecular absorption features associated with the Venusian atmosphere [Neefs et al., 2025]. Accurate knowledge of the wavelength scale and of the instrument spectral response function (ISRF) is therefore essential for the interpretation of the acquired spectra [Robert et al., 2024; Neefs et al., 2025].

The calibration of a high-resolution spectrometer requires narrow spectral stimuli whose spectral width is significantly smaller than the instrument response. The use of narrow-line sources is well established in the calibration of planetary infrared spectrometers. The NOMAD calibration campaign, for example, included detailed characterization of the spectral response and instrument line shape, demonstrating the importance of accurately determining the spectral response of high-resolution infrared channels [Thomas et al., 2022].

For VenSpec-H, DFB laser sources were selected as the basis of the narrow spectral source subsystem. Their narrow linewidth and wavelength stability make them suitable for generating discrete spectral references across the four science bands. The OGSE must, however, provide not only wavelength accuracy but also sufficient optical radiance to generate a useful detector signal.

In general, the spectral response measured by the detector results from the convolution of the source spectral distribution with the instrument spectral response function (ISRF). When the spectral width of the source is significantly smaller than that of the ISRF, as is the case for the laser sources used in the VenSpec-H OGSE, the source spectrum can be approximated as a Dirac delta function. Under this approximation, the measured signal at a given detector position provides a direct sampling of the ISRF at the corresponding source wavelength. The narrow-line source therefore acts as a localized spectral probe of the instrument response, enabling the characterization of the ISRF and the spectral calibration of the instrument.

This property makes narrow-line sources particularly suitable for the spectral characterization of high-resolution spectrometers. For VenSpec-H, DFB laser sources were therefore selected as the basis of the Spectral Source sub-system. Their narrow linewidth and wavelength stability make them suitable for generating discrete spectral references across the four

science bands. The OGSE must, however, provide not only adequate wavelength accuracy but also sufficient optical radiance to generate a useful detector signal.

Preliminary simulations performed during the OGSE development quantified this effect and shown sufficient radiance for the requested SNR for the characterization (SNR of approximately 1000 is required for the spectral calibration measurements). This analysis established a substantially higher radiance requirement for the DFB laser subsystem and became an important driver for its optical design.

This result is specific to the development and characterization of the VenSpec-H OGSE and complements the existing publications on the VenSpec-H instrument, which focus primarily on its scientific objectives, requirements, design, and critical instrument elements. It illustrates, however, how the published instrument requirements translate into concrete optical-source requirements for the ground calibration equipment.

The DFB laser subsystem must consequently combine narrow spectral linewidth and wavelength stability with adequate radiometric margin. Beam conditioning, optical coupling and source monitoring must be designed accordingly. The narrow spectral source is therefore not simply a wavelength reference; its radiometric performance is an integral part of the spectral calibration strategy.

2.3 Field-of-View Mapping and Line-of-Sight Determination

The VenSpec-H optical system has a highly elongated field of view of approximately 7° in the spectral direction and 0.2° in the spatial direction [Neefs et al., 2025]. This geometry is closely related to the nadir observation concept and to the way spatial and spectral information are distributed on the detector.

For the OGSE, the elongated field of view means that the determination of the instrument line-of-sight (LoS) and boresight cannot be reduced to a single measurement. The instrument response must instead be sampled at different positions across the relevant field in order to determine the actual field-of-view position and verify the expected LoS behaviour. This requires a compact optical source that can be accurately translated across the instrument field.

A small, high-radiance source mounted on precision XY translation stages is therefore required. The source must be sufficiently compact to provide a localized stimulus while maintaining sufficient radiance to generate a high-quality detector signal. Its position must be accurately known and repeatable throughout the scanning process.

Temporal stability is also critical. A complete field-of-view mapping sequence can extend over approximately thirty minutes, during which any variation in source output could be interpreted as a variation of the instrument response with position. The stability requirement of the source is therefore directly coupled to the accuracy of the field-of-view mapping and LoS determination. The micro-blackbody and its positioning system are consequently treated as an integrated calibration subsystem rather than as an independent source and mechanical stage.

The same scanning source can also support boresight determination and selected straylight measurements. This multifunctional use is one of the key drivers for the modular architecture of the OGSE, allowing a single compact source to perform several measurements requiring a localized, high-radiance stimulus.

It should be noted that this OGSE is not intended to characterize the imaging performance of the VenSpec-H instrument. In particular, parameters such as the point-spread function (PSF), modulation transfer function (MTF), or other image-quality metrics are outside the scope of the measurements enabled by this OGSE.

2.4 Polarization characterization

Polarization constitutes an additional dimension of the VenSpec-H characterization. The Venusian cloud system produces partially polarized radiation, and polarization-dependent effects are relevant to the interpretation of observations made by infrared and polarimetric instruments [Neefs et al., 2025].

From the calibration perspective, the instrument response must therefore be characterized for controlled input polarization states. A calibration source with a known and repeatable linear polarization state is required to determine the dependence of the measured signal on polarization orientation.

The OGSE implements this capability through a rotatable linear polarizer integrated into the radiometric optical path. The polarizer must provide adequate polarization purity and transmission over the VenSpec-H spectral range, while its angular position must be accurately known and repeatable.

The integration of the polarizer into the radiometric path also imposes an architectural constraint. Polarization measurements must be performed without compromising the spatial uniformity and radiometric stability required for the conventional radiometric calibration. The polarizer must therefore be introduced into the common optical path in a controlled manner while preserving the established optical alignment.

2.5 Optical path and environmental constraints

The physical configuration of the ground calibration campaign introduces a further set of constraints that are specific to the OGSE. VenSpec-H is operated inside a thermal-vacuum chamber during the calibration campaign, while the optical sources remain outside the chamber. The calibration radiation must consequently propagate from the external OGSE, through an infrared-transparent chamber window, and into the instrument entrance aperture.

This configuration creates a relatively long external optical path between the sources and the instrument ($\sim 1\text{m}$) and imposes stringent requirements on optical alignment, field-of-view coverage and mechanical stability. The OGSE must maintain the required relative geometry throughout the calibration campaign while allowing different optical sources to be selected and operated without compromising the established alignment.

A further challenge is introduced by atmospheric absorption along this external optical path. The VenSpec-H science bands lie in the near-infrared spectral region where water vapour produces significant absorption features. Such absorption would modify the spectral content of the calibration stimulus before it reaches the instrument and could therefore introduce systematic errors into both radiometric and spectral calibration.

This is particularly relevant because VenSpec-H itself exploits selected near-infrared atmospheric transmission windows for its scientific observations [Robert et al., 2024; Neefs et al., 2025]. The calibration system must therefore preserve the spectral fidelity of the source between its generation and the instrument entrance aperture.

The solution adopted for the OGSE is to enclose the complete optical path within a dedicated purge enclosure continuously flushed with dry nitrogen. Reducing the concentration of water vapour around the optical beam minimizes parasitic atmospheric absorption and ensures that the spectral stimulus delivered to the instrument remains representative of the intended calibration source.

The purge enclosure is consequently an integral part of the OGSE optical architecture rather than simply an environmental protection enclosure. It must accommodate the optical sources (not the DFB Laser) and beam-conditioning elements while maintaining the required enclosed volume, purge efficiency and optical alignment.

2.6 Consequences for the OGSE architecture

The calibration challenges described above lead directly to the principal architectural characteristics of the VenSpec-H OGSE. First, the system must provide fundamentally different classes of optical stimulus (sources). An extended, spatially uniform and highly stable source is required for radiometric calibration and detector characterization. Narrow-line sources are required for wavelength calibration and ISRF characterization. A compact, high-radiance scanning source is required for field-of-view mapping, boresight determination and selected straylight measurements. A controlled polarization capability must additionally be integrated into the optical path.

Second, these sources must operate within a common optical environment that preserves the spectral fidelity of the calibration stimulus. The thermal-vacuum interface, infrared-transparent chamber window and relatively long external optical path make mechanical stability and alignment essential. The nitrogen-purged enclosure is required to suppress atmospheric water-vapour absorption and therefore forms part of the optical calibration chain.

Third, the different calibration functions impose different temporal and spatial stability requirements. The extended-area blackbody must remain stable and uniform during radiometric measurements; the DFB laser subsystem requires accurate wavelength and optical-power control; and the micro-blackbody requires precise spatial positioning and radiance stability during scanning measurements. These requirements motivate a common monitoring and control infrastructure capable of coordinating the optical sources, positioning mechanisms and acquisition sequences.

The resulting architecture is therefore not a conventional single-source calibration bench. It is a modular system in which complementary optical sources, precision opto-mechanical mechanisms, environmental control and dedicated monitoring are combined to reproduce the optical stimuli required by the complete VenSpec-H calibration campaign.

The next section describes the resulting OGSE architecture and the implementation of these complementary calibration functions within a single integrated system.

3. VENSPEC-H OGSE ARCHITECTURE

The calibration requirements described in the previous section led to the development of a modular Optical Ground Support Equipment (OGSE) architecture capable of generating the different optical stimuli required for the VenSpec-H calibration and characterization campaign. Rather than relying on a single calibration source, the architecture combines complementary radiometric, spectral and spatial stimuli within a common optical and environmental framework.

The architecture was developed around four principal optical functions: an extended-area blackbody for radiometric calibration, a narrow spectral source based on infrared DBF lasers for spectral calibration and instrument spectral response characterization, a compact high-temperature source (called micro-blackbody source) for field-of-view measurements (and possibly straylight measurements), and a polarization characterization capability based on a rotatable linear polarizer. These functions are supported by a common opto-mechanical structure, a nitrogen-purged enclosure, dedicated positioning mechanisms and an Electrical Ground Support Equipment (EGSE) providing control, monitoring and test automation.

LusoSpace has been a member of the VenSpec-H consortium since the Phase A of the EnVision mission. This early involvement has provided a continuous opportunity to discuss the instrument requirements and calibration needs with the VenSpec-H team and, in particular, with the Royal Belgian Institute for Space Aeronomy (BIRA-IASB, Belgium), under the support and coordination of the European Space Agency (ESA). This close interaction between the instrument and OGSE teams has been essential in translating the scientific and instrument-level objectives of VenSpec-H into practical requirements for the ground calibration system.

Over the course of the development, the OGSE architecture has consequently evolved through an iterative process involving requirement analysis, optical modelling, preliminary design activities and technical discussions with the instrument team. This process has allowed the architecture to be progressively adapted to the needs of the instrument, while also taking into account the practical constraints associated with the thermal-vacuum calibration configuration, the available optical sources and the required calibration sequences.

It is important to emphasize that the OGSE development is still ongoing. The architecture presented in this paper represents the outcome of several months of design and technical assessment and is sufficiently mature to demonstrate the adopted design philosophy and the main solutions developed to address the VenSpec-H calibration needs. Nevertheless, some elements remain subject to further analysis, verification and optimization. Consequently, the architecture shown in this section should be regarded as the current baseline rather than as the final flight-support configuration.

Figure 1 presents an early Computer-Aided Design (CAD) representation of the OGSE architecture. This configuration illustrates the initial concept in which the different calibration functions were integrated into a single compact platform enclosed within a common nitrogen-purged volume. The front opening provides the optical interface towards the VenSpec-H instrument, while the three principal calibration configurations: radiometric, spectral and bright-source, are accommodated within the same overall architecture.

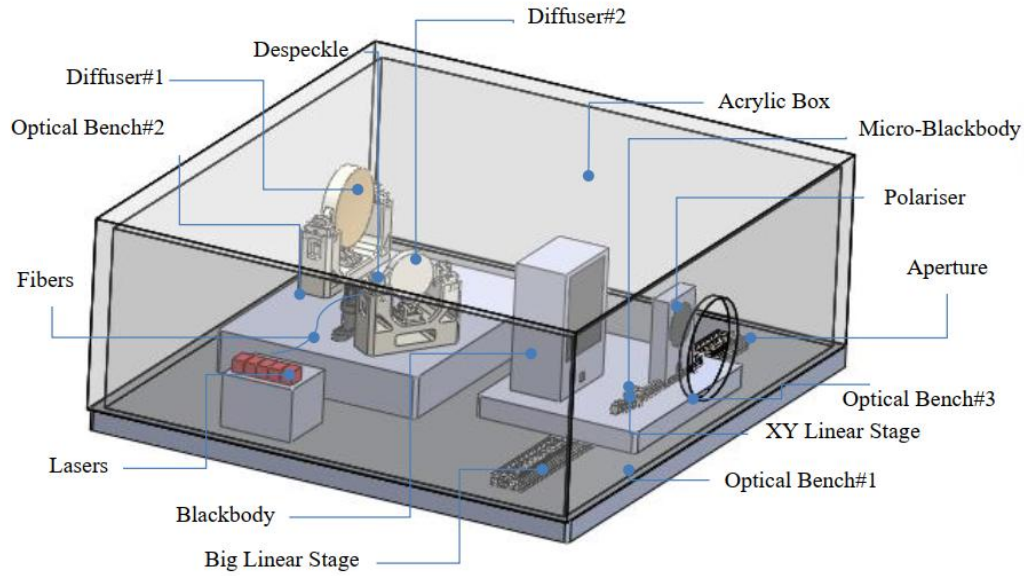


Figure 1 - First architecture approach

In this early configuration, the extended-area blackbody, the narrow spectral source and the scanning bright source are integrated within the same enclosure, illustrating the basic architectural concept that has remained central to the OGSE development: three complementary optical calibration functions implemented on a common platform. The figure also shows the initial arrangement of the laser sources inside the purge enclosure.

As discussed in the following sections, this configuration subsequently evolved as the optical and mechanical designs were refined. In particular, the location of the laser sources was reconsidered, leading to their separation from the main purged optical volume. Other significant changes also resulted from the progressive assessment of the optical path, source performance, mechanical positioning requirements and environmental constraints. These changes are part of the normal iterative development process and illustrate how the OGSE architecture has been progressively consolidated through the interaction between instrument requirements and subsystem-level engineering. The architecture presented in the remainder of this section should therefore be understood not as a fixed design from the outset, but as the result of an iterative process in which the calibration requirements of VenSpec-H have been progressively translated into an integrated ground-support system.

This approach follows the general philosophy adopted for the ground characterization of previous high-resolution planetary infrared spectrometers such as NOMAD, where radiometric, spectral, geometric and detector-related measurements required dedicated calibration configurations [Thomas et al., 2022a; Thomas et al., 2022b]. For VenSpec-H, however, the source architecture was specifically adapted to the four science bands, the elongated field of view and the external-to-TVAC optical configuration described in Section 2.

3.1 Overall architecture

The OGSE architecture is organized into three dedicated optical source sub-systems, integrated on a common support structure and enclosed, where required, within a nitrogen-purged optical box. The three optical functions are the Spectral Source sub-system, the Radiometric Source sub-system and the Small Bright Source sub-system. A dedicated Support Structure sub-system provides the common mechanical reference and positioning interfaces, while a Central Control PC provides command, monitoring and test automation.

Figure 2 shows a representation of the architecture. The concept integrates the three calibration configurations on a single platform, while maintaining a well-defined optical interface towards the VenSpec-H instrument installed inside the thermal-vacuum chamber. This arrangement follows directly from the different optical stimuli identified in Section 2 and provides a common geometrical reference for the calibration activities.

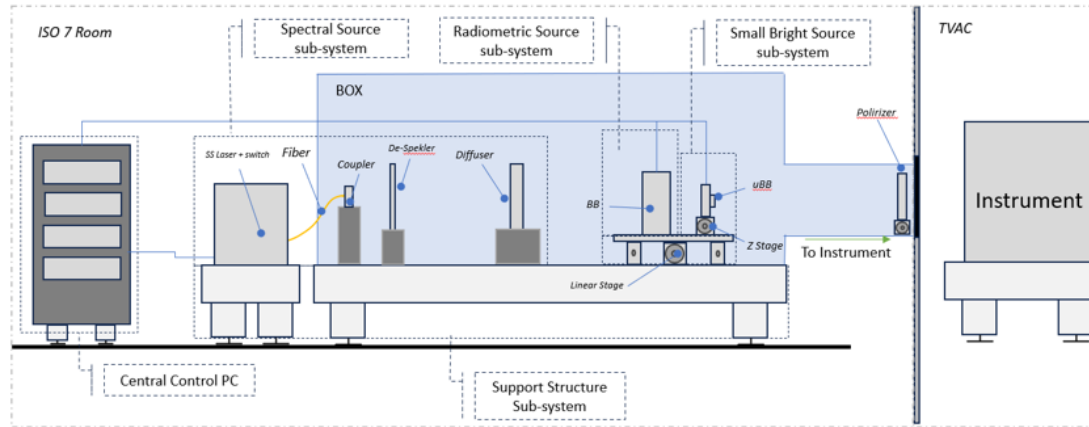


Figure 2 - Present architecture concept.

Figure 2 intermediate OGSE architecture showing the Spectral Source, Radiometric Source and Small Bright Source sub-systems integrated on a common support structure. The optical sources are located in an ISO 7 room, while VenSpec-H is installed inside the thermal-vacuum chamber. The figure represents an intermediate stage of the ongoing OGSE development. The architecture shown in Figure 2 should be considered an intermediate design stage rather than the final configuration. In particular, the laser sources are shown inside the general source area but are subsequently separated from the purged optical volume, with the laser radiation transported to the optical bench through fibres. Other details of the optical and mechanical arrangement have also evolved as a result of the ongoing optical analyses, breadboarding and interaction with the VenSpec-H team.

The three source sub-systems share the same basic optical reference and are positioned along the common support structure. This allows the calibration configuration to be changed while preserving the overall OGSE-to-instrument geometry. The following sections describe the function and implementation of each sub-system.

3.2 Spectral Source sub-system

The Spectral Source sub-system provides the narrow-band optical stimuli required for wavelength calibration and characterization of the VenSpec-H spectral response. Its design has to reconcile two different aspects of the calibration stimulus: the spectral properties of the source must remain well defined, while the spatial distribution at the instrument entrance pupil must be sufficiently homogeneous and cover the complete VenSpec-H field of view.

The adopted architecture consists of several narrow-line infrared sources followed by a wavelength-selection stage and a common optical-conditioning chain. The selected wavelength is coupled into a multimode fibre and transported to the OGSE optical bench, where the radiation is spatially conditioned before being directed towards the instrument. This arrangement also allows the laser sources to be located outside the main nitrogen-purged optical volume, as shown in the overall OGSE architecture in Figure 2.



Figure 3 – Spectral Source sub-system preliminary design.

Figure 3 showing the wavelength sources, selection stage, fibre interface, de-speckling element and diffuser chain.

The spectral source must provide at least one suitable wavelength within each of the four VenSpec-H science bands, with sufficient wavelength accuracy and stability for spectral calibration. The required spectral radiance is also significantly higher than the broadband-equivalent values might suggest. As discussed in Section 2, the VenSpec-H simulator showed that the signal generated by a narrow laser line depends on its position relative to the detector sampling and on the convolution with the instrument spectral response. The resulting SNR requirement therefore becomes a significant driver of the spectral source

design. The requirement analysis performed jointly during the OGSE development established a target SNR of approximately 1000 per relevant detector pixel, leading to substantially higher source radiance than a simple comparison with the broadband source would indicate

The selected DFB lasers provide an output power between 3 and 10 mW.

3.2.1 Spatial conditioning and speckle reduction

A major difference between the spectral and radiometric sources is the spatial coherence of the radiation. Laser illumination can produce speckle patterns at the instrument pupil, resulting in spatial intensity fluctuations that may be interpreted as non-uniformity of the calibration source.

The adopted solution combines two complementary mechanisms. First, the use of multimode fibre transport reduces the spatial coherence of the laser beam. Second, a dynamic diffusing element is introduced after the fibre. The latter continuously changes the optical phase distribution and consequently generates a sequence of different speckle patterns. During the detector integration, these patterns are averaged, reducing the resulting spatial modulation.

This approach was selected following the analysis of several possible solutions and is consistent with LusoSpace heritage from previous infrared calibration systems.

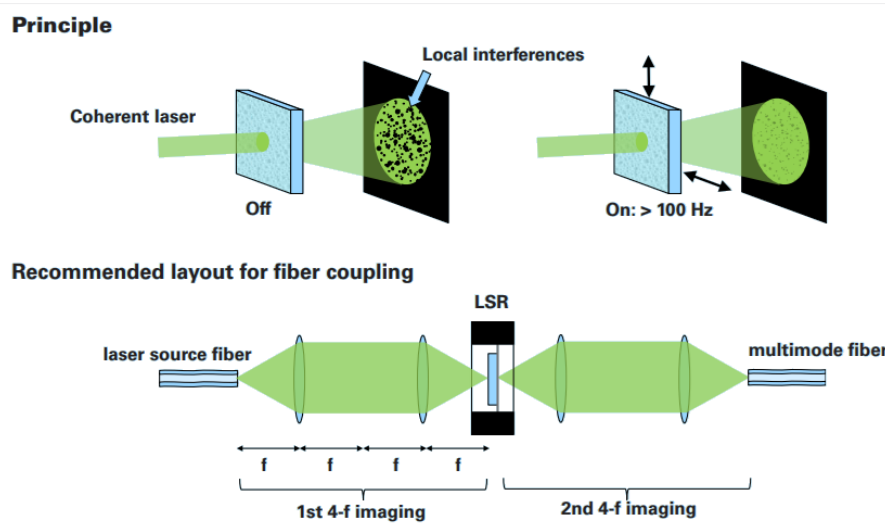


Figure 4 – principle of dynamic speckle.

Figure 4, The diffuser generates temporally varying speckle patterns that are averaged during the detector integration.

The effectiveness of this approach depends on the relationship between the temporal behaviour of the diffuser and the instrument integration time. Sufficiently rapid variation of the speckle pattern is required for temporal averaging to occur during the acquisition. This parameter is therefore considered together with the VenSpec-H acquisition conditions in the ongoing verification activities.

The OGSE development documentation also reports experimental heritage demonstrating the reduction of speckle using dynamic diffusion after multimode fibre propagation.

3.2.2 FoV coverage and angular distribution

Once the laser radiation has been spatially scrambled, the next challenge is to generate an angular distribution compatible with the highly elongated VenSpec-H field of view. The spectral source is required to illuminate the complete FoV, either instantaneously or through a controlled sequence, while maintaining an adequate spatial uniformity across the illuminated area. The current OGSE requirements specify an angular coverage of approximately $7^\circ \times 0.2^\circ$ at the OGSE exit pupil.

The adopted solution uses a single large-area transmissive diffuser downstream of the dynamic de-speckling stage. Its purpose is to transform the conditioned laser beam into an extended angular distribution capable of covering the required instrument FoV. The diffuser also contributes to spatial homogenization, complementing the speckle reduction already provided by the multimode fibre and dynamic de-speckler.

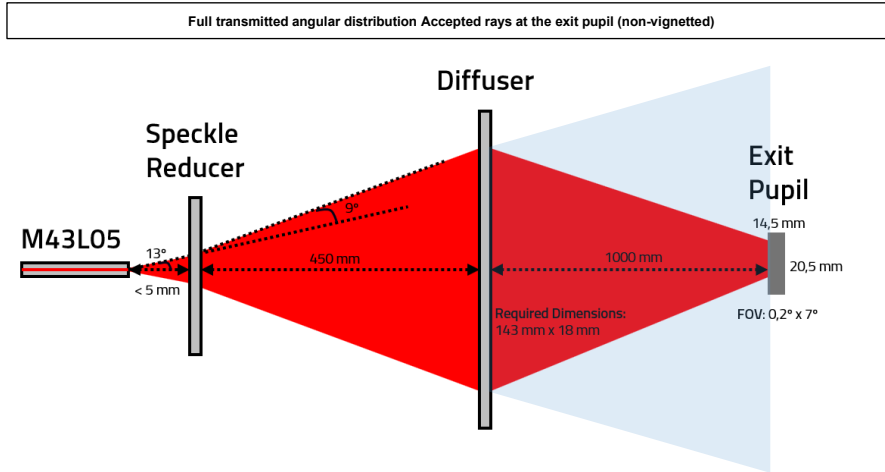


Figure 5 –Diffuser system (not scaled). Full angular distribution after the diffuser, blue region : Rays reaching the exit pupil (non-vignetted). The red region represents only the portion of the transmitted diffuser output that is accepted by the exit pupil.

Figure 5 shown the diffusive system adopted for the Spectral Source sub-system, showing the large-area diffuser used to generate the angular distribution required for VenSpec-H field-of-view coverage. In Figure 5, the blue region represents the full angular distribution of the light transmitted by the diffuser, while the red region represents only the portion of this distribution that reaches the exit pupil without being vignetted by its aperture. The red region should therefore not be interpreted as a converging beam generated by the diffuser.

The size of the diffuser is directly related to the distance between the OGSE and the instrument. For a given angular extent and pupil size, the required transverse dimension increases with the propagation distance. In the paraxial approximation, the relationship can be expressed as

$$D \cong 2L \tan\left(\frac{\theta}{2}\right),$$

Where D is the required transverse dimension, L is the propagation distance and θ is the required angular extent.

The preliminary optical analyses investigated this relationship for several possible working distances. For the initial 1 m configuration, a diffuser diameter of approximately 143mm x 18mm was found sufficient for the required angular coverage. This result was an important contributor to the subsequent OGSE architecture trade-off. Increasing the distance between the OGSE and the instrument does not simply modify the mechanical layout; it propagates into the optical source dimensions and therefore into the size of the enclosure and support structure.

The current design uses a diffuser with an active area sufficient to cover the required angular distribution for the baseline configuration, while maintaining adequate transmission across all VenSpec-H science bands. The selected diffuser concept is based on a transmissive glass element with a diffusing surface. Importantly, the diffuser is not intended to reproduce the spatial characteristics of the laser source itself. Its role is to provide the required angular étendue at the instrument interface. The optical design therefore considers the source area and angular distribution together, rather than treating the FoV coverage as a purely geometrical projection problem.

3.2.3 Spatial uniformity

The use of a diffuser to generate the required angular distribution introduces a second aspect of the optical design: spatial uniformity.

The spectral source requirements distinguish between the spatial non-uniformity associated with speckle over a single pixel and the overall non-uniformity across the complete FoV. The current requirements specify limits of 0.1% for the speckle contribution over a single pixel and 20% for the overall FoV uniformity.

The mitigation strategy therefore does not rely on the large diffuser alone. The multimode fibre provides an initial reduction in spatial coherence, while the dynamic de-speckler as mentioned before, generate time-varying fields from the remaining coherent interference pattern before the beam reaches the large-area diffuser.

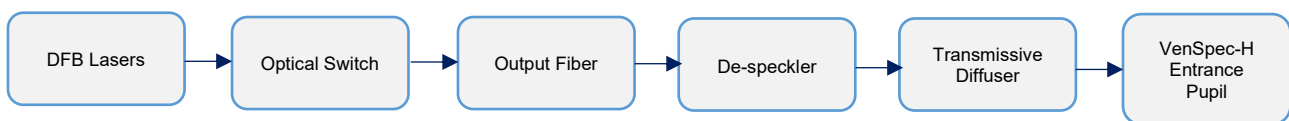
The internal analysis combines these two mechanisms to estimate the residual contrast for the four (Band 2 is separated into 2a and 2b) science bands. Using a conservative effective number of fibre modes, together with the expected number of statistically different patterns generated by the dynamic diffuser, the predicted residual contrast remains at the level of a few percent or below, depending on wavelength.

These values should be regarded as design predictions rather than measured performance. The final spatial uniformity can only be established after implementation and alignment of the complete spectral source. This distinction is important because the residual speckle depends on the actual optical coupling, diffuser behaviour, detector integration conditions and alignment of the assembled system.

The OGSE verification plan therefore includes a dedicated measurement of the spectral-source FoV uniformity, using a small-area detector scanned across the output field.

3.2.4 Current optical configuration

The resulting Spectral Source optical chain is therefore deliberately simple in terms of the number of optical conditioning elements:



Each element has a specific role. The laser sources provide the narrow spectral lines; the optical switch selects the wavelength; the multimode fibre provides optical transport and partial spatial scrambling; the dynamic de-speckler reduces the residual coherent speckle; and the final diffuser provides the angular distribution required to illuminate the complete VenSpec-H FoV. This architecture represents an evolution from the earlier preliminary concept, in which two reflective diffusive elements were considered. The current design consolidates the angular spreading function into a single large-area diffuser, while retaining the dynamic de-speckling stage as a separate function. This simplification reduces the number of optical surfaces and therefore avoids unnecessary transmission losses while maintaining the required angular coverage.

The final performance will depend on the measured properties of the assembled optical chain rather than on the individual component specifications alone. For this reason, the remaining development activities focus on the experimental verification of the combined source, including spectral throughput, FoV coverage, spatial uniformity and residual speckle.

3.3 Radiometric Source sub-system

The Radiometric Source sub-system provides the broadband, spatially extended and temporally stable illumination required for radiometric calibration and detector characterization of VenSpec-H. It is also used, in combination with a controllable linear polarizer, for the characterization of the instrument response to polarized radiation.

The sub-system is based on an extended-area high-temperature blackbody positioned directly in the OGSE optical path. Unlike the Spectral Source sub-system, no beam-conditioning optics are required between the blackbody and the instrument. This direct configuration minimizes additional transmission losses and avoids introducing spectral or spatial effects from intermediate optical elements (unless the TVAC optical window). The blackbody is mounted on the common positioning stage so that it can be moved out of the instrument field when another source configuration is selected. The overall functional decomposition of the OGSE identifies the blackbody and polarizer as the two elements of the Radiometric Source sub-system.

3.3.1 Radiometric requirements and source selection

The main requirements driving the radiometric source are spectral radiance, temporal stability, spatial uniformity and instantaneous FoV coverage. The source shall provide the required radiance levels within the four VenSpec-H science bands, remain stable over the calibration period and illuminate the complete instrument FoV.

The current requirements specify a radiance capability within $\pm 50\%$ of the reference values, a radiometric stability better than 1% over 30 min and a spatial uniformity better than 1% across the instrument FoV. The required instantaneous angular coverage is approximately $7^\circ \times 0.2^\circ$.

An extended-area blackbody was selected because it combines these characteristics in a single source. The proposed source provides a sufficiently large emissive area while allowing the emitted radiance to be controlled through the source temperature. The source operates at ambient pressure and temperature conditions, with the emissive surface temperature monitored by an integrated calibrated sensor.

The radiance of the blackbody source is primarily controlled through its operating temperature, while the actual spectral radiance also depends on the source emissivity. This relationship provides the basis for selecting the appropriate operating temperature for each calibration condition and ensuring the required radiance level at the instrument entrance.

The analysis shows that the proposed source can reproduce the required reference radiances across the VenSpec-H bands by adjusting its operating temperature. The required temperatures range from relatively low values for the low-radiance night-side conditions to substantially higher temperatures for the dayside measurements, with the shortest-wavelength dayside band representing the most demanding case.

The latter case is also an important design margin to be verified during the subsequent development. This aspect is therefore treated as part of the system-level radiometric verification rather than being considered solely from the nominal source specification.

3.3.2 FoV coverage and emissive area

The large angular extent of the VenSpec-H FoV is a direct driver for the required emissive area of the blackbody. For the baseline OGSE-to-instrument distance considered in the current architecture, the analysis established that the required emitting footprint is substantially smaller than the available emissive surface of the selected blackbody. The available area therefore provides margin for the geometrical coverage of the VenSpec-H entrance pupil.

The analysis also illustrates the strong coupling between working distance and source size. Increasing the separation between the OGSE and the instrument would require a larger emitting area to preserve the same angular coverage. The working-distance trade therefore affects not only the mechanical envelope but also the radiometric source itself. This is particularly relevant for the VenSpec-H configuration because the FoV is strongly asymmetric. The long dimension dominates the required source footprint, leading to an elongated illuminated region on the blackbody surface.

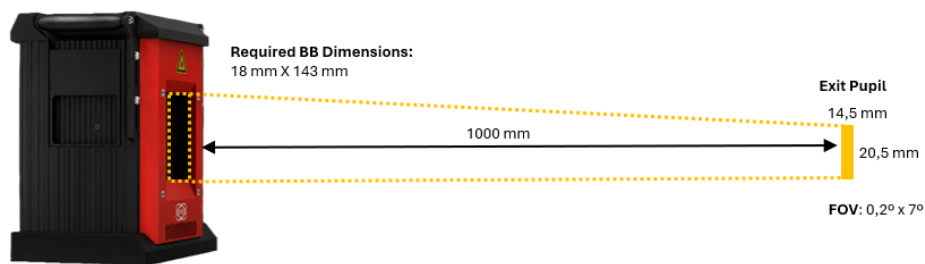


Figure 6 – Required blackbody dimensions (not scaled).

Figure 6 Geometrical relationship between the VenSpec-H field of view and the required radiating area of the extended-area blackbody.

The final source therefore provides the required angular coverage without requiring additional imaging or collimation optics. This direct illumination approach also contributes to the simplicity of the radiometric path.

3.3.3 Radiometric uniformity and stability

Uniformity and stability are fundamental properties of the radiometric source because variations in the source would otherwise be indistinguishable from variations in detector response.

During the preliminary design period, evaluation of the spatial uniformity of the blackbody through the temperature distribution over its emissive area, has been performed. At the considered operating condition, the predicted peak-to-valley variation of the corresponding spectral radiance remains below the 1% requirement. Similarly, the source temperature stability leads to a predicted radiometric variation significantly below the 1% requirement over the specified period.

The relationship between temperature stability and radiometric stability is particularly important for a thermal source. Since the emissivity of the surface can be considered stable over the calibration interval, changes in emitted radiance are primarily driven by changes in the emissive temperature. The integrated temperature monitoring therefore provides a direct means of monitoring the source radiometric stability.

The final verification will nevertheless be performed at system level. The manufacturer-provided source characterization will be combined with OGSE-level measurements to establish the radiometric performance in the actual calibration configuration.

3.3.4 Linear polarizer

The Radiometric Source sub-system also incorporates a controllable linear polarizer for polarization characterization of VenSpec-H.

The polarizer is mounted on a motorized rotation mechanism and can be positioned in front of the blackbody. The rotation mechanism provides continuous angular positioning, while the calibration procedure requires defined angular sampling. The current design specifies angular increments of 5° , a relative angular accuracy better than 0.1° , and an absolute angular accuracy better than 1° .

Because the VenSpec-H FoV is significantly larger than the polarizer aperture, the polarizer is mounted on an XY positioning mechanism. This allows the polarized illumination to be scanned across the instrument FoV rather than requiring a single polarizer large enough to cover the complete field instantaneously.

The polarizer therefore performs two independent functions within the calibration architecture: its rotational degree of freedom defines the polarization orientation, while its translational positioning provides spatial coverage of the instrument field.

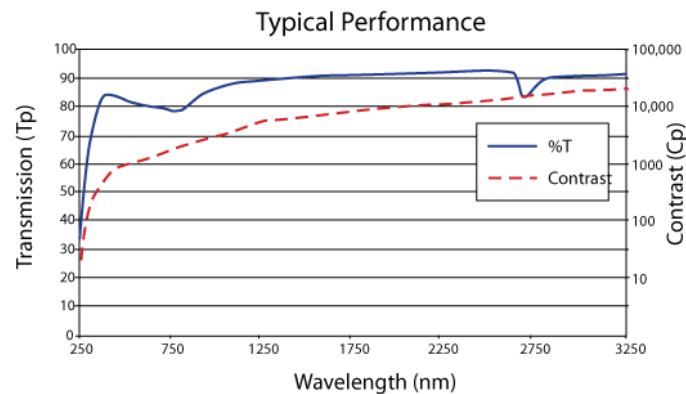


Figure 7 – Polarizer transmission. @ Edmund Optics

Figure 7 shown the transmission characteristic of the selected linear polarizer over the relevant spectral range.

The use of the same XY positioning capability associated with the small bright source also provides a degree of architectural commonality between the two calibration functions. The final mechanical implementation and interface allocation remain part of the ongoing OGSE development.

3.3.5 Thermal contribution

The high operating temperature of the blackbody introduces a specific integration constraint within the common OGSE architecture. Although the blackbody itself operates outside the thermal-vacuum chamber, its elevated emissive temperature can produce radiative loading on nearby OGSE components.

The design consequently considers thermal isolation between the blackbody and the surrounding mechanical structure, while avoiding unnecessary radiation towards components that are not involved in the radiometric measurement. The current design description identifies local radiative isolation as a potential implementation approach.

This aspect is particularly important because the radiometric source is integrated together with the spectral and small bright source configurations. Thermal management must therefore preserve the operating conditions of the remaining OGSE components without compromising the direct optical path.

3.4 Small bright Source sub-system

The Small Bright Source sub-system provides a localized, high-radiance stimulus that can be scanned across and outside the VenSpec-H field of view. Its purpose is fundamentally different from that of the extended-area blackbody: rather than illuminating the complete FoV uniformly, it generates a spatially localized stimulus whose known position can be used to characterize the spatial response of the instrument.

The current architecture combines a small thermal infrared (called micro-blackbody) source with a two-axis positioning mechanism. The source and positioning system are treated as a single functional sub-system, allowing the source to be translated in the two orthogonal directions required for field mapping.

3.4.1 Thermal contribution

The main requirements driving the Small Bright Source are source brightness, source stability, limited apparent angular size, scanning range and positional accuracy.

The source must remain sufficiently small compared with the VenSpec-H FoV, with an angular position coverage of approximately in the two scanning directions.

These requirements make the positioning system as important as the source itself. The calibration measurement is based on the known relationship between the source position and the instrument response; consequently, uncertainty in source position directly contributes to the uncertainty of the resulting spatial calibration.

3.4.2 Localized thermal source

The source is based on a small thermal emitter illuminating a defined target pattern, forming a micro-blackbody stimulus. The target pattern provides the effective emitting area, while the thermal emitter supplies the required infrared radiance.

The source temperature can be adjusted through the electrical power applied to the emitter. The design therefore allows the source radiance to be adapted to the different measurement conditions while maintaining a compact emitting area. The current design specifies a target temperature above 900 K and adjustable operation around the nominal value.

The source is operated in power-regulated mode to mitigate the effect of resistance changes during operation. Previous measurements performed for another project, showed that stable operation over several minutes is achievable, although the final stability performance will be established with the integrated source.

This source architecture provides a useful compromise between radiance and apparent angular size. A sufficiently bright source is required to maintain measurement SNR when the illuminated area is intentionally small, while the emitting region must remain small enough to act as a localized spatial probe.

3.4.3 Angular size and spatial resolution

At the nominal OGSE-to-instrument distance, the apparent size of the micro-blackbody remains substantially smaller than the complete VenSpec-H FoV.

This characteristic is important for several calibration activities. By moving the source across the field, the instrument response can be sampled at different angular positions, allowing the spatial extent and shape of the response to be reconstructed. The source can also be moved outside the nominal FoV. This capability extends the measurement range beyond the illuminated science field and supports measurements related to off-axis response and straylight.

3.4.4 XY scanning mechanism

The micro-blackbody is mounted on two orthogonal linear axes. The positioning mechanism provides the angular scanning capability required by the instrument calibration geometry.

For the nominal working distance, the design analysis establishes the required mechanical travel from the angular scanning range. The mechanism is dimensioned to cover the required angular range while maintaining the specified positional accuracy. The transformation between mechanical displacement and angular position is approximately

$$\theta = \tan^{-1}\left(\frac{x}{L}\right),$$

Where x is the transverse source displacement and L is the source-to-instrument distance.

This relationship also illustrates the sensitivity of the mechanical design to the working distance. Increasing L increases the required transverse displacement for the same angular coverage, which directly affects the size of the positioning mechanism and the overall OGSE envelope.

The use of two independent axes allows the source to generate a two-dimensional spatial scan. This capability is particularly useful for mapping the response of individual detector rows and for determining the instrument boresight.

3.4.5 Calibration applications

The Small Bright Source provides three principal capabilities.

First, scanning the source through the nominal FoV allows the spatial response of the instrument to be mapped. Secondly, the location of the maximum or reference response can be used to determine the boresight relative to the OGSE reference frame. Finally, moving the source outside the nominal field provides a controlled localized stimulus for investigating off-axis response and straylight.

These measurements are complementary to those performed with the extended-area blackbody. The radiometric source establishes the response under spatially extended illumination, whereas the Small Bright Source probes the instrument response as a function of angular position.

4. VERIFICATION STRATEGY

The verification philosophy of the OGSE follows a combination of supplier characterization, analysis and system-level measurement. This approach reflects the different nature of the requirements associated with the three source sub-systems.

For parameters intrinsic to commercial source components, such as blackbody temperature, emissivity or source characteristics, available supplier characterization can be incorporated into the OGSE performance and uncertainty budgets. For parameters that depend on the integration of several components, such as FoV coverage, spatial uniformity, source stability or positional accuracy, verification is performed at OGSE level. The Design Description explicitly identifies these two complementary verification approaches.

4.2 Spectral Source verification

The Spectral Source verification combines supplier characterization of the narrow-band sources with OGSE-level measurements of the complete optical chain.

The principal parameters are:

- spectral bandwidth;
- central wavelength and wavelength accuracy;
- wavelength stability;
- source radiance;
- optical throughput;
- FoV coverage;
- spatial uniformity;
- residual speckle.

The last three parameters are particularly important because they cannot be inferred from the laser source alone. They depend on the combined performance of the fibre, dynamic de-speckling stage and single diffuser.

The FoV uniformity will therefore be measured at the OGSE output using a small-area detector scanned over the relevant angular range

4.3 Radiometric source verification

The radiometric source will be verified through four principal measurements:

- **Radiance:** verification of the source radiance at the required operating conditions, supported by the blackbody emissivity and calibrated temperature measurements.
- **Stability:** monitoring of the emissive surface temperature over the required measurement interval.
- **Uniformity:** verification of the spatial radiance distribution over the emissive surface and its projected coverage at the instrument.
- **FoV coverage:** geometrical verification that the emitting area covers the required instrument angular extent.

The current verification concept uses source characterization data together with OGSE-level geometrical measurements. In particular, a theodolite-based measurement is foreseen for confirming the angular coverage of the blackbody at the instrument position.

The polarizer will be verified separately for transmission, angular sampling and angular positioning accuracy. Its translation across the FoV will also be verified as part of the integrated calibration configuration.

4.3.1 Small bright source verification

The Small Bright Source will be verified through:

- source radiance or brightness characterization;
- temporal stability;
- apparent source size;
- positional coverage;
- positional accuracy.

The source size can be assessed geometrically, while the positioning accuracy can be verified by relating the mechanical displacement to the angular position seen from the instrument reference point.

The verification of the scanning capability is particularly important because the source position constitutes an independent variable in the spatial calibration measurements.

4.4 Integrated verification

The final verification will not consider each subsystem in isolation only. The OGSE will ultimately be evaluated in the integrated configuration in which the different sources share the same mechanical reference, optical interface and environmental enclosure (purging box).

This is essential because alignment errors, mechanical deformation, source-to-instrument distance and environmental conditions can affect more than one calibration function simultaneously.

The verification strategy therefore follows a hierarchical approach:

component characterization → subsystem verification → integrated OGSE verification → calibration-campaign readiness.

This approach provides traceability from the individual source characteristics to the performance delivered at the VenSpec-H instrument interface.

5. DISCUSSION

The OGSE architecture results from the need to accommodate three complementary calibration functions within a common mechanical and optical reference. The main design challenge was therefore to integrate sources with fundamentally different requirements while preserving the geometrical and environmental conditions required by the VenSpec-H calibration campaign.

The design analysis identified the OGSE-to-instrument distance as an important system-level parameter. It affects not only the optical path, but also the required dimensions of the radiometric source, the spectral diffuser and the scanning mechanism. The selected architecture therefore represents a compromise between optical coverage, mechanical envelope and integration within the thermal-vacuum test configuration.

For the Spectral Source, the principal challenge is the combination of narrow spectral emission with adequate spatial uniformity over the large VenSpec-H FoV. The adopted fibre-based de-speckling and single-diffuser architecture addresses these requirements, while the final performance will be established through integrated measurements of FoV coverage, uniformity and residual speckle. The current architecture is fully compatible with the adoption of other wavelengths, provided that DFB lasers are available and that their emission falls within the required bands.

For the Radiometric Source, the current analysis demonstrates adequate performance over the required spectral bands, although the highest-radiance dayside condition represents the most demanding operating point and will require particular attention during final verification.

The Small Bright Source introduces a different requirement: the accuracy of the spatial calibration depends directly on the knowledge and repeatability of the source position. Its positioning mechanism is therefore an integral part of the calibration function rather than merely a mechanical support.

Overall, the current design has reached a sufficient level of maturity to establish the principal OGSE architecture and its verification approach, while leaving room for optimization as subsystem characterization and integrated testing progress. The remaining activities are consequently focused on demonstrating the predicted performance at the OGSE-to-instrument interface.

6. CONCLUSION

The VenSpec-H calibration requirements impose a combination of spectral, radiometric and spatial constraints that cannot be addressed by a single optical source. The LusoSpace OGSE consequently adopts an integrated architecture comprising three complementary source sub-systems: a narrow-band Spectral Source, an extended Radiometric Source and a scanning Small Bright Source.

The Spectral Source combines narrow-line infrared sources with fibre transport, dynamic spatial de-speckling and a single large-area diffuser. This architecture provides the spectral purity required for wavelength and spectral-response measurements while addressing the challenges associated with laser coherence and the large VenSpec-H field of view.

The Radiometric Source uses an extended-area high-temperature blackbody to provide spatially uniform and temporally stable illumination. Its direct optical configuration towards the instrument minimizes additional optical losses, while the associated polarizer provides the capability for polarization characterization.

The Small Bright Source uses a localized thermal source mounted on a two-axis positioning mechanism. It provides a controlled angular stimulus for spatial response mapping, boresight determination and off-axis characterization.

A common mechanical reference and integrated environmental enclosure allow the three source functions to be implemented within a single OGSE. The continuous nitrogen purge of the optical volume further ensures that atmospheric absorption features do not compromise the near-infrared calibration measurements.

The design analyses performed to date indicate that the proposed architecture can address the principal VenSpec-H calibration requirements. Nevertheless, several parameters, most notably integrated radiometric performance, spatial uniformity and residual speckle, must ultimately be demonstrated at system level. The verification campaign will therefore combine supplier characterization, analytical predictions and dedicated OGSE measurements.

The OGSE is currently in an active development phase. The architecture presented here represents the result of the iterative interaction between instrument requirements, optical analysis and engineering design, while allowing further optimization before final verification. The work demonstrates how a multi-functional ground calibration system can be developed around a common optical and mechanical reference while preserving the distinct requirements of spectral, radiometric and spatial characterization.

7. ACKNOWLEDGEMENTS

The authors would like to acknowledge the Royal Belgian Institute for Space Aeronomy (BIRA-IASB), as the principal scientific institution of the VenSpec-H project, for its continuous scientific and technical support throughout the development of the OGSE. We also acknowledge the Instituto de Astrofísica e Ciências do Espaço (IA) in Lisbon, represented by Dr. Pedro Machado, Co-Principal Investigator of the EnVision mission and coordinator of the Portuguese contribution to the VenSpec-H consortium, for its scientific leadership and support.

The authors further acknowledge all members of the VenSpec-H consortium for the excellent collaboration and the joint effort that has contributed to the development of the instrument. The continuous interaction between the scientific, engineering, and industrial teams has been essential to the progress of the OGSE development.

Finally, the authors gratefully acknowledge the European Space Agency (ESA), through the PRODEX programme, and the Portuguese Space Agency for their financial support of this work.

8. REFERENCES

- 1) ESA - Envision factsheet - https://www.esa.int/Science_Exploration/Space_Science/Envision
- 2) E. Neefs, A.C. Vandaele, R. DeCock, J. Erwin, S. Robert, I.R. Thomas, S. Berkenbosch, L. Jacobs, P. Bogaert, B. Beeckman, A. Brassine, N. Messios, E. DeDonder, D. Bolsée, N. Pereira, P. Tackley, T. Gerya, S. Kögl, P. Kögl, H.-P. Gröbelbauer, J. Jimenez, 2025. **VenSpec-H spectrometer on the ESA EnVision mission: Design, modeling, analysis**. Elsevier, volume 226, Part 1. <https://doi.org/10.1016/j.actaastro.2024.10.018>

- 3) J. Helbert, A. C. Vandaele, E. Marcq, S. Robert, C. Ryan, G. Guignan, Y. Rosas-Ortiz, E. Neefs, I. R. Thomas, G. Arnold, G. Peter, T. Widemann, L. Lara, 2019. **The VenSpec suite on the ESA EnVision mission to Venus**. SPIE. The VenSpec suite on the ESA EnVision mission to Venus
- 4) Colin F. Wilson, Emmanuel Marcq, Cédric Gillmann, Thomas Widemann, Oleg Korablev, Nils T. Mueller, Maxence Lefèvre, Paul B. Rimmer, Séverine Robert & Mikhail Y. Zolotov. 2024. **Possible Effects of Volcanic Eruptions on the Modern Atmosphere of Venus**. Space Science Reviews. Springer Nature. <https://doi.org/10.1007/s11214-024-01054-5>
- 5) Roderick De Cock, Séverine Robert, Eddy Neefs, Justin Erwin, Michael Vervaeke, Hugo Thienpont, Etienne Renotte, Philippe Klinkenberg, Benoît Borguet, Solal Thomas, Wouter Moelans, Aaron Algoedt, Lieve De Vos, Ramatha Sørensend, Moshe Blaud, Ann Carine Vandaele, Ian R. Thomas, Sophie Berkenbosch, Lars Jacobs, Pieter Bogaert, Bram Beeckman, Ansje Brassine, Neophytos Messios, Erwin De Donder, David Bolsée, Nuno Pereira, Bojan Ristic, Paul J. Tackley, Taras Gerya, Stefan Köglf, Paola Köglf, Hans-Peter Gröbelbauer, Florian Wirz, Gerhard Stefan Székely, Nick Eaton, Elena Roibás-Millán, Ignacio Torralbo, Higinio Rubio-Arnaldo, José Miguel Álvarez, Daniel Navajas Ortega, Daphne Stam, Jose M. Castro-Marin, Jaime Jiménez Ortega, Luisa Lara, Jörn Helbert, Giulia Alemanno, and Emmanuel Marc, 2024, **Design of the VenSpec-H instrument on ESA's EnVision mission: development of critical elements, highlighting the FFCP and grating**. SPIE. <https://www.spiedigitallibrary.org/conference-proceedings-of-spie/13144/3027637/Design-of-the-VenSpec-H-instrument-on-ESAs-EnVision-mission/10.1117/12.3027637.full>
- 6) S. Robert, J.T. Erwin, R. De Cock, I.R. Thomas, N. Pereira, L. Jacobs, S. Berkenbosch, D. Bolsée, F. Vanhellemont, E. Neefs, S. Aoki, B. Bézard, E. Marcq, G. Alemanno, J. Helbert, and A.C. Vandaele. 2024. **Scientific objectives and instrumental requirements of the IR spectrometer VenSpec-H onboard EnVision**. <https://www.spiedigitallibrary.org/conference-proceedings-of-spie/13144/3027948/Scientific-objectives-and-instrumental-requirements-of-the-IR-spectrometer-VenSpec/10.1117/12.3027948.full>
- 7) Ian R. Thomas, Shohei Aokia, Loïc Trompet, Severine Robert, Cedric Depiesse, Yannick Willame, Guillaume Cruz-Mermy, Frederic Schmidt, Justin T. Erwin, Ann Carine Vandaele, Frank Daerden, Arnaud Mahieux, Eddy Neefs, Bojan Ristic, Laszlo Hetey, Sophie Berkenbosch, Roland Clairquin, Bram Beeckman, Manish R. Patele,f, Jose Juan Lopez-Moreno, Giancarlo Bellucci, the NOMAD Team. 2022. **Calibration of NOMAD on ESA's ExoMars Trace Gas Orbiter: Part 2– The Limb, Nadir and Occultation (LNO) channel**. Elsevier. Calibration of NOMAD on ESA's ExoMars Trace Gas Orbiter: Part 2 - The Limb, Nadir and Occultation (LNO) channel