

Development of the Vigil Heliospheric Imager: Design optimization, expected performance, and on-ground calibration of the Front Baffle

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ABSTRACT

Vigil is an upcoming ESA deep-space mission designed to monitor space weather, with a particular focus on the solar corona and the interplanetary space between the Sun and Earth. The Vigil spacecraft will be placed at the fifth Lagrange point of the Sun-Earth system (SEL5). The Heliospheric Imager (HI) is part of the suite of instruments on-board this spacecraft, designed to observe the solar corona and mid-course tracking of solar wind features including very faint Coronal Mass Ejections (CMEs).

This article discusses some of the most important issues related to the practical implementation of the HI optical concept and, in particular, the baseline design of the Front Baffle (FB) module, one of the key optical components of the HI instrument, designed to suppress direct stray-light from the solar disk.

In addition, we report an original approach to high-precision metrology of stray light, including the vacuum facility being developed for the FB on-ground calibration under conditions of extremely weak measured light signals. The presented measurement bench involves a number of original engineering solutions making it possible to measure the optical response of the FB designed to provide a stray light suppression efficiency better than 10^{-9} .

Keywords: Vigil mission, Solar observation instruments, Heliospheric Imager, On-ground testing, Front baffle

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1. INTRODUCTION

Vigil is an upcoming ESA deep-space mission designed to monitor space weather, with a particular focus on the solar corona and the interplanetary space between the Sun and Earth. The Vigil spacecraft will be placed at the fifth Lagrange point of the Sun-Earth system (SEL5), which will ensure the best conditions for continuous monitoring of the solar corona and, in particular, mid-course tracking of solar wind features including Coronal Mass Ejections (CMEs).

One of the optical observation instruments included in the Vigil spacecraft's payload designed to observe the solar corona and very faint CME is a Heliospheric Imager (HI) instrument. The HI instrument features a dual-camera design operating in the 500–850 nm wavelength range and covering a very wide field of view (FOV), enabling the monitoring of almost the entire space between the Sun and Earth.

A simplified view of the current baseline HI configuration is depicted in Figure 1.

To mitigate specific sources of stray light, the HI instrument incorporates a series of specialized baffling systems: front, internal, peripheral, and rear baffle assemblies.

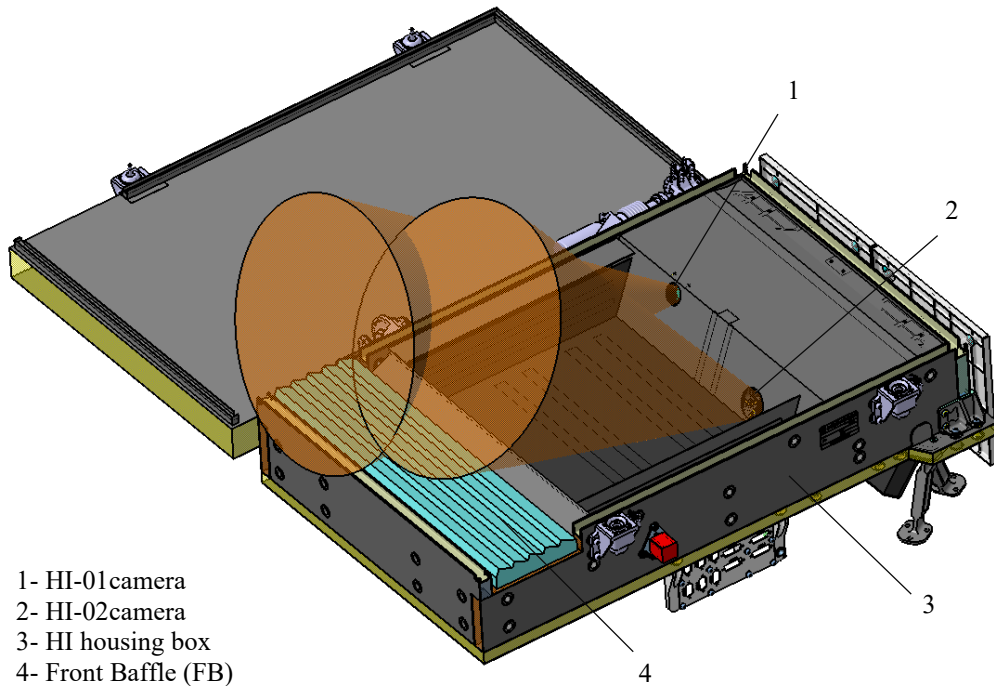


Fig. 1. Optical layout of the HI instrument: (3D CAD model).

In this paper, we present the baseline design of the wide-angle Front Baffle (FB), currently under development at the Centre Spatial de Liège (CSL) to protect the Vigil HI cameras from direct solar stray light.

It is worth noting that the CSL has prior experience developing a similar FB. In particular, our research group developed the FB for the STEREO Heliospheric Imager [1-5].

Accordingly, the basic concept of the FB currently under development for the Vigil HI instrument, as well as some of the engineering solutions required for its practical implementation, were already validated experimentally. In particular, it was demonstrated that, since the space available for installing the FB assembly in the HI is very limited, the optimal optical concept for this baffle is one that involves a set of cascading diffractive vanes oriented perpendicular to the solar flux, a so-called multi-stage diffractive vane (MSDV) structure (Fig. 1).

The operating principle of such FBs is that direct sunlight rays passing over the MSDV structure are successively diffracted at the edges of diffractive vanes, and each intermediate vane, starting from the second, partially blocks the light diffracted by the previous ones [2-6].

To achieve the requisite stray-light rejection for the Vigil HI instrument, preliminary studies have shown that the MSDV structure used in the FB must contain at least eight diffractive vanes (for comparison, the FB developed for the STEREO HI instrument contained only five vanes). Such a large number of diffractive vanes makes it extremely challenging to practically implement the FB concept using the same technological approach as that employed earlier for the STEREO HI project, i.e., via sequential assembly and independent alignment of each diffractive vane. Hence, the design concept of the FB intended for Vigil HI instrument is significantly different from the one we developed previously for the STEREO HI, although it will adapt some of the engineering ideas from the aforementioned previous work.

In particular, the original FB design concept reported in this paper involves a specific wedge MSDV module and a dedicated supporting assembly optimized to meet accommodation constraints within the HI, taking into account both the alignment accuracy requirements of the entire HI optical system and the thermo-mechanical stability of the FB.

Finally, it is worth noting that as part of its contribution to the Vigil project, CSL is responsible not only for the optical design of the FB, but also for its manufacturing and on-ground calibration. Accordingly, in this paper, we consider key issues related to its practical implementation. In particular, we present an original optical test bench developed by our research group for the FB on-ground calibration under conditions of extremely weak measured light signals.

2. CONCEPT CONSIDERATION

The Front Baffle under consideration is shown in Figure 2. It consists of a wedge-shaped MSDV module (1) and a thermo-mechanically stabilized supporting assembly (2) that provides the required spatial positioning of the MSDV module (1) relative to HI observation cameras (HI-01 and HI-02; not shown in Figure 2).

The FB supporting assembly consists of a set of bipods (3) and a mounting panel (4) on which both MSDV modules are mounted.

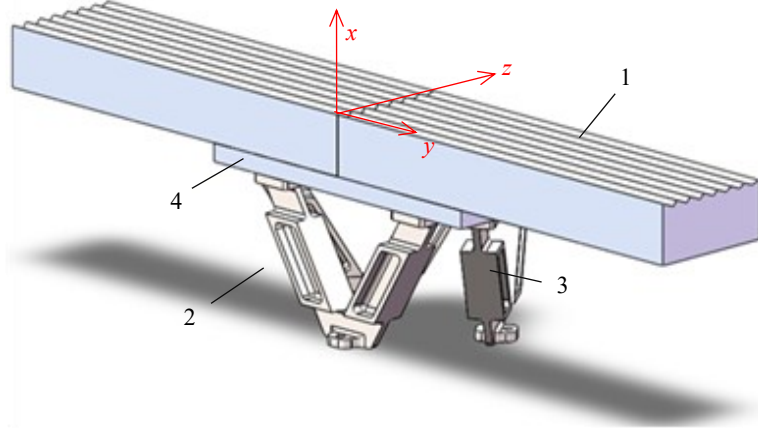


Fig.2. FB assembly 3D CAD model (general view)

The wedge-shaped geometry of the MSDV structure ensures very high thermo-mechanical stability of the FB, and, therefore, low sensitivity of its optical response to temperature fluctuations. Furthermore, such a geometric structure is much easier to manufacture at the required accuracy than a set of knife-edge linear diffractive vanes similar to those used in the FB designed for the STEREO HI.

As the main *objective function* used in this work for optimizing the FB design, we used the efficiency of the direct solar disk stray light suppression, determined by the average spectral value of the stray light rejection coefficient (SLRC) ensured by this baffle at the HI-01 (HI-02) camera entrance.

The main requirement for the FB, according to the Vigil HI performance specification, is that it should suppress the solar disk stray-light flux with an efficiency, expressed in terms of average spectral SLRC at the input of the HI-01 and HI-02 observation cameras, of at least 10^{-9} and 10^{-10} , respectively (over the whole wavelength range of interest and with respect to the optical design parameters of these cameras, their position relative to the FB, as well as the angular size and shape of the Vigil HI's FOV of interest).

The *constraint* parameters used in the optimization procedure were three angles, ω , θ and ψ , defining the required FOV geometry of both HI-01 and HI-02 cameras, the relative position of these cameras, determined by distances D and H (see Fig.3 below), as well as the diameters of their entrance apertures.

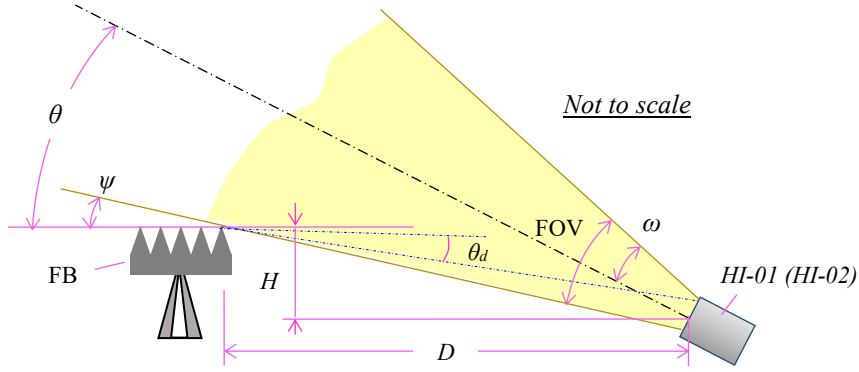


Fig.3. Input constraint parameters used in the MSDV structure optimization procedure.

Figure 4 shows the results of the optimization of a MSDV structure designed for the HI camera's Field-Of-View (FOV= 32° , the FOV critical angle $\psi = 3.8^\circ$, HI camera's input aperture diameter $D_e = 19.5$ mm, and this aperture diameter $D = 549.7$ mm, cf. Fig.3).

As for *decision variables* involved in the MSDV design optimization procedure, i.e., design parameters to be adjusted to achieve the best possible outcome (in terms of the SLRC), in the presented work, these were the number of diffractive vanes and distances between vane edges.

The FB design concept presented in this paper involves MSDV structures featuring equidistantly spaced vanes, whose edges are arranged along an arc. In this arrangement, the diffraction angle θ_d , defined as the angle between the Sun limb direction and the line connecting the last vane edge and the upper edge of the HI-01 optical entrance aperture (cf. Fig.3), is equally divided among the vane of the MSDV structure [2-6].

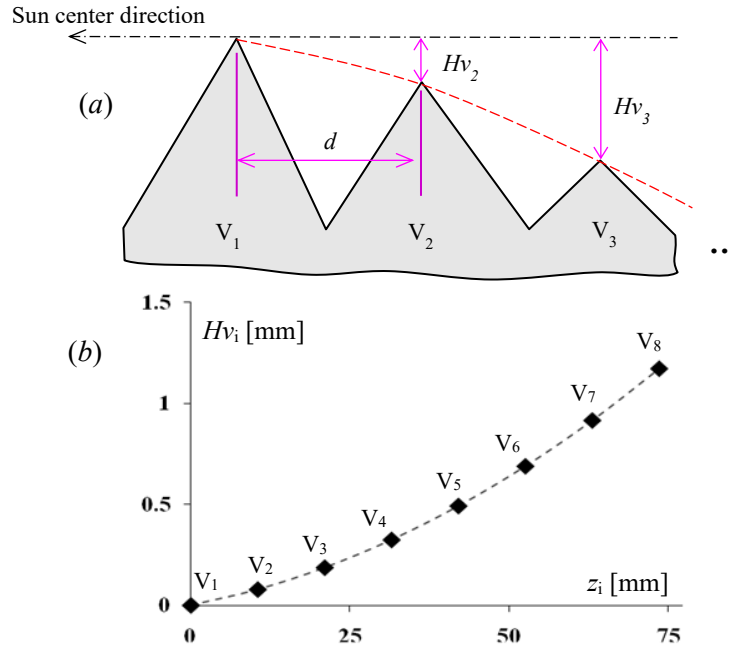


Fig.4. (a) Schematic diagram of the MSDV structure (not in scale); (b) heights (Hv_i) and relative positions (P_i) of the diffractive vane edges relative to the first vane tip calculated for a MSDV structure in the nominal configuration

Figure 5 depicts the qualitative behavior of the optical response of the MSDV structure under consideration, as predicted by the analytical model involving the scalar diffraction theory (SDT) approach [2-7].

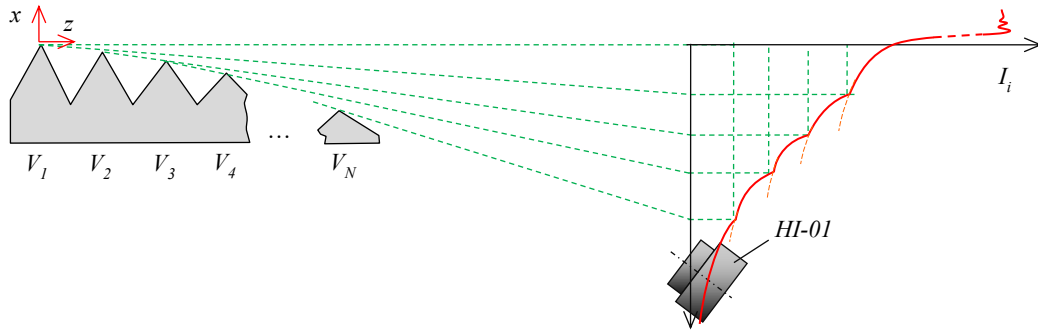


Fig.5. Optical response of the cascade MSDV structure.

The stepped appearance of the SLRC graph in Figure 5 originates from the operating principle of the cascaded MSDV, according to which each intermediate diffractive vane partially blocks the light diffracted by the preceding ones.

The average spectral SLRC value, calculated for the optimized MSDV structure, is approximately 3.2×10^{-10} and 1.4×10^{-11} for HI-01 and HI-02 cameras, respectively (cf. Fig.4b for diffractive vane heights and positions).

Thus, the optimized FB provides a stray-light rejection efficiency significantly higher than that specified in the design requirements.

The results of the numerical simulations performed using the SDT model for this MSDV structure are shown in Figure 6.

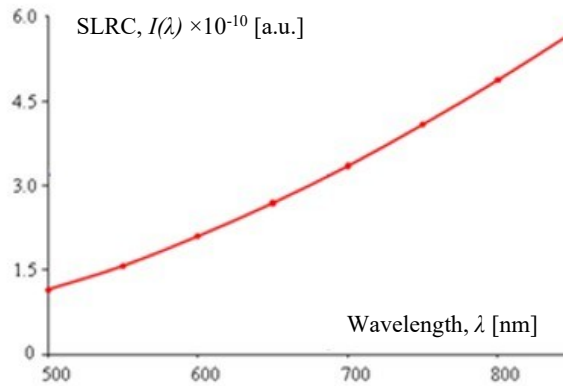


Fig.6. SLRC values calculated at the entrance aperture of the HI-01 camera for the MSDV structure in the nominal configuration

3. OPTICAL CALIBRATION BENCH

As noted above, the HI FB should provide a stray light suppression efficiency better than 10^{-9} . In practice, this requires that the calibration bench designed for on-ground testing of the FB has to ensure accurate measurement of extremely weak optical signals (on the order of 10^{-11} W or better [3, 4]).

The practical implementation of such a calibration bench is a non-trivial problem, requiring several original, non-standard engineering solutions.

Figure 7 shows the optical calibration bench developed by Ir. E. Mazy's CSL team for characterizing HI FBs.

The optical part of the calibration bench includes a fiber-coupled light source assembly (1), a dedicated optical collimator (2) mounted on a collimator positioning hexapod (3).

The light source collimator (2) forms a probing beam with a rectangular cross-section featuring a uniform irradiance distribution, which mitigates the effects of uncertainty related to the beam's vertical position relative to the FB under test on measurement accuracy, and therefore ensures more predictable outcomes compared to a circular cross-section. The FB under test (4) is mounted on a supporting frame installed between the collimator (2) and the fibered collimator (5) of the detector assembly. The collimator (5) is mounted on a positioning hexapod (6). Positioning hexapods (3) and (6) are used for the mutual alignment of both collimators (2) and (5), as well as for their movement along the vertical axis to bring them in a position corresponding to the required measurement configuration, and to hold them in this position during measurements.

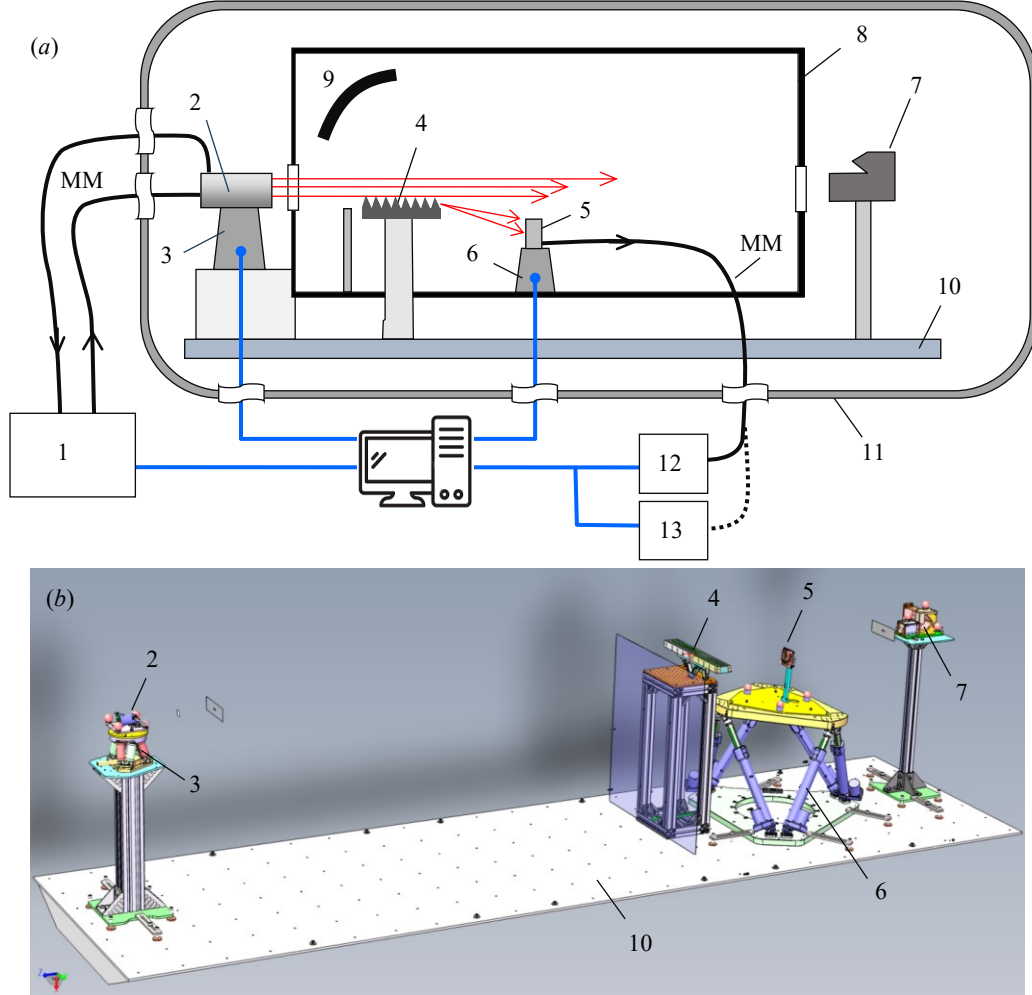


Fig.7. Measurement bench for on-ground characterization of the FB: (a) simplified functional diagram; (b) optical bench 3D CAD model.

The intensity of stray light entering the aperture of the detector's collimator (5), due to scattering and stray reflections within the measurement bench, must be significantly lower than the measured intensity of light diffracted by the FB under test. To fulfill this requirement, the following engineering solutions were implemented:

- The upper part of the collimated probing beam, which does not interact with the FB under test, is extinguished using a dedicated rear light trap (7);
- The optical bench is enclosed in a dedicated black box (8), with high isolation from stray-light interference;
- A super-black optical shield (9) is mounted in front of the FB under test to absorb stray light arising from reflection and scattering at this FB;

- To exclude the effect of light scattering at air molecules on the measurement results, the entire metrology bench, including the optical table (10), is placed in a large-volume vacuum chamber (11).

The FB SLRC measurement procedure involves two operating modes: reference mode and scanning mode. The operating mode selection is carried out using two hexapods (3) and (6), while the FB under test (4) itself remains fixed in the laboratory coordinate system (associated with the optical bench).

The measurement bench is switched to the reference mode to measure the collimated probing beam irradiance during the bench calibration. During reference mode, the FB under test (4) is moved out of the probing beam, while the detector collimator is moved to the center of the beam.

The results of the reference measurements are used to filter out the effect of uncontrollable fluctuations in the output power of the light source assembly, such as those induced by thermal changes or supply voltage variations, from the SLRC measurement data.

In the scanning mode, the edge of the FB under test is illuminated by the probing laser beam, and the detector collimator (5) is successively moved using the hexapod (6) deeper into the shadow region behind the FB under test (4). The measurement bench is switched to this operating mode for measuring the diffracted beam flux at various diffraction angles, which allows, on the one hand, to verify the used theoretical model of the FB optical response, and, on the other hand, to determine the SLRC value depending on the HI camera's vertical position and angular orientation (averaged over its entrance aperture and/or entrance pupil).

During the scanning, the optical response of the FB is measured using a diffracted light detecting assembly (12) operating in photon-counting mode. The detecting assembly (12) includes a Single-Photon Avalanche Diode (SPAD) module and a counter module. The optical signal from the fibered collimator (5) is transmitted to the SPAD module via a vacuum-compatible multimode fiber (MM).

As for the practical implementation of the reference operating mode, the intensity of the probing beam (simulating the direct sunlight) is measured using a direct sunlight detecting assembly (13), which includes a trap detector, a set of neutral-density filters, and a femto-ammeter module. The trap detector is preferred due to its highly linear response. This detector operates in the conventional energy-integrating detection mode. The neutral-density filters are used to optimize the dynamic range of the direct sunlight detecting assembly.

The above concept of the detector assembly developed for the measurement bench enables the measurement of optical signals over a very large dynamic range: from units of watts when performing reference measurements, to tens of picowatts when measuring the optical response of the FB under test.

The practical implementation of the presented measurement bench required the development of a number of non-standard functional modules, such as the light source collimator, the fiber-coupled light source assembly, and the rear light trap (labeled in Figure 7 as 1, 2, and 7, respectively).

Figure 8 shows the functional diagram of the fiber-coupled light source assembly (labeled as (1) in Figure 7).

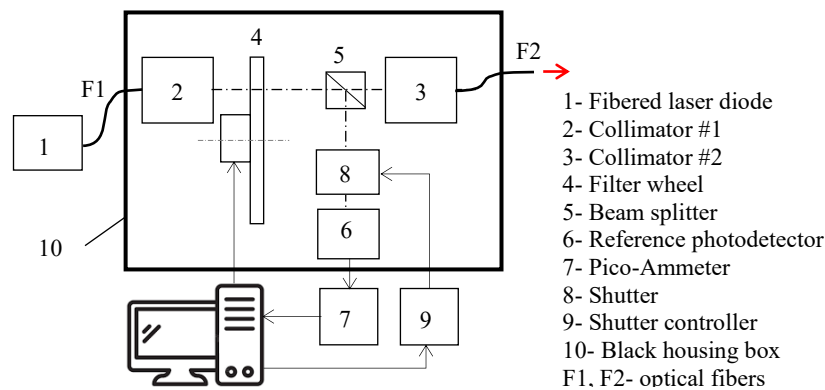


Fig.8. Light source assembly (schematic functional diagram)

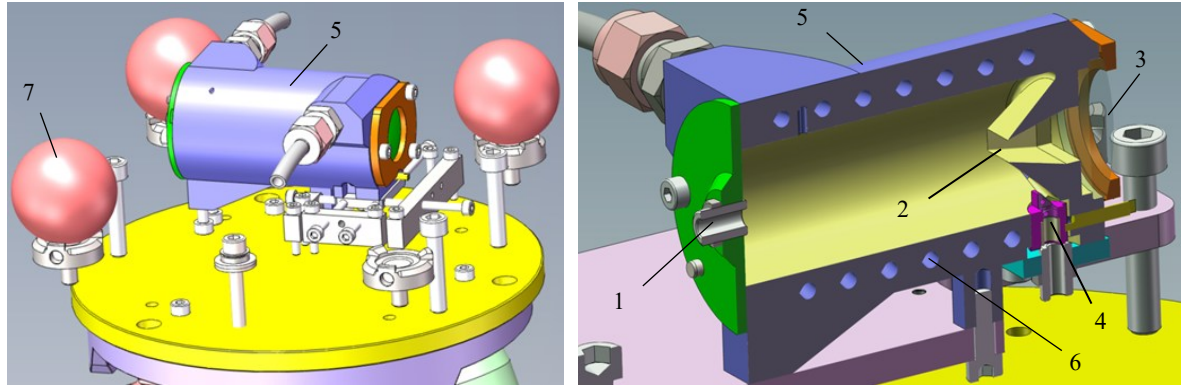
This assembly consists of a continuous laser (1) module (a fiber-coupled laser diode with a central emission wavelength of 808 nm and an output power of 100 W) and an optical relay system designed to monitor the output power of the light

source. The latter system includes two fibered collimators (2) and (3), a filter wheel (4), and a beam splitter (5) that diverts and directs a small portion of the light source output power to a reference photodetector (6).

The light source assembly is mounted outside the vacuum chamber for accessibility purposes, and it is linked to the light source collimator (labeled as (2) in Figure 7) by two vacuum-compatible multimode fiber optic cables: one for transmitting high-power laser radiation to the collimator and one for receiving the monitoring signal from it. The monitoring signal from the light source collimator, measured in situ during the on-ground calibration, is used in conjunction with the reference signal to filter out uncontrollable fluctuations in the output power of the light source assembly from the measurement data.

Thus, the implemented concept of the measurement bench involves dual-loop monitoring of the laser probe beam optical power, which ensures extremely high accuracy and precision when measuring the stray-light attenuation profile of the FB under test.

Figure 9 depicts the vacuum-compatible light source collimator assembly.



- | | |
|--|---------------------------------------|
| 1- Fiber port assembly | 5- Vacuum compatible housing assembly |
| 2- Beam-shaping baffle | 6- Helical coil heat exchanger |
| 3- Collimator lens | 7- Laser Tracker Targets |
| 4- Fiber collimator coupler of the monitoring system | |

Fig.9. Light source collimator assembly: general and cross-sectional views (a 3D CAD model).

As noted above, the laser radiation entering the collimator exhibits high optical power (up to 100 W). Accordingly, the geometric designs of the beam-shaping baffle and the inner cavity were optimized to minimize the stray light contribution to the output probing beam of the collimator and to ensure a uniform irradiance distribution across its cross-section. This optimization was performed numerically using ray-tracing simulations.

Thermal stability of the light source collimator is maintained by a vacuum-compatible cooling system, which includes a spiral heat exchanger integrated into the collimator housing.

Figure 10 depicts the detector collimator assembly (a 3D CAD model).

This collimator assembly is based on a compact fiber-coupled reflective collimator mounted in a dedicated mount equipped with a calibrated baffle.

Both collimators (2) and (5) are mounted on breadboards equipped with a set of Laser Tracker Targets (LTT), which enable highly accurate measurements of the spatial orientation of these collimators. This is crucial for achieving precise component alignment, which is essential when the measurement bench operates in the scanning mode.

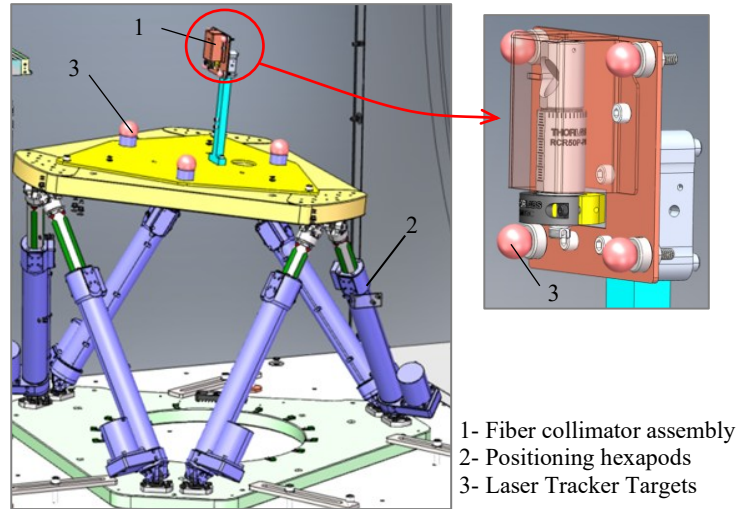


Fig.10. Detector collimator assembly. Inset figure: enlarged view of the fiber collimator module.

Figure 11 depicts the developed rear light trap.

The design of this trap is based on the two-stages baffling concept, the high efficiency of which was demonstrated in the previous STEREO project [2-4]. The rear light trap consists of an entrance tube (1) with a set of baffling vanes (the first trap stage) and a light trap based on a set of successive absorbing filters (F1-F3) mounted in a black cavity (the second trap stage).

All internal surfaces of the trap are coated with a highly scattering Aeroglaze Z306 black coating.

The housing box of the rear light trap is equipped with a set of Laser Tracker Targets allowing for precise alignment of the device with respect to the probing beam.

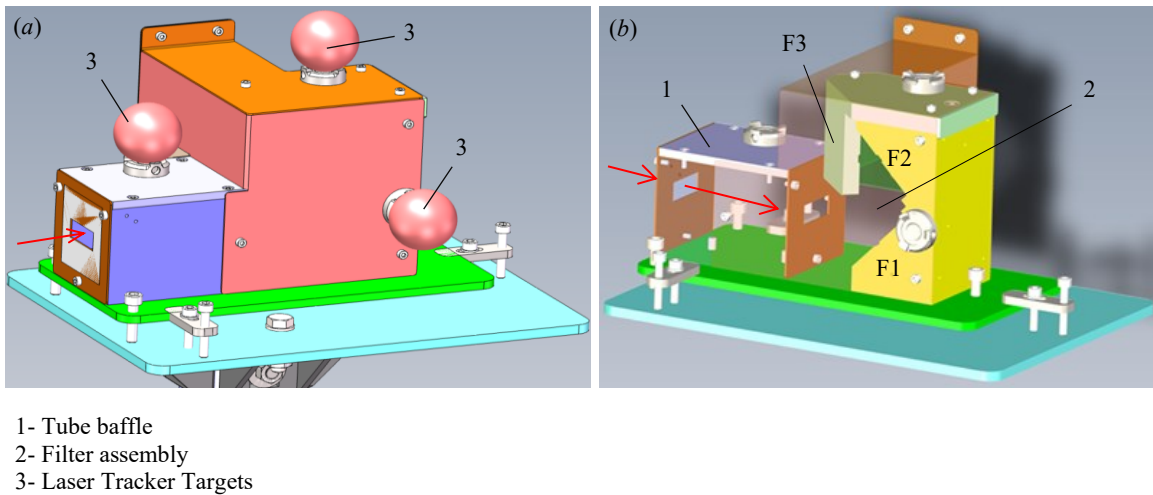


Fig. 11. Rear light trap 3D CAD model: (a) general and (b) vertical cross-sectional views. The probing beam is represented by the red arrow.

In summary, the optical calibration bench represents an advanced metrological system requiring extensive design trade-offs and experimental validation, the complete details of which are omitted here for conciseness. Further details on specific subsystems and component characterizations are available in prior work [2-4, 6].

4. CONCLUSIONS AND PERSPECTIVES

In this paper, we report an original concept of the Front Baffle (FB) of the ESA Vigil Heliospheric Imager (HI), alongside an innovative measurement bench developed for on-ground optical calibration of this baffle. The FB under consideration includes a multi-stage diffractive vanes (MSDV) structure and a dedicated high-stability support assembly.

The presented metrology bench enables high-accuracy characterization of MSDV structures designed to provide a stray light suppression level below 10^{-9} . Such a high sensitivity is achieved by implementing a dual-loop optical power monitoring of the laser probe beam, an approach that mitigates system instability, stray light, and residual fluctuations in the light source intensity on the total error budget.

The practical implementation and optical characterization of both the FB prototype and the metrology bench are currently underway.

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