

Design optimization of the Forward Baffle of the ESA Vigil Heliospheric Imager

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ABSTRACT

Vigil is an upcoming ESA satellite mission designed to monitor space weather, with a particular focus on the solar corona and the interplanetary space between the Sun and Earth.

This paper introduces the basic design of a Forward Baffle (FB), currently being developed for the Heliospheric Imager (HI) instrument included in the Vigil spacecraft's payload to observe very faint coronal mass ejections (CME) across a wide field of view.

The presented wide-angle FB is one of the key optical components of the HI designed to suppress direct stray-light from the solar disk. It consists of a multi-stage diffractive vanes (MSDV) module involving multi-wedge structures with a high-reflectivity surface coating and a dedicated thermo-mechanically stabilized FB supporting assembly providing the required spatial and angular position of the MSDV relative to two observation cameras of the HI instrument. The FB supporting assembly is designed to meet the accommodation constraints of the HI instrument.

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

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1. INTRODUCTION

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

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. This instrument is designed to operate over a wide angular field of view, allowing it to monitor almost the entire space between the Sun and Earth.

In this context, it is instructive to note that the natural object space background level (B) varies from 10^{-7} - 10^{-14} of the brightness of the solar disk (B_0) and the CME signal is only 10^{-2} of the night sky at high elongation, or 10^{-15} - 10^{-16} B_0 , [1]. Accordingly, the main challenges in designing the HI are to provide imaging capabilities over a very wide angular field of view (FOV) and faint-light detection capability with irradiance levels down to 10^{-15} B_0 (B_0 being the solar irradiance at 1 AU), [2].

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

The HI instrument is equipped with a double camera design (HI-01 and HI-02) covering an asymmetric field-of-view (FOV) across 4° to 53° of elongation angle on the ecliptic plane, and $\pm 30^\circ$ outside the ecliptic plane projection. Both HI-01 and HI-02 cameras are designed to cover the 500-850 nm wavelength range (VIS/NIR spectral bands).

The HI instrument also includes a set of different baffling systems, each of which is designed to mitigate a specific set of stray light sources: forward, internal, peripheral, and rear baffles assemblies.

In the frame of the Vigil project, the Centre Spatial de Liège (CSL) is responsible for the design, manufacturing, verification, calibration, and delivery of the wide-angle Forward Baffle (FB), one of the key optical components of the HI, designed to mitigate the direct stray-light from the solar disk.

It is worth noting here that the CSL team of experts has already developed an FB, similar to the one intended for the Vigil HI instrument, within the framework of the previous STEREO ESA project, [2-4].

Both STEREO and Vigil HI instruments are designed to operate under the same physical environmental conditions, and the optimization of their optical design parameters is subject to the same requirements (specified by the objectives of scientific observations and the nature of the observed objects). Accordingly, some of the optimal engineering solutions, as well as the optimal relationships between design parameters, that have already been found and experimentally validated within the framework of the STEREO mission, can also be applied to the current Vigil project.

In particular, as established within the framework of the STEREO project [2-4], since the space available for installing the FB in the HI is very limited, the most optimal design for this baffle should embrace a multi-stage diffractive vanes (MSDV) structure consisting of a set of cascading diffractive vanes oriented perpendicular to the solar flux. This engineering solution will also be adopted in the HI instrument under development within the framework of the Vigil project (Fig. 1).

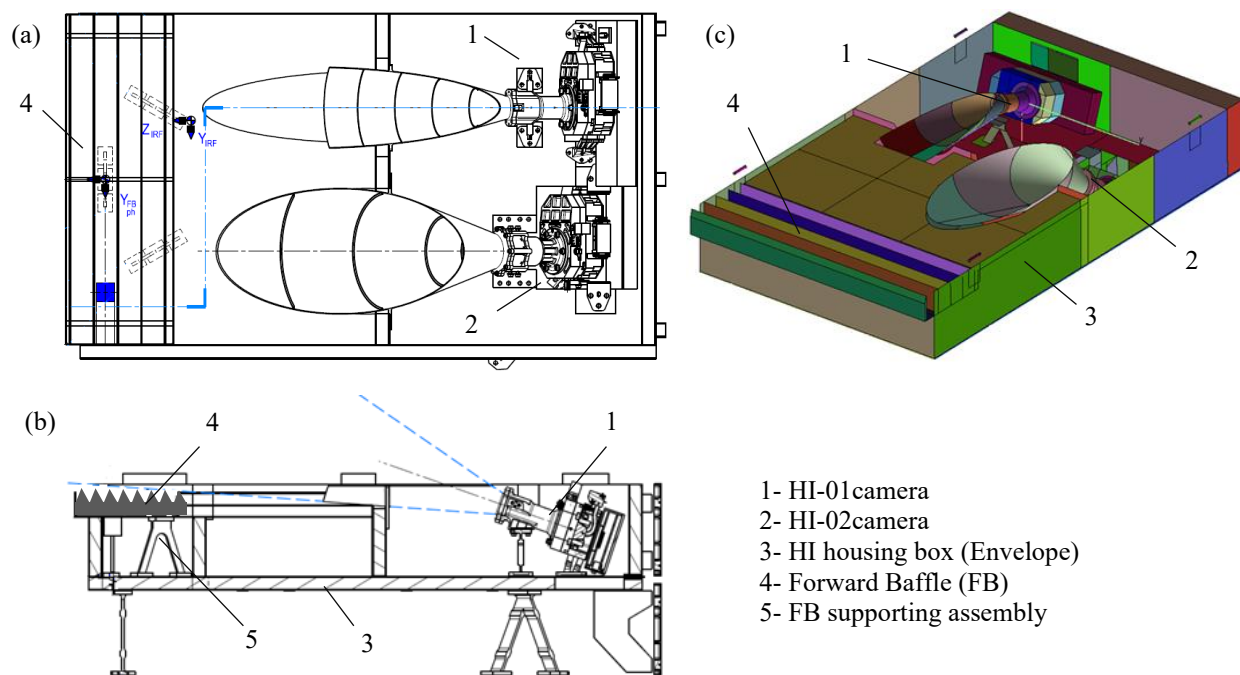


Fig. 1. Optical layout of the HI instrument: (a) top view, (b) cross-section view (only HI-01 is shown), (c) 3D CAD model.

The operating principle of the FB involving cascade MSDV structures is that direct sunlight rays passing along the set of diffractive vanes are successively diffracted at the edges of the vanes, and each intermediate vane, starting from the second, partially blocks the light diffracted by the previous ones [2-5]. It should be noted that proper optimization of MSDV structural design parameters (i.e., the number of diffractive vanes, their relative positions, and heights) enables significant attenuation of the intensity of sunlight diffracted onto the HI camera's entrance aperture. For example, in the case of the HI instrument developed within the STEREO project, the intensity of stray sunlight at the HI-01 camera's entrance aperture did not exceed 10^{-9} of the intensity of the incident sunlight for the longest wavelength in the operating spectral range ($\lambda_{\max}=730$ nm).

In practice, the optimization of the FB design parameters is a quite complex iterative procedure involving, on one hand, the optical parameters of both HI-01 and HI-02 cameras (such as their operating wavelength ranges, entrance pupils positions and sizes, required fields of view, the stray light achievable rejection level inside the cameras, etc.), and, on the other hand, the relative position of the cameras in the HI housing box optimized in accordance with the requirements for the HI integral field-of-view characteristics.

In this context, it should be noted that, as shown in the preliminary study of the optical concept of the Vigil HI instrument, achieving the level of stray light suppression required by the scientific objectives of the Vigil mission requires the MSDV structure used in the FB to 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 difficult to directly implement the same FB design concept used in the STEREO HI, especially because fabricating the MSDV structure by sequentially assembling the diffractive vanes with precise, independent alignment, as done in the STEREO project, is in practice extremely challenging (if it is even feasible).

In addition, in the Vigil HI instrument, the HI-01 and HI-02 cameras are not placed one above the other in the same vertical plane, as in the case of the STEREO HI, but are mounted side by side, with some horizontal offset (Fig.1).

Accordingly, the design concept of the FB intended for Vigil HI instrument will be significantly different from the one we developed previously for the STEREO HI, although it will borrow some of the ideas and engineering solutions found in our aforementioned previous work.

In this paper, we present the baseline design of the FB, which our research group is currently developing for the Vigil HI instrument.

The presented FB design concept involves a wedge MSDV structure and a dedicated supporting assembly. It is optimized to meet accommodation constraints on the HI, considering the requirements for alignment accuracy of the entire HI optical system as well as the thermo-mechanical stability of the FB's spatial position. The introduced wedge MSDV structure is fabricated from a bulk aluminum block using an original high-precision machining method, thereby significantly simplifying FB alignment in practice.

In this paper, we also address key issues related to the practical implementation of the proposed FB, including the engineering aspects of its optical characterization. In particular, we present an original optical test bench developed by our research group for the FB on-ground calibration under extremely weak measured light signals.

2. CONCEPT CONSIDERATION

2.1 FB baseline design

The FB under consideration is depicted in Figure 2.

It consists of a wedge MSDV assembly (1) and a thermo-mechanically stabilized FB supporting assembly (2) that provides the required spatial positioning of the MSDV assembly (1) relative to two observation cameras of the HI instrument HI-01 and HI-02 (not shown in Fig.2).

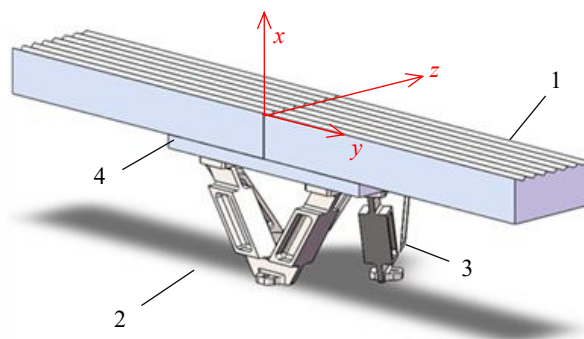


Fig.2. FB assembly 3D CAD model (general view)

The wedge-shaped geometry of the MSDV structure is chosen since it 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 fabricate with the required accuracy for the intended application than a set of knife-edge linear

diffractive vanes (KELDV) similar to those used in the FB designed for the STEREO HI. It is also worth noting that the use of the FB relative involving MSDV structures made from bulk metallic blocks significantly simplifies the overall alignment procedure for the HI optical system (compared to the alignment procedure used in the previous STEREO project, where the MSDV structure was assembled from five independently aligned KELDV). This allows for an increase in the number of diffractive vanes in the MSDV structure and, therefore, significantly improves the stray light suppression efficiency.

To reduce heating of the MSDV assembly by direct sunlight, its surface is coated with a dedicated highly reflective coating. As shown in Fig. 2, the MSDV assembly (1) is composed of two MSDV modules. The choice of this design was imposed by the limitations on the length of the workpiece that can be processed using the available high-precision machining equipment. In this context, it is worth noting that, to reduce the contribution of the interface between two MSDV modules to the stray light budget, this interface employs a dedicated high-precision mounting system, and additional baffles have been introduced into the HI baffling system (not shown in Fig. 2 for clarity).

The MSDV assembly (1) is also equipped with an alignment cube (not shown) used to measure small angular deviations of the FB from the required angular orientation.

Figure 3 shows a more detailed view of the MSDV module, as well as the FB supporting assembly.

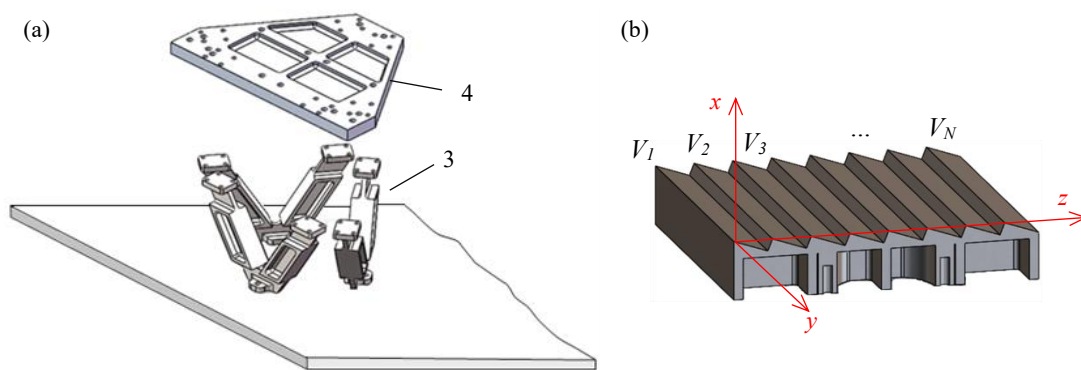


Fig.3. (a) FB supporting assembly (disassembled view) and (b) MSDV module (cross-sectional view; not in scale)

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

During the launch of the satellite, its payload, including the Vigil HI instrument, despite the vibration isolation system, will be subjected to relatively high level of vibration (so called “rocket launch-induced vibration”, RLIV) which could affect the alignment of the FB and, consequently, lead to a deterioration of its optical performance (especially when the RLIV frequency matches a natural frequency of the FB assembly). Accordingly, in our work, special attention was paid not only to the precise alignment of the FB assembly but also to solving engineering problems related to the FB's immunity to vibrations (i.e., the stability of the alignment under conditions of intense vibrations).

To ensure the required vibration stability of the FB alignment, it is necessary to prevent the excitation of resonant oscillations in the FB assembly. The best way to achieve this is to increase the natural frequency of the assembly, making it significantly higher than the RLIV frequency. In practice, this can be achieved by reducing the weight of the MSDV assembly and increasing the stiffness of the FB supporting assembly.

In the case of the presented FB, to reduce the MSDV modules weight, they are made partially hollow (Fig.3b). As for the FB assembly, its high stiffness, ensuring the required vibration immunity and the thermal stability of the FB, can be achieved by optimizing the design of the bipods and their relative positions inside the HI housing box (see Fig. 3a above for one of the possible engineering solutions to this issue). Both these approaches were used in our work to immunize the FB assembly against RLIV. For the sake of brevity and clarity, this paper does not provide the design parameters of the mechanical part of the FB assembly (such as the dimensions of the internal cavities and the bipod supports, the weight and strength characteristics of the components, etc.). All these parameters were optimized to ensure that the lowest natural frequency of vibration of this assembly exceeds 350 Hz (in accordance with the design specification requirements).

Finally, the design of the FB supporting assembly (2) is also optimized to meet the accommodation constraints of the HI instrument housing box, taking into account, among other things, that some HI components are located in the space beneath the MSDV assembly.

2.2 FB design optimization

In the present work, the *objective function* for optimizing the FB design was the average spectral value of the stray light rejection coefficient (SLRC) of this baffle at the entrance of the HI-01 (HI-02) camera.

The SLRC, $I(\lambda)$, is defined as the ratio of the radiant flux of the stray light entering the HI camera's entrance aperture, Φ_d (i.e., not being blocked by the FB), to that of the direct sunlight impinging on this aperture in the absence of the FB, Φ_0 . Accordingly, the SLRC average spectral value $\langle I \rangle_\lambda$ is defined as follows:

$$\langle I \rangle_\lambda = \frac{1}{\lambda_{\max} - \lambda_{\min}} \int_{\lambda_{\min}}^{\lambda_{\max}} I(\lambda) d\lambda = \frac{1}{\lambda_{\max} - \lambda_{\min}} \int_{\lambda_{\min}}^{\lambda_{\max}} \Phi_d(\lambda) / \Phi_0(\lambda) d\lambda \quad (1)$$

, where λ is the wavelength of the incident light beam and $[\lambda_{\min}; \lambda_{\max}] = [500 \text{ nm}; 850 \text{ nm}]$ is the FB operating wavelength range.

The primary requirement for the FB, according to the Vigil HI performance specification, is that it should reject the solar disk stray-light intensity with attenuation (i.e., the SLRC average spectral value) of the order of, or better than, 10^{-9} and 10^{-10} at the input of the HI-01 and HI-02 observation cameras, 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).

Figure 4 shows a schematic of the MSDV module and summarizes the main design parameters used in its optimization.

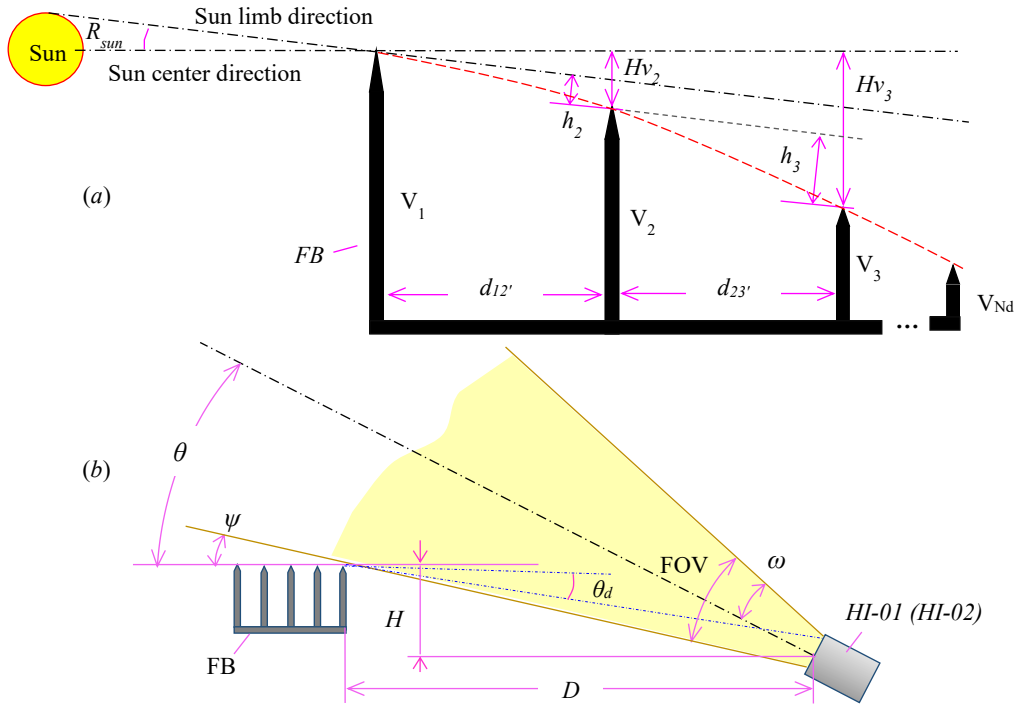


Fig.4. Schematic diagram of the MSDV module (not in scale); for the sake of visibility, in this figure, instead of the MSDV module with wedge-shaped geometry, an equivalent one with knife-edge linear diffractive vanes is shown

As for the *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 Nd and the distances between them d_{ij} (see Fig.4a).

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 (Fig.4b), as well as the diameters of their entrance apertures.

In a first approach, the SLRC of a given MSDV structure can be evaluated using the well-known analytical model involving Fresnel's second-order approximation to the Kirchhoff-Fresnel diffraction integral for a semi-infinite half-screen [2-5]. In other words, this approach is based on the simplifying assumption that the optical field at the tip of a given diffractive vane, generated by diffraction from the previous one, can be described fairly accurately by the Fresnel approximation [6].

The FB design concept presented in this paper involves MSDV structures with equidistantly separated vanes (i.e., $d_{ij} = d$), whose edges are arranged along an arc in such a way that 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 (Fig.4b), is equally shared between each vane of the MSDV structure [2-5]. The diffraction angle can be calculated using the following equation (obtained from simple geometric considerations):

$$\theta_d = a \tan \left(\frac{(D - (D_e/2) \cdot \sin \theta) \cdot \tan(\psi) - D_e \cdot \cos \theta}{D + (D_e/2) \cdot \sin \theta} \right) - R_{sun} \quad (2)$$

, where D_e is the diameter of the HI-01 camera entrance aperture, and R_{sun} is the solar angular radius as seen from 1 AU ($R_{sun} \approx 0.265^\circ$).

In the considered case, the heights of the i -th diffractive vane edge relative to the first vane edge (Hv_i , see Fig.4a) can be approximately calculated using the following fitting equation:

$$Hv_i(z_i) \approx u_0 + u_1 \cdot \text{ch} \left(u_2 \cdot \sqrt{z_i} \right) \quad (3)$$

, where (u_0, u_1, u_2) are the fitting parameters and z_i is the position of this diffractive vane.

MSDV structures of this type are preferred since they are the easiest to manufacture with the accuracy required for the intended application (using the machining tools available in our work). In addition, this design concept proved very successful in the previous project STEREO [2-5].

Thus, in this paper, we limit ourselves to a simplified analytical model specifically designed to model the optical response of MSDV structures of this type only. Since, in such structures, the height of the diffractive vanes is unambiguously determined by their relative positions, the number of adjustable parameters in the optimization procedure is reduced to two (see above), which significantly simplifies the practical implementation compared to MSDV structures with arbitrary vane arrangements.

Optimizing the MSDV structure design is an iterative process. Each iteration step begins by selecting the number of diffraction vanes Nd , and involves optimizing the distances between edges of adjacent vanes d to minimize the SLRC for the given configuration (i.e., for the chosen number of vanes). The MSDV structure optimization procedure is completed not merely when the SLRC value reaches the required target value, but when it becomes significantly lower than that, which ensures the stability of the FB's optical response to errors in its manufacturing and alignment.

2.3 FB optical response modelling

In the case of MSDV structures we consider in this work, the SLRC calculated for each of the intermediate diffractive vanes (from the second to the penultimate) will have the same values, and the overall SLRC of the FB can be calculated using the following equation [2-5]:

$$I_{tot} = \prod_{i=1}^{Nd} I_i \approx I_1 \cdot I_2^{n-2} \cdot I_{last}(x) \quad (4)$$

The terms I_i in this equation can be computed as follows:

$$I_1 = \frac{1}{2} \cdot \left[\left(\frac{1}{2} + C \left(\sqrt{\frac{2}{\lambda \cdot d}} \cdot x_1 \right) \right)^2 + \left(\frac{1}{2} + S \left(\sqrt{\frac{2}{\lambda \cdot d}} \cdot x_1 \right) \right)^2 \right] \quad (5)$$

$$I_2 = \frac{1}{2} \cdot \left[\left(\frac{1}{2} + C \left(\sqrt{\frac{4}{\lambda \cdot d}} \cdot \cos \gamma_2 \cdot x_2 \right) \right)^2 + \left(\frac{1}{2} + S \left(\sqrt{\frac{4}{\lambda \cdot d}} \cdot \cos \gamma_2 \cdot x_2 \right) \right)^2 \right] \quad (6)$$

$$I_{Nd}(x) = \frac{1}{2} \cdot \left[\left(\frac{1}{2} + C \left(\sqrt{\frac{2}{\lambda}} \cdot \left(\frac{1}{d} + \frac{1}{D} \right) \cdot \cos \gamma_{Nd} \cdot x \right) \right)^2 + \left(\frac{1}{2} + S \left(\sqrt{\frac{2}{\lambda}} \cdot \left(\frac{1}{d} + \frac{1}{D} \right) \cdot \cos \gamma_{Nd} \cdot x \right) \right)^2 \right] \quad (7)$$

, where λ is the wavelength of the incident light, the subscript 'Nd' labels the terms related to the last diffractive vane, the characteristic angles γ_2 and γ_{Nd} are defined as:

$$\gamma_2 = a \tan \left(\frac{tg \theta_2 + tg \theta_1}{2} \right) \quad (8)$$

$$\gamma_{Nd} = a \tan \left(\frac{D \cdot tg \theta_{Nd} + d \cdot tg \theta_{Nd-1}}{D + d} \right) \quad (9)$$

In the equations above, the terms $C(\omega)$ and $S(\omega)$ are the Fresnel's integrals defined as [6]:

$$C(\omega) = \int_0^{\omega} \cos \left(\frac{\pi}{2} \cdot x^2 \right) dx \quad (10)$$

$$S(\omega) = \int_0^{\omega} \sin \left(\frac{\pi}{2} \cdot x^2 \right) dx \quad (11)$$

The other variables and terms used in the set of equations above are explained in Figure 5 (see also Fig.4).

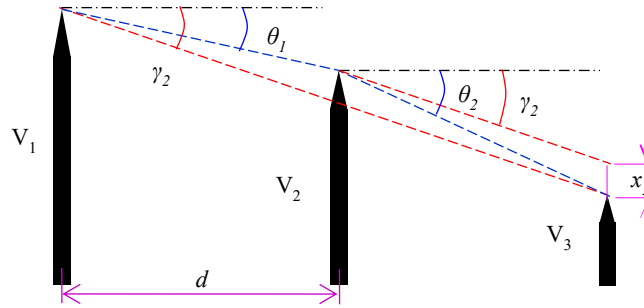


Fig.5. Characteristic angles and distances involved in calculating the optical response of the MSDV structure.

Fig. 6 shows the qualitative behaviour of the optical response of the MSDV structure under consideration, as predicted by the above analytical model.

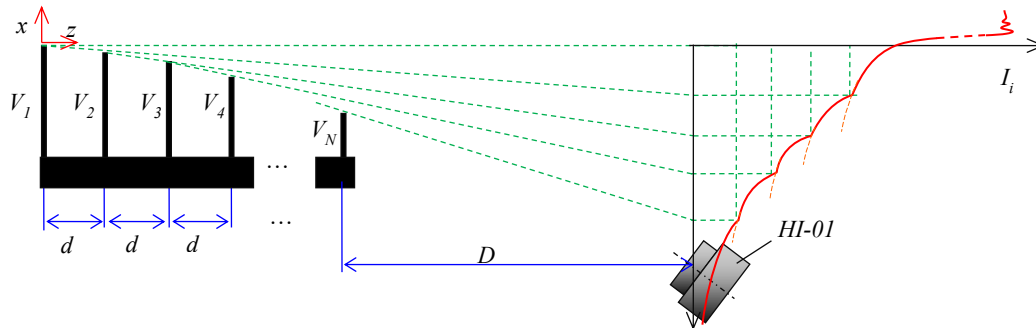


Fig.6. Optical response of the cascade MSDV structure (qualitative behavior; not in scale)

The stepped appearance of the SLRC graph in Fig.6 follows from the operating principle of the cascaded MSDV, according to which each intermediate diffractive vane partially blocks the light diffracted by the previous ones.

The set of equations above describe only the basic part of the analytical model used to calculate the optical response of the FB under consideration. In this paper, a number of simple relationships, not essential for understanding the calculation principle, are omitted for brevity and clarity.

In particular, the analytical method described above can only be applied to model MSDV structures in the so-called nominal configuration, which provides the maximum possible effectiveness in suppressing stray light. The simplifying approximation made on the right-hand side of Eq.4, according to which it is assumed that the contribution of each diffractive vane, from the second to the penultimate, to the SLRC of the MSDV is the same, is only valid for this configuration. However, it is not applicable for modelling the optical response of MSDV structures of arbitrary geometry (which is necessary, for instance, when studying the sensitivity of its optical response to the diffractive vanes manufacturing accuracy and/or FB alignment errors). In the latter case, the above equations must be rewritten in a slightly different form, which, of course, does not change their physical meaning and calculation principle. In this paper, for brevity, generalized equations for calculating the optical response of such MSDV structures are not provided, as these equations can be obtained straightforwardly using the standard scalar diffraction theory (SDT) [6].

The MATLAB simulation program developed in our work for numerically optimizing the design of MSDV structures involves a more complete set of equations, enabling calculation of the optical response of the structure for arbitrary diffractive vane heights. The results of the numerical study obtained using this simulation program are presented in the following paragraph.

In conclusion to this section, it would be useful to offer a few general comments on the limitations of the numerical model presented above, as well as on numerical approaches that enable more accurate modelling of MSDV structures.

First, the above analytical model is based on many simplifying assumptions and is, therefore, by definition, approximate. In addition to all basic simplifications adopted in the SDT, the numerical simulation method developed in our work is also limited to considering a simplified physical model of the MSDV structures. For example, numerical simulations of the optical response of these structures are performed without accounting for the dielectric properties of the materials from which they are made. Furthermore, instead of a two-dimensional wedge-shaped MSDV structure, the developed model numerically simulates an equivalent one-dimensional MSDV structure with linear knife-edge diffractive vanes.

Accordingly, this numerical model is suitable only for a rough estimate of the guaranteed level of stray light suppression at the first stage of the FB design optimization procedure (i.e., the upper limit value of the SLRC, which cannot be exceeded in more accurate calculations).

In this context, it should be noted that the objective of the FB design optimization, according to the Vigil HI instrument performance specification, is not so much to achieve a precisely specified value of the SLRC, but rather to ensure such a level of direct solar stray light suppression that does not exceed the threshold required for reliable observation of the solar corona and CME (i.e., 10^{-9} and 10^{-10} at the input of the HI-01 and HI-02 observation cameras). The use of approximate numerical solutions in optimizing the MSDV structure design is quite acceptable (provided, of course, that the above condition is met).

The presented approach provides the most reasonable compromise between the accuracy of numerical solution of the diffraction problem in the far-field zone and the required computational time. This is especially important in studying the sensitivity of the MSDV structure optical response to errors in its manufacturing and alignment (since in such a study, the number of design parameter configurations, randomly generated for the MSDV structure under investigation, for which the optical response should be calculated, can exceed several thousand).

As for other methods of numerical modelling of the optical response of MSDV, the most accurate results can be obtained using finite element methods (FEM) and the corresponding commercially available software that provides rigorous solutions to Maxwell's equations (such as COMSOL, OPTIWAVE, etc.). However, FEM has a significant drawback: a very high computation time, which increases rapidly with the size of the computational domain. Accordingly, FEM software commonly provides only near-field solutions, while the far-field ones, describing the propagation of electromagnetic waves to the plane of the entrance aperture of the HI instrument, are calculated using auxiliary software tools that involve conventional diffraction theory. Therefore, despite the high accuracy of the near-field solutions obtained from FEM simulations, the far-field solutions, which are of real practical interest in our case, will still be approximate. In other words, in our particular case, the advantage of high numerical accuracy provided by FEM numerical approaches cannot be fully realized.

For the above reasons, the numerical approach presented in this paper appears to be the most practical for optimizing the design of MSDV structures, despite the relatively low accuracy of the results.

3. NUMERICAL STUDY RESULTS

Table 1 provides the parameter values used as input to the MSDV structure optimization procedure (as specified by the Vigil HI instrument requirements).

Table 1: Input constraint parameters used in the MSDV structure optimization procedure

Design parameters (cf. Fig.4)	Value
HI camera's Field-Of-View (FOV)	32°
Critical angle (ψ)	$3,8^\circ$
HI camera's input aperture diameter (D_e)	19,5 mm
HI camera's input aperture position (D)	549,7 mm

As a result of numerical optimization of the design of the MSDV structure, it was found that, for the input parameters values given in Table 1, in order to achieve the required SLRC value (i.e., at least 10^{-9} and 10^{-10} at the input aperture of the HI-01 and HI-02 observation cameras), this structure should involve at least $Nd = 8$ equidistantly separated diffractive vanes with spacing of 10.5 mm.

Figure 7 shows the heights of diffractive vane edges (Hv_i for $i = 1..8$) as a function of their positions (P_i) relative to the first vane tip.

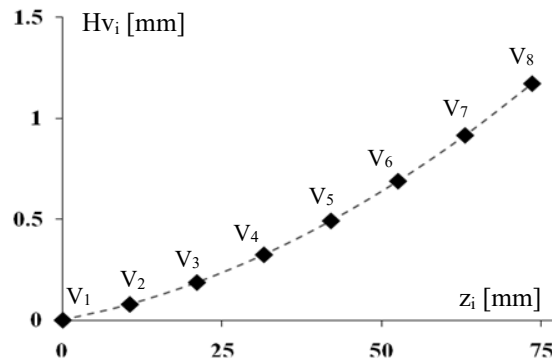


Fig.7. MSDV structure nominal configuration: heights (Hv_i) and relative positions (P_i) of the diffractive vane edges relative to the first vane tip (cf. Eq.3)

Figure 8 depicts the results of the SLRC calculations performed using the above-presented analytical model for the nominal MSDV structure configuration (cf. Fig. 7 for different vane heights and positions).

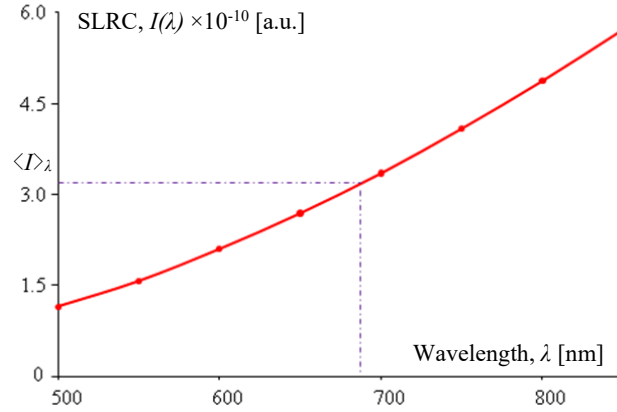


Fig.8. SLRC values calculated at the entrance aperture of the HI-01 camera for the MSDV structure in the nominal configuration

The average spectral SLRC value calculated for the nominal MSDV design configuration is approximately 3.20×10^{-10} and 1.39×10^{-11} for HI-01 and HI-02 cameras, respectively (i.e., it closely meets the design requirements).

Regarding the impact of MSDV structure manufacturing inaccuracies on the performance of the FB, this was investigated numerically using the Monte Carlo method. That is, using a random number generator, a set of MSDV structures with a random distribution of heights of diffractive vanes was created, assuming that inaccuracies in the heights of the wedges follow a normal distribution with mean values corresponding to the heights calculated for the nominal configuration and the standard deviation value corresponding to the manufacturing precision. Then, for each of these structures, the corresponding SLRCs are calculated using the analytical model presented above (Eqs.4-11). Finally, the results of these calculations were analysed using conventional statistical methods.

Typically, to obtain reliable statistical data in a numerical test, the dataset contained up to several thousand (at least 2000) randomly generated configurations.

The tolerance study results suggest that the permissible manufacturing inaccuracy of the MSDV structure under consideration, in terms of diffractive vane edge heights, is about $\delta H v_i \approx \pm 10 \mu\text{m}$. The high-precision machining method used allows for significantly higher manufacturing accuracy.

Finally, as part of the tolerance study, we also conducted a numerical analysis of the SLRC's sensitivity to FB assembly alignment errors (using the analytical model presented above).

From the results of this study, it can be concluded that the average spectral SLRC of the MSDV structure, calculated for misalignment of ± 1 [arcmin] from the nominal configuration, does not exceed the permissible limits specified by design technical requirements (i.e., 10^{-9}) and the SLRC's sensitivity to alignment errors does not exceed $3 \cdot 10^{-11}$ [arcmin $^{-1}$]. In this context, with the equipment at our disposal, the alignment accuracy of the FB assembly is no worse than 1 arc minute (i.e., ± 30 arc seconds).

4. EXPERIMENTAL STUDY

4.1 MSDV structure manufacturing

As noted above, the MSDV structure is made from a bulk aluminium block. However, since aluminium is a relatively soft metal with high plasticity, precisely shaping the diffractive vane edge profile through mechanical processing (cutting, milling, diamond turning) is, in practice, extremely challenging.

On the other hand, according to the FB operating principle, it is precisely the diffractive vane edge that determines the intensity distribution of the diffracted light field in the far zone (since the interaction between the incident light wave and the diffractive vane is localized at its edge). Accordingly, when developing the process for manufacturing the MSDV structure, the strictest requirements should be imposed precisely on the quality of the vane edges (especially, regarding the absence of microdefects).

In our work, to tackle this challenging task, that is to prevent the formation of micro-defects on the diffractive vane edges due to the high plasticity of aluminium, it was proposed to perform the high-precision finishing of the MSDV structure using two-stage diamond turning.

The proposed approach is illustrated in Figure 9.

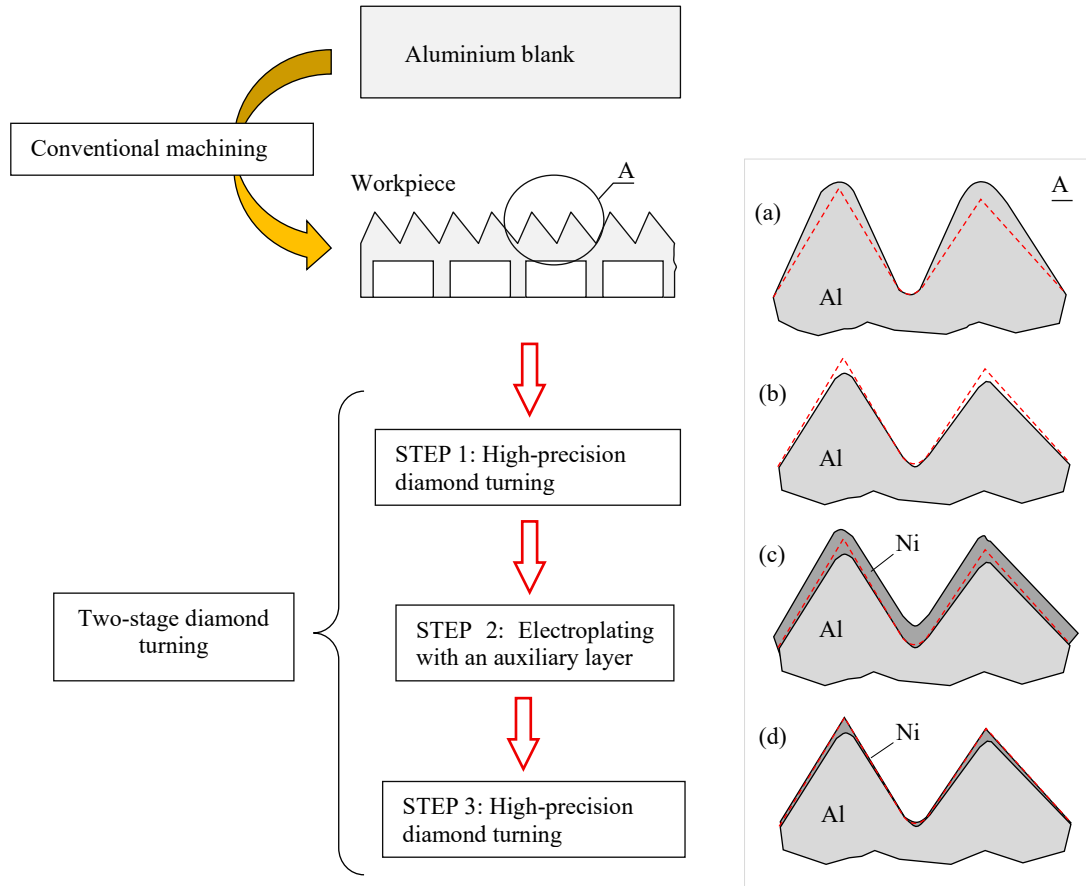


Fig.9. Principle of MSDV structure fabrication. The inset figure depicts the enlarged view of the diffractive vane structure: (a) before and (b) after the first diamond turning; (c) after electroplating this structure with a Nickel-based alloy layer; (d) after the second diamond turning. The red dashed line shows the nominal vane edges profile. Note: for the sake of brevity, this figure shows only the basic steps of the proposed approach

As indicated in Figure 9, in the first stage, a workpiece is manufactured from the primary aluminium blank, whose shape and dimensions are close to those of the designed FB. The workpiece can be made from an aluminium blank using conventional machining methods (high-precision milling, linear shaping, drilling, etc.).

Then, the first diamond turning of the workpiece is performed. After this stage, the multi-wedge structure of the workpiece is electroplated with an auxiliary Nickel-based alloy layer. After completion of this process, the workpiece undergoes the second diamond turning.

The plasticity of the auxiliary nickel layer is significantly lower than that of the aluminium substrate. This makes it possible to significantly reduce the risk of microdefect formation during the second diamond turning of diffractive vanes edges (compared to the first diamond turning of the aluminium substrate).

The technological process of MSDV manufacturing is completed by their cleaning of fabrication residues and surface coating.

As for the choice of materials for the FB coating, it is dictated by each surface's functional role and, consequently, its location on the FB.

For example, a high-reflective coating (gold) is preferable on the first edge of the multi-wedge structure, which reduces the magnitude of MSDV temperature variations due to direct sunlight absorption. The rear surfaces, as well as the last edge of the FB, are preferably coated with a black coating, which reduces the risk of stray light reflected from these surfaces entering the HI camera lens.

4.2 Measurement bench

As noted above, the HI FB should provide a required level of the stray light suppression better than 10^{-9} . This requirement entails the necessity of accurately measuring extremely weak optical signals (on the order of 10^{-11} W). The practical implementation of a method for reliably calibrating the fabricated MSDV structure, and, primarily, the corresponding measurement bench, is a non-trivial engineering problem.

That accurate measurement of the optical response of MSDV structures becomes practically unfeasible at stray light suppression efficiency better than 10^{-8} , due to the relatively large contribution to the measured signal of stray light resulting from light scattering in air [2-4]. Accordingly, the FB on-ground calibrating test must be performed in a vacuum environment. In addition, the detector assembly of the measurement bench must be able to measure optical signals over a very large dynamic range: from units of watts during reference measurements to tens of picowatts when measuring the optical response of the MSDV structure under test. Accordingly, it must support two detection modes: conventional energy-integrating and photon-counting.

Figure 10 shows the optical calibration bench developed by the CSL team to characterize the FB.

It was built on the measurement bench previously developed by our research team within the framework of the STEREO project [3-5].

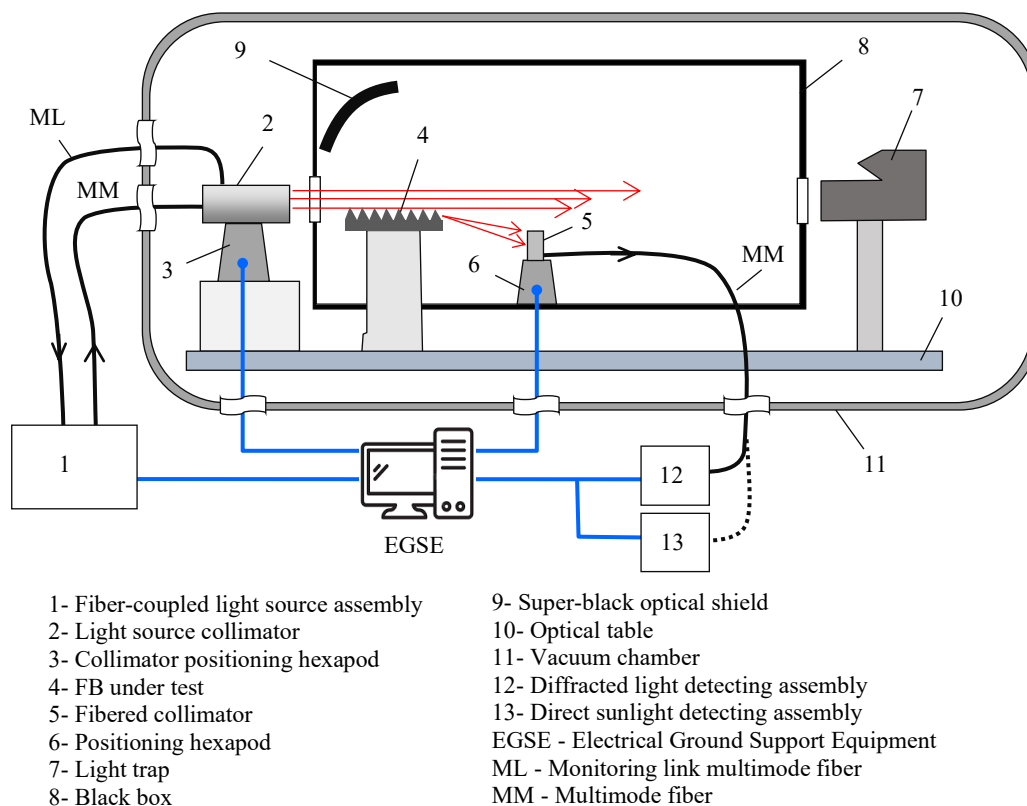


Fig.10. Measurement bench for characterization of the FB (simplified functional diagram)

The optical part of the calibration bench consists of a fiber-coupled light source assembly (1), a dedicated optical collimator (2) mounted on a collimator positioning hexapod (3). The FB under test (4) is fixed on a supporting frame installed between the light source collimator (2) and the fibered collimator (5) of the detector assembly. The latter collimator 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. The light source collimator (2) assembly produces a collimated pencil beam with a rectangular cross-section using a dedicated beam-shaping baffle assembly.

The intensity of stray light entering the detector's collimator aperture, due to scattering and stray reflections within the measurement bench, must be significantly lower than the measured intensity of light diffracted by the MSDV structure under test. To fulfill this requirement, appropriate studies were conducted, resulting in the following engineering solutions:

- The upper part of the collimated pencil beam, not interacting with the MSDV structure under test, is projected onto the entrance of a highly absorbing rear light trap (7);
- The free space optical part of the bench, except for the light source assembly, is placed in a large volume black box (8), with high isolation from light interference;
- A super-black optical shield (9) with VANTABLACK coating was installed in front of the FB under test (this optical shield absorbs stray light reflected/scattered by the FB);
- The entire metrology bench with the optical table (10) is placed in a large volume vacuum chamber (11).

The FB SLRC measurement procedure involves two operating modes: reference and scanning.

In the former mode, the FB under test is outside the source to detector collimators optical path, and the detector collimator is moved to the center of the incident light beam. The measurement bench is switched to this operating mode to measure the irradiance of the collimated laser beam during bench calibration. 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 (caused by thermal fluctuations, supply voltage fluctuations, etc.) from the SLRC measurement data.

As for the scanning mode, in this case, the FB under test (4) is partly illuminated by the collimated laser beam, and the detector collimator (5) is successively moved using the positioning hexapod (6) deeper into the shadow region behind the FB. 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).

The switching between two operating modes is carried out using two hexapods, while the FB under test itself remains fixed in the laboratory coordinate system (associated with the vacuum chamber).

The optical response of the MSDV structure is measured using a diffracted light detecting assembly (12) operating in photon-counting mode (since the photon flux of light diffracted by this structure is extremely weak).

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.

As for the practical implementation of the reference measurement, the intensity of the collimated laser beam (simulating 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. Neutral-density filters are used to optimize the dynamic range of the direct-sunlight-detecting assembly.

The practical implementation of the above measurement bench required the development of several non-standard functional modules, including the fiber-coupled light source assembly (1) and the rear light trap (7).

Figure 11 shows the functional diagram of the fiber-coupled light source assembly (1 in Fig.10).

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 a relay optical system designed to monitor the light source's output power. 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 (1 in Fig.10) is mounted outside the vacuum chamber for accessibility purposes, and it is linked to the light source collimator (2 in Fig.10) assembly by two vacuum-compatible multimode fibers: 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, in the measurement data, the effect of uncontrollable fluctuations in the output power of the light source assembly. Thus, the implemented concept of the measurement bench involves the method of dual-loop monitoring of the laser probe beam optical power, which ensures an extremely high accuracy and precision in measuring the optical response of the FB under test.

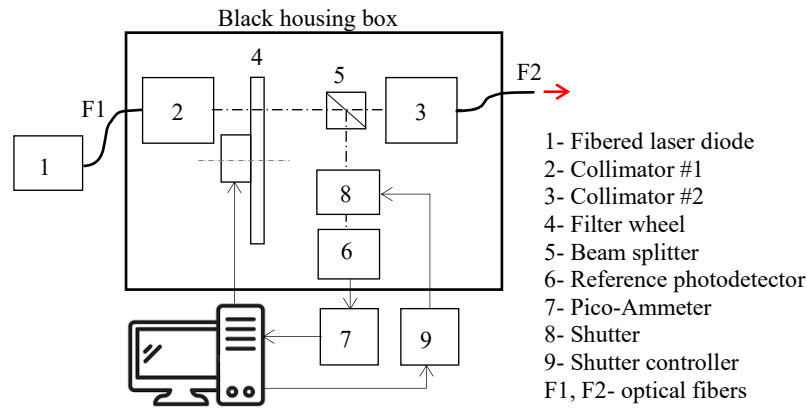


Fig.11. Light source assembly (schematic functional diagram)

Figure 12 depicts the schematic diagram and 3D CAD model of the rear light trap (7 in Fig.10).

The design of this trap is based on the two-stage baffling concept, whose high efficiency was demonstrated in the STEREO project. 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 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.

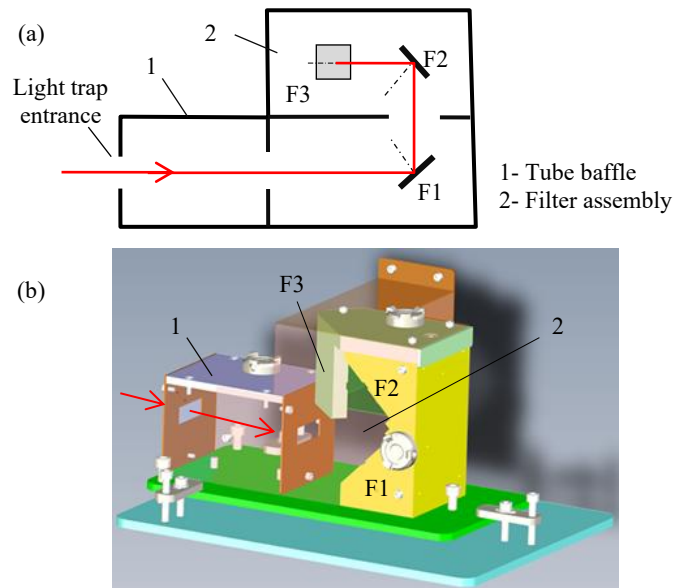


Fig. 12. Rear light trap schematic diagram: (a) assembly schematic diagram; (b) 3D CAD model

Almost all of the above functional modules are implemented using commercially available components.

To conclude this section, the developed measurement bench is a rather complex and expensive metrology system, the implementation of which required significant engineering effort and numerous auxiliary experimental studies, the details of which are omitted in this article. A more detailed description of some of these subsystems and components can be found in our earlier publications [2-4] and in our forthcoming papers.

5. CONCLUSIONS AND PERSPECTIVES

In this paper, we introduce an original concept of the Forward Baffle (FB) of the ESA Vigil Heliospheric Imager, as well as an innovative measurement bench developed for calibrating this baffle. The FB under consideration includes a multi-stage diffractive vanes (MSDV) structure and a dedicated supporting assembly.

The presented measurement bench implements a high-precision approach for stray-diffracted-light metrology, enabling measurement of the optical response of MSDV structures designed to achieve a stray-light suppression level better than 10^{-9} [a.u.]. The measurement approach implemented in the presented bench involves the dual-loop monitoring of the laser probe beam optical power, which allows bypassing the issues related to the impact on the total error budget of the measurement system instability, stray light, residual fluctuations in the intensity of the light source, etc.

Finally, in this paper, we also discuss some key engineering aspects of the FB practical implementation (such as the numerical design optimization principle, the manufacturing method of the MSDV structure, etc.).

The practical implementation of the introduced optical concept of the FB and metrological approach to its on-ground calibration is currently in progress. A specific paper will be published soon after the first experimental validation of the above instrumental approaches.

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