

OPTICAL DESIGN OF THE VIGIL HELIOSPHERIC IMAGER

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ABSTRACT

Vigil Heliospheric Imager (HI) is one of the instruments onboard the European Space Agency Vigil mission. The aim of the mission is to perform observations of the space between the Sun and the Earth from the L5 Lagrange point, to provide measurement data for space weather and to monitor solar activity. Vigil HI have a focus on detecting slow and faint phenomena of Coronal Mass Ejection (CMEs), with signal levels as low as few percent of the background, and on monitoring their propagation along the ecliptic plane and as they travel towards Earth.

The main optical components of the Vigil HI optical bench include a baffling system, consisting of a front baffle and an inner baffle, and two optical imagers composed by an optical assembly integrated with a focal plane array (HI-01 and HI-02) and enclosed by a protective camera cover.

The front baffle (FB) is a diffractive rejection system designed to minimize straylight from the solar disk entering the cameras entrance pupil, while the inner baffle (IN) is designed to reduce out of field straylight on the optical bench caused by bright planetary sources, both static and dynamic, moving across the ecliptic plane. The instrument features a double camera optical imager (HI-01 and HI-02) based on a dioptric system, resulting from a trade-off between achieving optical quality over a wide field of view and board spectral bandwidth, while complying with volume envelope constraints. These cameras cover a field of view from 4° to 50° in elongation angle and $\pm 32^\circ$ outside the ecliptic plane. Both cameras share the same optical layout, composed of 6 lenses and a spectral bandpass filter exposed to the space. A key design feature is the positioning of the entrance pupil close to the mechanical aperture. This configuration, which is usually uncommon, is useful to maximize the efficiency of the front baffle within the allocated volume.

The paper presents the opto-mechanical design of the barrels, describing both optical and mechanical design. The optical performance of the system is assessed, along with the design solutions implemented to optimize the overall instrument performance. An overview of the operating principle of the diffractive baffle and the design criteria of the inner baffle is also provided, highlighting the integrated approach adopted to achieve the required performance in a compact instrument.

Keywords: VIGIL, Heliospheric Imager, Optical Design, Straylight, Baffle Design

1. INTRODUCTION

The observation of Coronal Mass Ejections (CMEs) in the inner heliosphere requires optical instruments capable of detecting extremely faint signals in the presence of much brighter radiance sources. As a consequence, straylight rejection often becomes a primary design driver, influencing not only the baffling architecture but also the optical layout and mechanical implementation of the instrument.

The Vigil Heliospheric Imager (HI) was developed to meet these challenges through a compact dual-camera architecture combining wide-field imaging capabilities with a multi-level straylight mitigation strategy. The design was driven by the need to achieve the required optical performance while ensuring efficient rejection of solar and planetary straylight within a constrained volume envelope.

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This paper describes the optical and opto-mechanical design of the Vigil HI cameras and presents the integrated approach adopted for straylight control, including the camera barrel design, the implementation of dedicated lens mounting solutions and the instrument baffling architecture.

2. SYSTEM OVERVIEW

2.1 Instrument architecture

The Vigil Heliospheric Imager (HI) consists of two identical optical channels, namely HI-01 and HI-02, mounted on a common optical bench together with a dedicated straylight suppression assembly, see Figure 1. The instrument is designed to observe Coronal Mass Ejections (CMEs) over a wide angular region extending from approximately 4° to 53° elongation from the Sun and $\pm 16^\circ$ outside the ecliptic plane, corresponding to a total angular coverage of 32° . The overall architecture combines two camera assemblies, a Front Baffle providing solar disk rejection and an Inner Baffle dedicated to the suppression of planetary and background straylight. These subsystems were developed as a single integrated solution to satisfy the stringent radiometric requirements of heliospheric imaging.

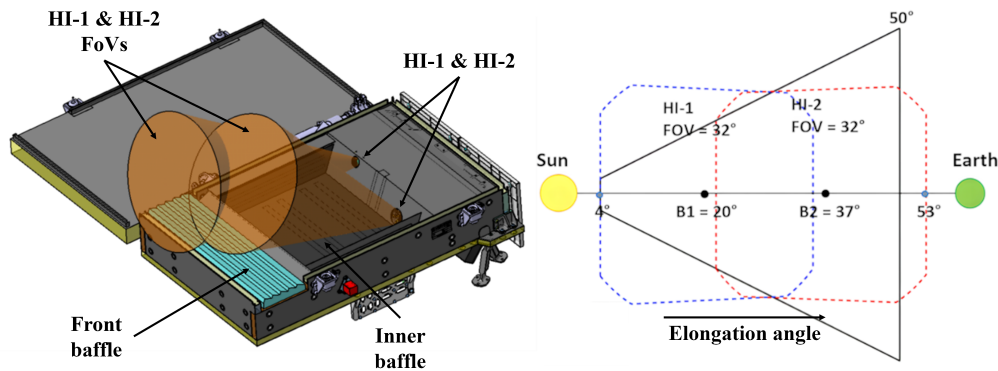


Figure 1. Vigil HI architecture overview.

2.2 Design drivers and constraints

The design of the Vigil HI optical system was driven by a combination of challenging optical, mechanical, and straylight requirements. From an optical perspective, the instrument is required to deliver adequate image quality over a large angular coverage while operating across the broad spectral range from 500 nm to 850 nm. These requirements favor a refractive architecture capable of controlling aberrations over a wide field of view. At the system level, severe packaging constraints imposed a highly compact camera design. The optical train, mechanical barrel, and straylight suppression features had to be accommodated within a limited volume allocation on the optical bench. A key design driver originated from the Front Baffle architecture. The efficiency of the diffractive rejection system is strongly dependent on the position of the entrance pupil. To maximize solar rejection and minimize the acceptance of diffracted light propagating from the baffle towards the optics, the entrance pupil was intentionally moved close to the external aperture of the instrument. This solution differs from conventional refractive imagers, where the stop is typically located deeper inside the optical train. Although beneficial for straylight suppression, this choice significantly constrained the optical optimization process and required the entire optical layout to be developed around the pupil location. The final architecture therefore results from a trade-off between field of view, image quality, compactness, and interaction with the straylight control system. Consequently, the optical layout, camera barrel and baffling subsystems were not designed independently but optimized concurrently as part of a unified straylight mitigation strategy.

3. OPTICAL DESIGN OF THE CAMERA ASSEMBLY

3.1 Optical configuration

The two optical channels, HI-01 and HI-02, share an identical optical design. Each camera, characterized by an F-number of 3.35, provides a full field of view of 32° and operates over the spectral range from 500 nm to 850 nm. The optical system is optimized for operation in vacuum at a nominal temperature of -32°C . The design can also be operated and tested at ambient conditions, although with a predictable degradation of optical performance due to the different thermo-optical environment. Following a trade-off analysis, a dioptric architecture was selected as the most effective solution to achieve the required image quality over the wide field of view while maintaining compliance with the stringent envelope constraints imposed at instrument level. The optical assembly consists of six lenses preceded by a band-pass filter directly exposed to the space environment. One of the lenses incorporates an aspheric surface that contributes to the correction of off-axis aberrations across the full field. The entrance pupil is defined by an aperture stop positioned between the band-pass filter and the first lens of the system. This unconventional stop position was selected to improve the coupling between the optical system and the Front Baffle and represents one of the key features of the instrument architecture. The total length from the filter to the focal plane is approximately 84 mm.

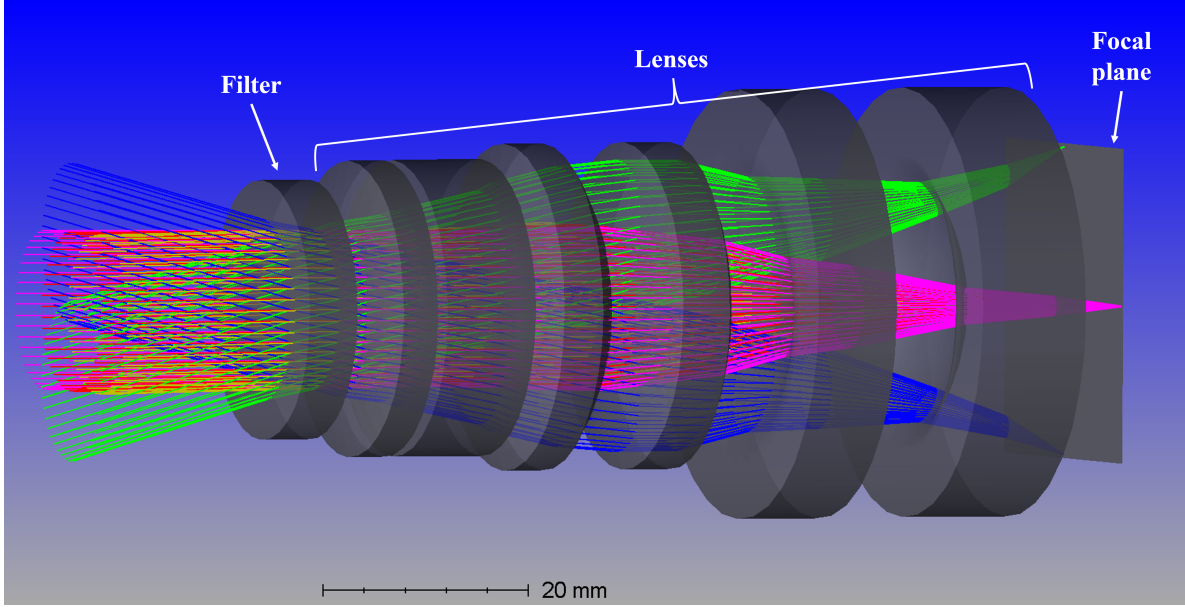


Figure 2. Optical layout of the HI cameras.

Table 1. Main optical parameters of the HI cameras.

Parameter	Value
F-number	3.35
Field of view	32°
Spectral range	500–850 nm
Optical length	84 mm

The selection of optical materials was driven by three primary criteria:

- optical performance over the required spectral range;
- resistance to radiation-induced transmission degradation;
- thermal stability compatible with operation around -32°C .

The final material set includes radiation-resistant optical glasses selected to preserve transmission throughout the mission lifetime despite the expected space radiation environment. Particular attention was devoted to the use of calcium fluoride (CaF_2) for some lenses. These elements provide a significant contribution to the chromatic correction of the optical system over the broad spectral bandwidth, but require dedicated mounting solutions due to their relatively fragile nature and sensitivity to thermo-mechanical loads.

3.1.1 Optical performances

The optical design was optimized to provide near diffraction-limited performance over the entire field of view while maintaining compatibility with the compact instrument envelope and straylight-driven pupil location. Figure 3 shows the spot diagrams evaluated at several field positions across the full FoV. The spot size remains well contained within the detector pixel area throughout the field, demonstrating good control of both on-axis and off-axis aberrations despite the wide angular coverage. The resulting image quality is confirmed by the encircled energy analysis, which shows diffraction-limited performance at the required radius for all field points. Similarly, the Modulation Transfer Function (MTF) remains close to the theoretical diffraction limit, reaching approximately 98% of the diffraction-limited response at the specified spatial frequency. Geometrical distortion is maintained below 1% across the field of view, ensuring accurate localization of observed heliospheric structures and simplifying subsequent image processing activities.

The main optical performance parameters are summarized below:

- Spot diagrams compliant with the detector sampling requirements;
- Encircled energy: diffraction-limited at the specified radius;
- MTF: approximately 98% of the diffraction limit at the specified spatial frequency;
- Distortion: below 1% over the full field of view.

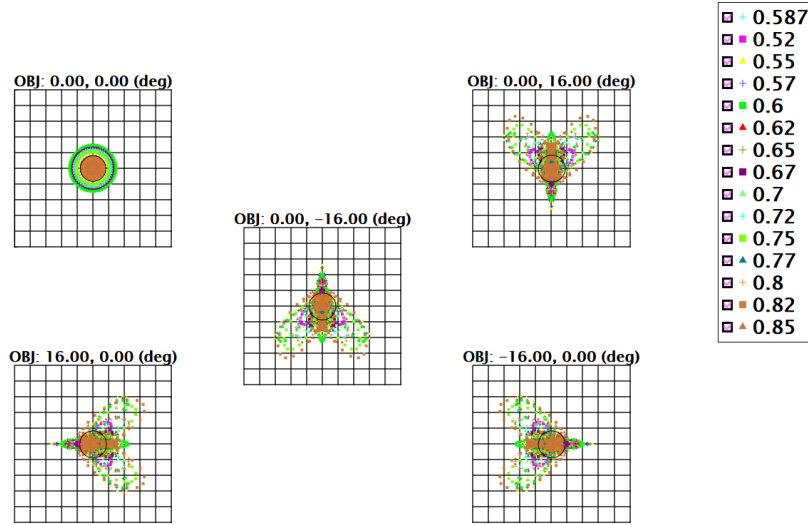


Figure 3. Spot diagrams across the field of view for the nominal optical design. The box size corresponds to the detector pixel size.

4. STRAYLIGHT MITIGATION ARCHITECTURE

4.1 Straylight environment

The observation of CMEs requires the detection of extremely faint structures embedded within a scene dominated by significantly brighter sources. As a result, straylight minimization represents a primary design driver for the instrument. Potential straylight sources can be divided into static and dynamic contributors. Static contributors include the solar disk, the F-corona and K-corona, the galactic and stellar background, and the Earth, located at approximately 60° elongation angle. Dynamic contributors are mainly represented by bright planets moving across the ecliptic plane during mission operations. To satisfy the required sensitivity, a multi-level straylight mitigation strategy was implemented combining the Front Baffle, the Inner Baffle and internal camera baffling features.

4.2 Straylight optimization with opto-mechanical design

In addition to the external baffling architecture, a dedicated straylight suppression strategy has been implemented within the camera barrel itself. A series of internal diaphragms is distributed along the optical path, with one or more apertures positioned between successive optical elements, as shown in Figure 4. These diaphragms are designed to intercept unwanted off-axis radiation before it can propagate further within the optical system and contribute to the detector background signal. Their geometry and position were optimized through non-sequential straylight analyses in order to maximize the rejection of out-of-field light while preserving the nominal field of view and avoiding vignetting of the useful beam. The internal diaphragms also contribute to limiting the propagation of scattered light and reducing the possibility of multiple reflection paths between optical and mechanical surfaces. As a result, the camera barrel acts not only as a mechanical support structure for the optical elements, but also as an active component of the overall straylight mitigation architecture.

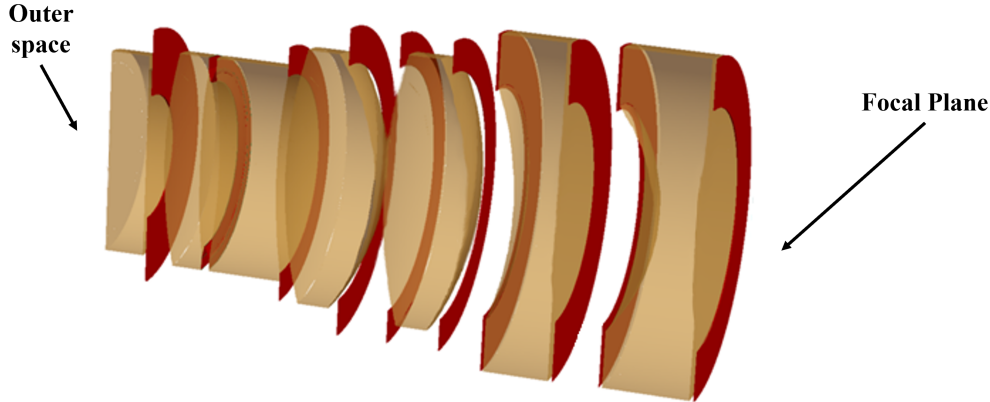


Figure 4. Cross section of the camera barrel showing the internal diaphragms (highlighted in red) used for straylight suppression.

4.3 Front Baffle

The VIGIL HI front baffle sub-system is one of the critical items of the whole instrument. The function of the front baffle is to attenuate the Sun light irradiance, down to an acceptable level for the scientific objectives of the faint CME imaging. Starting from the instrument stray light suppression needs, the front baffle Sun light irradiance attenuation at HI-01 camera aperture shall be less than 10^{-9} , while at HI-02 camera one less than 10^{-10} . Such attenuation performance can be achieved with a cascade multi-stage-diffractive-vane (MSDV) structure, as already demonstrated in previous generation heliospheric imagers like STEREO^{1,2}. In a cascade MSDV the direct Sun light pass through a set of diffractive vanes is successively diffracted at the edge of vanes. Each intermediate vane, starting from the second, partially blocks the light diffracted by the previous one. Figure 5 compares the attenuation of single diffractive vanes with that of a MSDV structure. The attenuation

of the single diffractive vane is enhanced by that of the following diffractive vanes. The Sun light irradiance attenuation profile at the camera aperture is given by the product of the attenuations of each single diffractive vanes joined in the MSDV structure^{1,2}. With a MSDV it is possible to reach the requested Sun light attenuation keeping the instrument envelope, in terms of distance between the MSDV and the camera apertures, much smaller respect the case of a single diffractive vane.

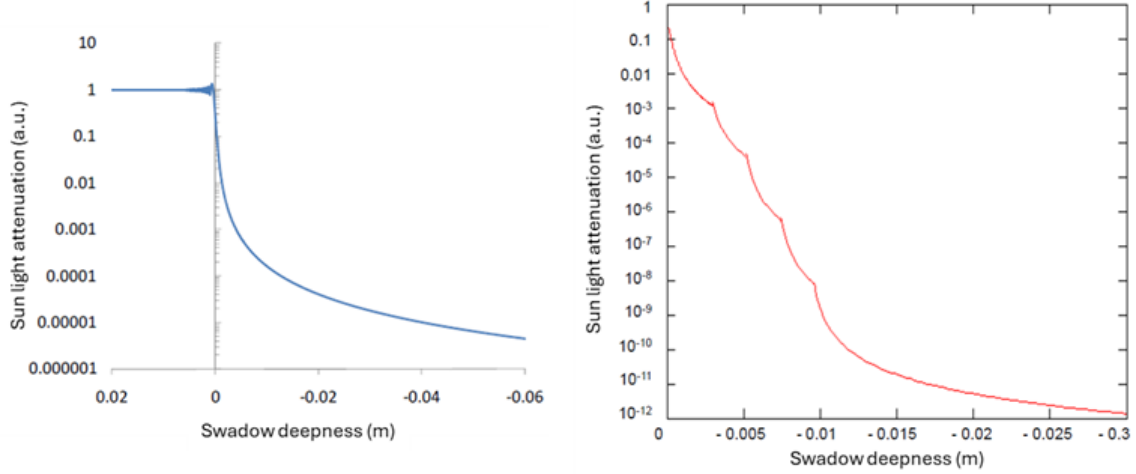


Figure 5. Comparison between Sun light irradiance attenuation at 500 nm wavelength and at a distance of 500 mm form single diffractive vane (left) and a MSDV structure made by five diffractive vanes.

The design and procurement of Vigil HI front baffle is in charge of CSL (Centre Spatial de Liège). The MSDV optimization approach is the same followed for STEREO HI front baffle, but the final design is different. The VIGIL HI cameras are not placed one above the other in the instrument symmetric plane like in STEREO HI, but are mounted side by side with an horizontal offset. Such architecture allows to split the single MSDV structure of STEREO in two independents smaller MSDV structures one of each cameras. These two MSDV structures share the same design made by 8 equidistance diffractive vanes. The Sun light irradiance as-design performance, averaged over the VIGIL HI waveband from 500 nm to 850 nm, is 3.20×10^{-10} for HI-01 camera and 1.39×10^{-11} for HI-02 (see Figure 6).

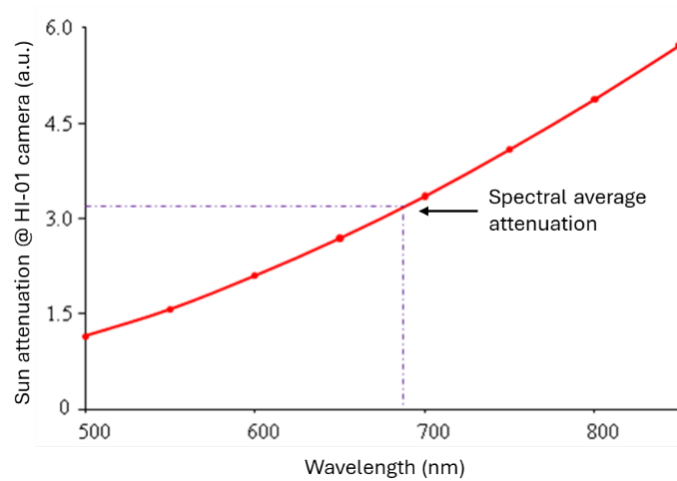


Figure 6. Sun light irradiance attenuation at the entrance aperture of HI-01 camera

Because of the reduced dimensions, each MSDV will be machined from a single light weighted aluminum blank. The vanes will be replaced by a wedged shaped geometry structure. The tight mutual position tolerance between vane top edged can be reached Nickel plating the pre-machined aluminum structure followed by a high precision diamond turning machining. This approach significantly simplifies the alignment procedure respect the case of STEREO where each vane of the MSDV was independently aligned. Furthermore, the wedge geometry ensures very high thermo-mechanical stability, and, therefore, low sensitivity of its optical response to temperature fluctuations.

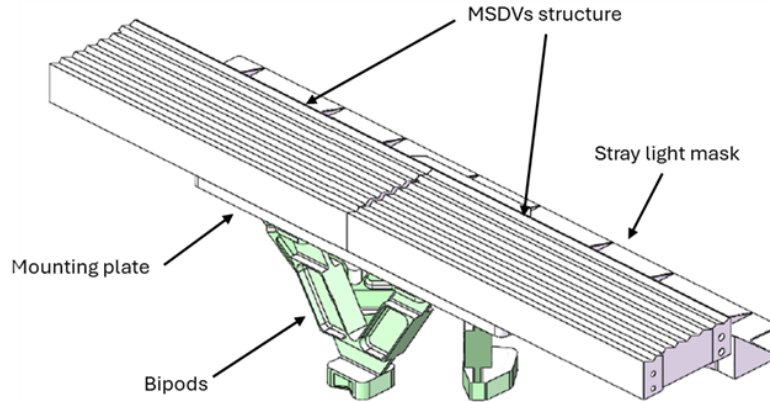


Figure 7. Front baffle structure.

The two MSDV structure are joined together on a mounting plate (Figure 7). In order to prevent stray light and light leakage, the interface between the two MSDV will be manufactured and mounted with a high precision system. Moreover, the interface is equipped with a light trapping structure. The mounting plate is connected to a set of three titanium bipods which provides the feet for the installation and alignment of the front baffle on the instrument baseplate. The bipods design and relative positions have been optimized to ensure the required stiffness and not exceed the specified interface loads at the instrument baseplate, and at the same time, been insensitive to vibrations and thermal fluctuation.

4.4 Inner Baffle

The Inner Baffle is positioned between the Front Baffle and the camera assemblies and is intended to suppress straylight generated by the Earth, diffuse scene background and other off-axis sources. The adopted architecture consists of an aluminum structure incorporating a series of tilted vanes coated with highly absorbing black surfaces (see Figure 8). The vane distribution is designed to block direct lines of sight between illuminated surfaces and the camera apertures while forcing multiple reflections on low-reflectance surfaces. Particular attention was devoted to the Earth contribution, identified as one of the dominant off-axis straylight sources. The vane orientations were optimized through non-sequential FRED analyses to minimize the irradiance reaching the camera entrance apertures. In addition to the main vane set, a dedicated vane is located near the interface with the Front Baffle to limit reflections generated by the last diffractive edge. Several design configurations were investigated, including different vane layouts and alternative coating technologies. The final solution resulted from a trade-off between optical performance, manufacturability and technology readiness.

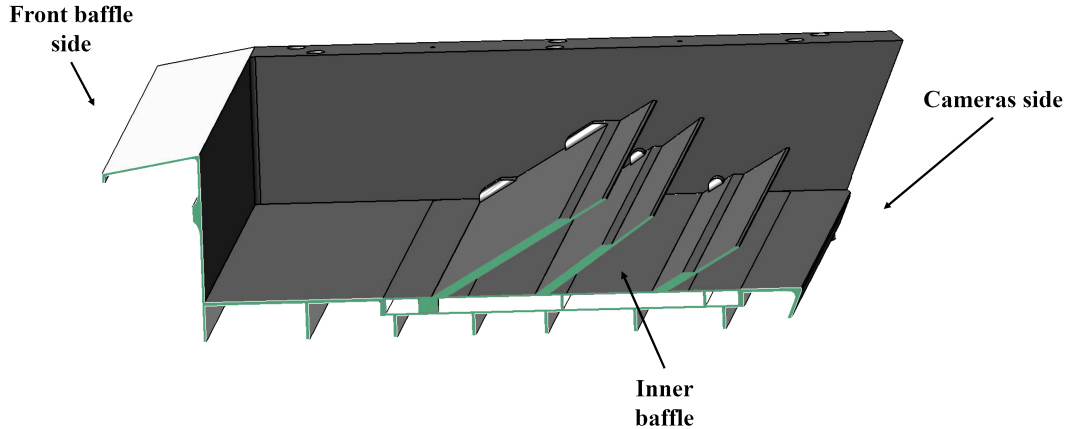


Figure 8. Inner baffle architecture showing the optimized vane arrangement.

5. CONCLUSIONS

The Vigil HI optical design combines a compact wide-field dioptric optical system with a multi-level straylight mitigation architecture. The unusual location of the entrance pupil near the mechanical aperture enables effective coupling with the diffractive Front Baffle while preserving optical performance within the available volume envelope. Dedicated opto-mechanical solutions were implemented to accommodate sensitive optical materials and maintain alignment stability. The combination of the Front Baffle, Inner Baffle and internal barrel stops provides the straylight rejection required for heliospheric imaging in the challenging solar observing environment.

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