

The VIGIL Heliospheric Imager: addressing operational straylight challenges for high-availability Space Weather monitoring

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ABSTRACT

The ESA Vigil mission will provide continuous operational Space Weather monitoring from the Sun-Earth L5 Lagrange point. Within the mission payload suite, the Heliospheric Imager (HI) is responsible for observing Coronal Mass Ejections (CMEs) as they propagate through the inner heliosphere, supporting accurate and timely forecasting of potentially hazardous solar events.

Due to the requested observational geometry and wide Field of View (FOV) of HI, the instrument regularly will encounter bright planetary sources along or near the ecliptic plane. Among these, Venus represents the most critical contributor to scene-dependent straylight. This paper assesses the impact of planetary straylight on Vigil HI observations through radiometric simulations and analysis of heritage heliospheric imaging data.

End-to-end radiometric modelling based on instrument Single Point Source Transmittance (SPST) maps indicates that Venus-induced straylight can significantly degrade the detectability of faint CME signatures during substantial fractions of the mission lifetime. These findings are supported by analyses of historical STEREO/HI observations, providing experimental evidence of similar contamination effects in flight data. A temporal analysis of planetary viewing conditions further shows that Venus will remain within or close to the instrument field of view for a large portion of routine operations.

Building on Leonardo's experience with advanced Earth Observation instruments, an initial assessment of achievable straylight correction performance is presented, together with a preliminary identification of the dominant contributors to correction error. The results demonstrate that dynamic mitigation of planetary straylight is a key enabling capability for maintaining the observational availability and operational performance of the Vigil Heliospheric Imager.

Keywords: Vigil, Heliospheric Imager, Space Weather, Coronal Mass Ejections, Straylight correction

1. INTRODUCTION

The ESA Vigil mission will establish a permanent operational capability for Space Weather monitoring from the Sun-Earth L5 Lagrange point, enabling continuous observations of solar activity and the heliosphere for forecasting and warning applications [1]. Within the mission payload suite, the Heliospheric Imager (HI) is the only instrument dedicated to the observation of the interplanetary medium between the Sun and Earth and the tracking of Coronal Mass Ejections (CMEs) during their propagation toward Earth.

The instrument is a wide-field visible-light radiometer (Figure 1, left image) composed of two optical channels, HI-01 and HI-02, covering elongation angles from 4° to 50° along the ecliptic plane and $\pm 30^\circ$ outside the ecliptic projection. Both channels share the same optical architecture, consisting of a six-lens refractive optical system operating in the 500-850 nm spectral range, aligned to a focal plane encompassing a CCD pseudo-frame transfer detector and connected to a proximity electronics (Camera Electronics Box, CEB) optimized for low readout noise. The two cameras provide complementary coverage of the heliosphere through boresight directions centered at 20° and 37° elongation angle, respectively (Figure 1, right image).

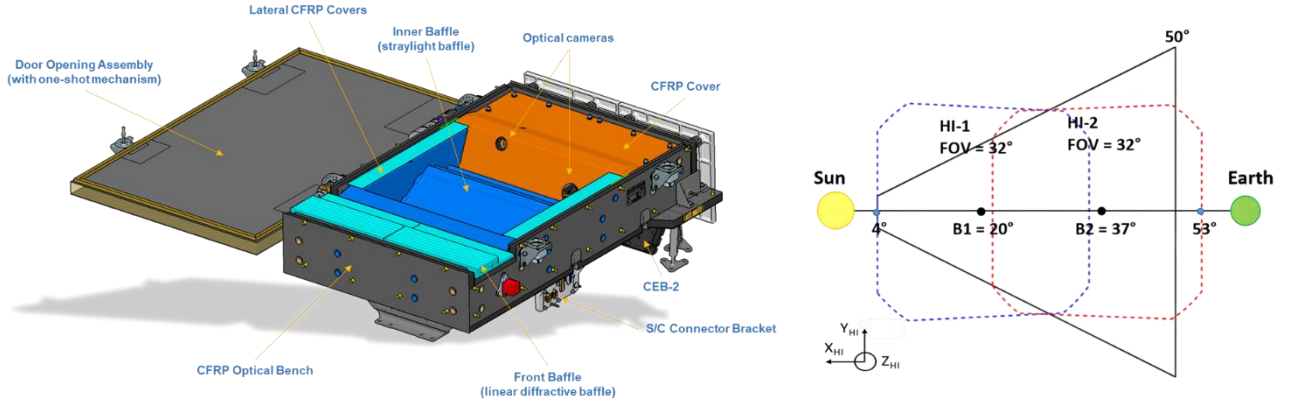


Figure 1 Left image, VIGIL HI Opto-Mechanical Unit (OMU); Right image, HI FOV coverage from Sun-Earth L5 Lagrange point: black trapezoid represents the applicable FOV as per mission requirement; blue dotted box represents HI-01 FOV; red dotted box represents HI-02 FOV

Detecting CMEs in white light represents a particularly challenging radiometric task, as the target signatures can be as faint as few percentages of the observed heliospheric background (specifically, about 1% of the observed background as per instrument requirement). Moreover, careful instrument dynamics range adjustment is mandatory to image Sun F+K Corona signal evolution along the ecliptic plane, as more than two decades of signal decrease is expected from 4° to 50° of elongation angle.

Besides the demanding radiometric performance, HI is developed for an operational Space Weather service and is therefore subject to stringent availability requirements. The instrument is required to support an overall observational availability of 0.99 under both nominal Quiet Sun conditions and Severe Space Weather events. This requirement places strong constraints not only on the instrument sensitivity but also on its ability to maintain the required CME detectability across the wide range of observing conditions encountered during the mission.

To achieve the required sensitivity, HI combines long-exposure acquisitions, multi-frame accumulation and averaging, low detector readout noise, high full-well capacity and stringent thermal stability. In nominal operation, each image is generated from the accumulation of tens of individual exposures acquired over approximately 30 minutes of measurement cadence, maximizing the achievable signal-to-noise ratio for faint transient detection. While this strategy improves the detectability of faint and slowly varying coronal structures, it also increases the susceptibility of the detector to transient artifacts caused by Solar Energetic Particles (SEPs) and cosmic rays. For this reason, an on-board particle cleaning algorithm based on temporal filtering of consecutive exposures is implemented at Firmware (FW) level in the Control and Data Processing Unit (CDPU) of the instrument [2].

Even if all sources of spurious contributor coming from SEPs, dark, smearing signal are minimized at electronics and FW design levels, it is clear that for improving imaging performance of CMEs with typical intensities of few percentage of the acquired background, straylight suppression becomes a primary design driver throughout the instrument development [3]. The HI OMU incorporates both a multi-edge diffractive front baffle developed by Centre Spatial de Liège (CSL) [4], derived from the heritage of the STEREO Heliospheric Imager [5][6], and an internal baffling system optimized to suppress in-field and out-of-field illumination. These subsystems are specifically intended to minimize unwanted contributions from the Sun, the heliospheric background and bright off-axis sources with a fixed angular direction like Earth, located at 60° of elongation angle on the ecliptic plane as seen from the Sun-Earth L5 Lagrange point.

Nevertheless, not all straylight can be minimized by optical design. In fact, for VIGIL HI specific observational regime straylight offenders can be classified in two types, depending on their apparent motion with respect HI:

$$SL = SL_{stable} + SL_{dynamic}(t)$$

The static straylight SL_{stable} is given by astronomical light sources that do not change in magnitude nor position with respect to HI within the nominal instrument observation timeframe for CMEs detection (specifically, about 1 day as per instrument requirement). The main contributors to SL_{stable} include: the heliospheric scene background comprising the F-corona, K-corona, diffuse galactic and stellar background; the Earth, whose straylight is minimized by the internal baffling

system and the objectives internal optical stops system; the Sun, whose light is attenuated by the front baffle by about 9 decades of rejection ratio.

The dynamic stray light $SL_{dynamic}(t)$ is, on the other hand, due to astronomical light sources that change in magnitude and position with respect to HI within the nominal instrument observation timeframe of 1 day. Due to its temporal dependence, this error contributor shall be accounted for within HI radiometric stability performance budget, ruled by a very challenging requirement of about 0.1% of the observed background in 1 day timeframe.

During the retrieval of Coronal Mass Ejections (CMEs), straylight is mitigated by comparing image acquisitions taken up to one day apart and subtracting the acquired heliospheric background to highlight CMEs structures. In this process, SL_{stable} is fully removed. As a consequence, the main impact of this term is the actual reduction of the useful instrument dynamic range, which shall be optimized to accommodate more than two decades of background signal decaying from 4° to 50° of elongation angle, avoiding saturation at lowest elongation angles (closer to Sun) and ensuring enough Signal to Noise Ratio (SNR) performances at largest elongation angles (farther from Sun).

On the other hand $SL_{dynamic}(t)$, being time-dependent, varies within the time interval of the heliospheric background subtraction. The residual differences caused by these variations are directly impacting the challenging HI radiometric stability budget. The main astronomical sources contributing to dynamic straylight are the planets, except for Earth which remains fixed in the observational frame at 60° of elongation angle and therefore is included in SL_{stable} term.

Finally, the operational observing geometry of HI inherently aligns the main region of interest on the ecliptic plane. This is a direct consequence of the mission objective, since Earth-directed CMEs propagate predominantly along the ecliptic and therefore HI imaging performances shall be optimized in this region. However, the major planetary bodies of the Solar System also remain confined close to the ecliptic plane. As a result, the brightest dynamic straylight sources are expected to appear precisely within or near the region where CME detectability is most critical.

In particular, Venus combines high apparent brightness with frequent transits through the HI field of view and its immediate surroundings. The resulting scene-dependent straylight and ghost patterns are therefore projected onto the same region where faint heliospheric structures, travelling towards Earth, must be detected and tracked. Unlike solar straylight, which can be effectively mitigated through dedicated baffling, these planetary contributions evolve continuously with time and observing geometry, making them particularly challenging to suppress through hardware design alone. For this reason, Venus is expected to represent the dominant dynamic straylight contributor during a significant fraction of the mission lifetime. Quantifying its impact on CME detectability and assessing possible mitigation strategies constitute the focus of the present work.

2. PLANETARY STRAYLIGHT IN THE ECLIPTIC OBSERVATION REGION

Venus represents the worst-case dynamic straylight source for HI. To quantify its impact on instrument performance, its temporal evolution and apparent brightness have been analysed for the nominal Vigil observing configuration at the Sun-Earth L5 point.

Venus Temporal Evolution in the HI Observation Domain

A simplified orbital model was implemented assuming circular and coplanar planetary orbits, with the observer located at the Sun-Earth L5 point. The resulting Venus elongation profile is reported in top graph of Figure 2, black solid line, compared with elongation angular ranges covered by HI-01 and HI-02 FOVs, red and blue dotted lines. Since significant straylight contributions can be generated both by in-field and out-of-field planetary sources, it is clear that Venus shall be considered a recurrent target of HI imaging rather than an occasional disturbance.

The apparent motion of Venus is not constant throughout the orbital cycle. The largest apparent angular velocities (around ~ 500 days in the simulated cycle) occur close to solar conjunction, where Venus also becomes extremely faint because of the unfavorable phase geometry. However, within the elongation range relevant to HI observations (4° - 50°), Venus remains a very bright source during extended portions of the orbital cycle (for example, in the 0-200 day and 600-800 day intervals). For these extended timeframes, the planet trajectory is characterized by an approximately linear behaviour: a linear regression performed on one representative descending branch of the elongation curve, corresponding to the first ~ 200 days of the simulated cycle, yields a characteristic apparent angular speed of about $0.23^\circ/\text{day}$. To ensure a conservative assessment of dynamic straylight effects, a value of $0.25^\circ/\text{day}$ was adopted in the subsequent analyses.

Although small compared to the instrument field of view, this daily displacement (corresponding to about 15 detector pixels) is sufficient to modify the corresponding straylight distribution within the nominal instrument observation timeframes. As a result, the associated straylight pattern cannot be completely cancelled through standard background-subtraction techniques and may generate residual signals in running-difference products used for CMEs detection.

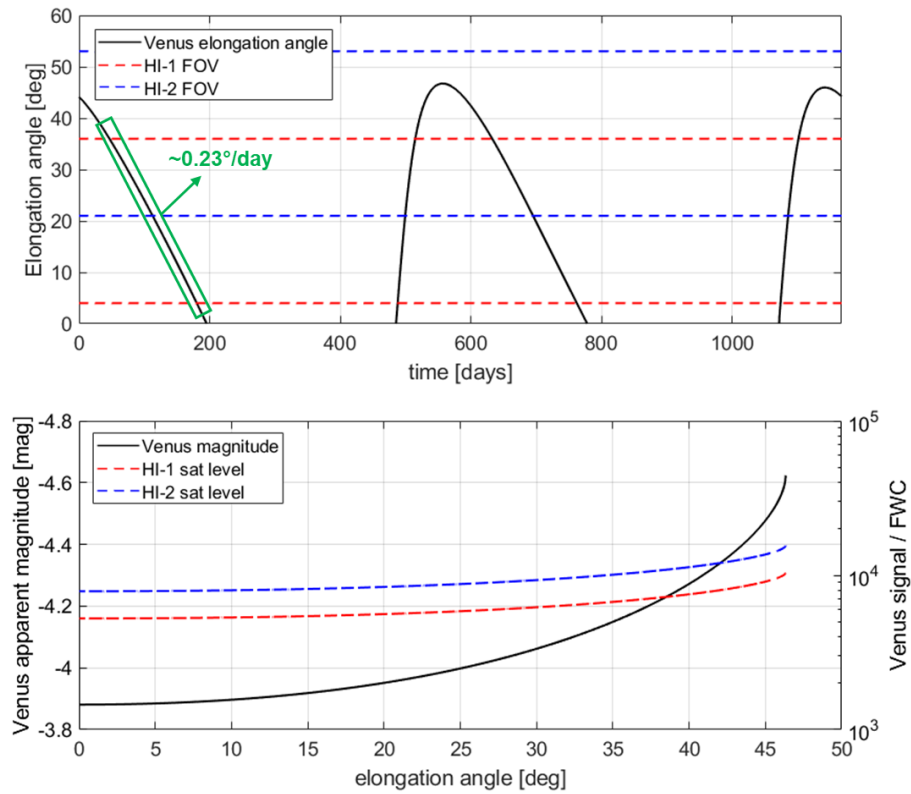


Figure 2 Top: apparent elongation of Venus as seen from the Sun-Earth L5 point. The dashed lines indicate HI-01 and HI-02 FOV edges. Bottom: Venus apparent magnitude (left axis) and corresponding detector signal normalized to the CCD full-well capacity (right axis). Although the apparent magnitude remains approximately constant throughout the analysed HI operational elongation range, the expected detector signal exceeds the pixel saturation threshold by approximately 10⁴ Full Well Capacity (FWC) for both cameras. Consequently, even a small fraction of scattered Venus flux may generate straylight levels comparable to or larger than the faint CME signatures targeted by the instrument

Venus Apparent Brightness Along the Ecliptic Plane

In addition to its continuous apparent motion, Venus is also the brightest planetary source encountered within the HI observation domain. The orbital simulations indicate that, throughout most of the operational elongation range, its apparent magnitude remains remarkably stable, typically varying between approximately -4.6 and -3.9 in the first ~ 200 days of the simulated cycle, see Figure 2 (bottom graph, left axis). Therefore, Venus remains a persistently bright source throughout nearly the entire region of interest for Earth-oriented CMEs monitoring.

Venus as a Worst-Case Straylight Source

The relevance of Venus for the straylight assessment is not only related to its frequent presence within the HI observation domain, but also to its extreme radiometric intensity. Using the instrument radiometric model, the flux generated by Venus at the detector level was estimated and compared with the CCD full-well capacity (FWC), see Figure 2 (bottom graph, right axis). The analysis indicates that the Venus signal exceeds the pixel saturation threshold by approximately 10⁴ FWC for both HI-01 and HI-02 cameras.

Consequently, even when Venus is located outside the nominal field of view, a small fraction of the planetary flux scattered by optical surfaces may generate straylight levels comparable to, or larger than, the signals of interest (i.e. the CMEs).

This result confirms that Venus represents the dominant dynamic straylight offender for the Vigil HI. The combination of extreme brightness, long residence time within the observation region, and daily apparent motion makes Venus the most demanding source for the assessment of residual straylight signatures in background-subtracted CMEs retrieval. For this reason, Venus is adopted in the following sections as the reference worst-case planetary source.

3. RADIOMETRIC ASSESSMENT OF STRAYLIGHT IMPACT

As shown in previous section, Venus constitutes a recurrent and exceptionally bright source within HI in-field and out-of-field regions. In the present section, we demonstrate the actual impact of this time-varying straylight contribution, given by the planet apparent motion, on the instrument imaging performances.

To quantify the effect, a dedicated analysis was performed by means of the instrument radiometric model representative of each camera detection chain taking as input SPST maps generated with FRED optical engineering software. The objective of this activity was to evaluate the expected straylight level at HI focal plane generated by Venus, for some representative FOV cases, and to assess related impact on the detectability of faint CME signatures close to the instrument radiometric stability requirement of 0.1% of heliospheric background.

Dynamic Straylight introduced by Venus

In Figure 3, left column, SPST distributions are reported for HI-01 (top map) and HI-02 (bottom map), corresponding to a primary signal located in a mid FOV angle of illumination. With reference to the HI instrument observing geometry and FOV coverage (see right image of Figure 1) this case is representative of Venus location at 28° of elongation angle. SPST values are normalized with respect primary signal and reported in $\log_{10}$ scale. The maps show that a non-negligible fraction of straylight is redistributed across the focal plane through sharp high-frequency circular features (ghosts) and broad low-frequency contributors (scattering from lenses roughness and contamination).

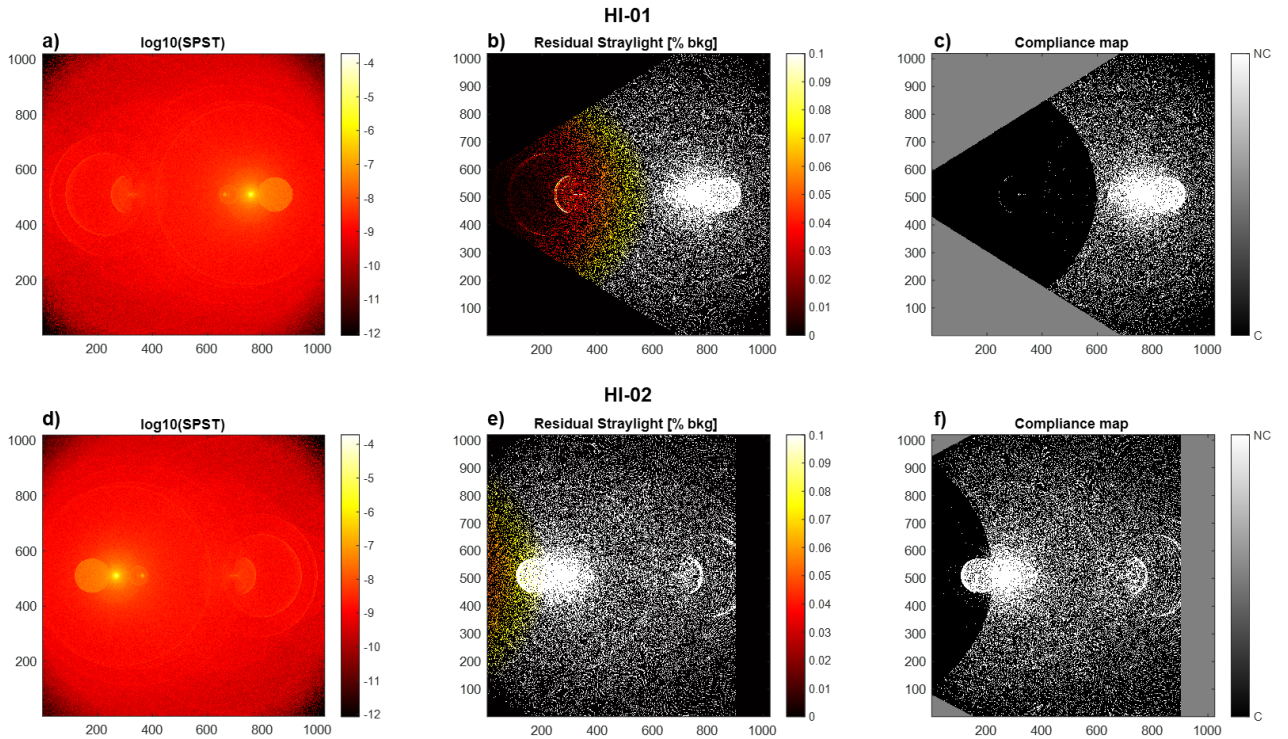


Figure 3 - Impact of Venus apparent motion on HI radiometric stability. Top and bottom rows correspond to HI-01 and HI-02, respectively. The first column, maps a) and d), shows the logarithmic SPST distributions (values normalized with respect primary signal) associated with a representative Venus location corresponding to both HI cameras mid-field-of-view (i.e. at 28° of elongation angle). The second column, maps b) and e), reports the residual straylight $SL_{dynamic}$ resulting from a 0.25° apparent displacement of Venus over one day, normalized to the local heliospheric background. Colorbar is limited up to 0.1% background which is the applicable radiometric stability requirement. The third column, maps c) and f), highlights detector regions exceeding the 0.1%

requirement (white), together with compliant regions (black) and areas outside the applicable field of view (grey). Although the planetary displacement is small compared to the instrument field of view, significant localized regions exceeding the radiometric stability budget are observed in both channels.

Then, $SL_{dynamic}$ term given by Venus is evaluated as difference between two SPST sample maps, generated by shifting the primary signal of about 0.25° between the two samples. The magnitude of this shift corresponds to the expected daily motion of Venus in HI-01 and HI-02 FOV, as explained in previous section. Calculating the difference of the two SPST maps is representative of the current HI images processing baseline of comparing image acquisitions taken up to one day apart and subtracting the acquired heliospheric background to highlight CMEs. It is worth noticing that being Venus angular extension well within one instrument pixel, no specific SPST convolution method with the primary scene is requested to evaluate corresponding straylight scene.

$SL_{dynamic}$ maps, weighted with Venus expected signal as seen by HI cameras, are reported in Figure 3, central column for HI-01 (top map) and HI-02 (bottom map). Straylight residual values are expressed as percentages of the local heliospheric background, allowing a direct comparison with the instrument radiometric stability requirement of 0.1%. In both channels, localized regions are found to reach or exceed the 0.1% stability threshold. In fact, the corresponding compliance logical maps reported in Figure 3, right column, indicate that the requirement violation is mainly concentrated in specific regions associated with the dominant residual ghost structures. This result demonstrates that even a 0.25° of apparent displacement of a bright planetary source like Venus can generate radiometric error contributors comparable to the stability budget allocated for CME detection.

Impact on CME detectability (Venus in mid FOV)

To assess the actual impact of Venus straylight ghost residuals on CME detectability, a pattern of synthetic CME signatures was introduced in the analysis. Maps a) and b) of Figure 4 report the observed CMEs, as seen by HI-01 (left) and HI-02 (right) respectively, in nominal observations where Venus is not within the instrument operational FOV (4° - 50° elongation angles). The pattern is generated such that each CME wavefront has a peak brightness corresponding to 1% of the local heliospheric background, consistently with the mission detectability requirement. Instrument noise is included in the simulated maps. Pixels outside applicable FOV (refer to black trapezoid in right image of Figure 1) are excluded.

In maps c) and d) of Figure 4 Venus-induced residual straylight term $SL_{dynamic}$ is added to the CMEs and noise contributors. Venus is located at 28° of elongation angle, corresponding to mid FOV position for both HI-01 and HI-02 cameras. All maps are expressed as percentages of the local heliospheric background and share a common color scale fixed up to 1%, allowing a direct visual comparison between CME signal levels and residual straylight contamination.

Maps c) and d) clearly show that, in close proximity to the dominant residual ghost structures, dynamic straylight generated by Venus can exceed the signal level of a CME at the mission detectability threshold of 1%. Under these conditions, faint CME signatures become indistinguishable from the residual planetary contamination and may therefore remain undetected. Since the strongest residuals are predominantly distributed along the ecliptic plane, where Earth-directed CMEs are expected to be observed, this effect directly impacts the operational objectives of the instrument.

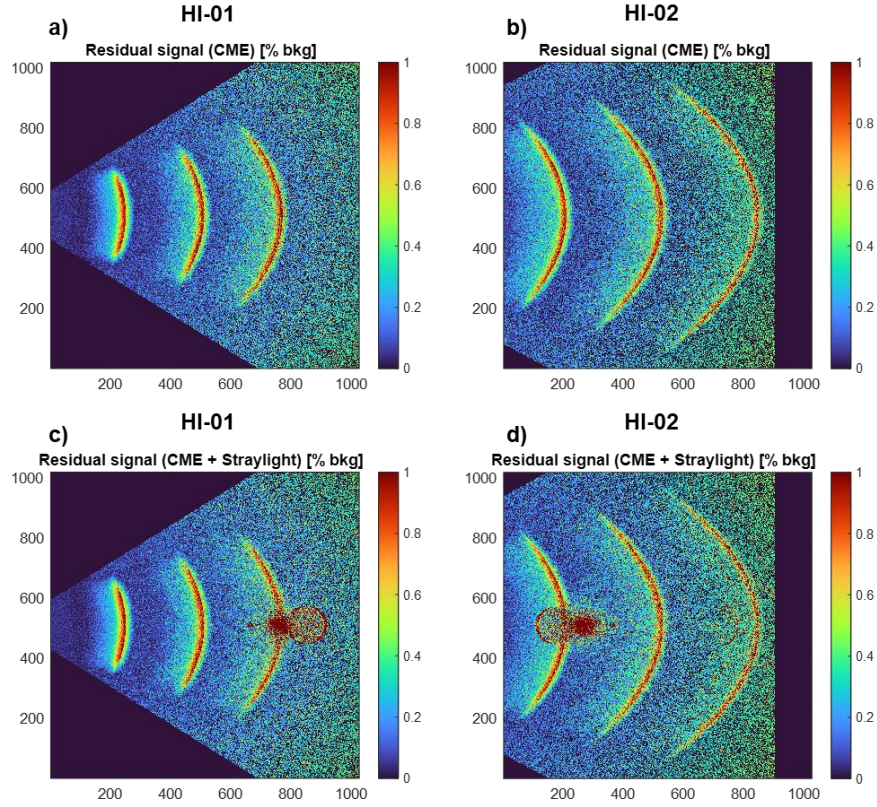


Figure 4 Detectability assessment of synthetic CME signatures in the presence of Venus residual straylight for a representative mid FOV configuration, i.e. Venus at 28° of elongation angle. The top row reports reference maps, after background subtraction, including instrument noise and a pattern of synthetic CMEs located at different elongation angles. Bottom row includes also residual straylight contribution generated by the apparent daily motion of Venus. Left and right columns refer to HI-01 and HI-02, respectively. Pixels outside applicable FOV (black trapezoid in right image of Figure 1) are excluded. All maps are expressed as percentages of the local heliospheric background and use a common color scale normalized to the reference CME brightness level (1% of the local background).

Impact on CME detectability (Venus on-axis and out of field)

To further assess the operational impact of Venus-induced dynamic straylight, two limiting observing configurations were analysed. These correspond to the geometries in which Venus is located on the boresight of one HI channel while simultaneously lying approximately 1° in the out of field of the other channel.

The resulting simulations are reported in Figure 5. In the first configuration, maps a) and b), Venus is located on the boresight of HI-01 (20° elongation angle) while appearing 1° in the HI-02 out of field. In the second configuration, maps c) and d), Venus is located on the boresight of HI-02 (37° elongation angle) while lying 1° in the HI-01 out of field. As for Figure 4, instrument noise is included, and all maps are expressed as percentages of the local heliospheric background with a common color scale fixed up to 1%.

The largest degradation of CME detectability obviously occurs, for each HI camera, when Venus is in field. In both channels, the dominant residual ghost structures generate localized signals comparable to, or larger than, the reference CME intensity. As a consequence, synthetic CME signatures crossing these regions become partially or completely masked by residual straylight, preventing reliable identification through standard background-subtraction techniques. At the same time, results also indicate that the effect does not disappear when Venus reaches the out of field. Although significantly weaker than in the corresponding on-axis and mid FOV cases, measurable residual structures are still present in both cameras also for Venus position corresponding to the out of field.

Particularly critical is the fact that the strongest residual straylight structures remain concentrated close to the ecliptic plane, where Earth-directed CMEs are expected to propagate and where the operational performance of HI must be maximized. Furthermore, the results indicate that the impact of Venus is not confined to a single HI channel. Travelling throughout the elongation range relevant to HI observations (4° - 50° , see Figure 2), Venus will always remain either within the in field of both cameras or in the in field of one channel while in the immediate out-of-field region of the other channel. Consequently, no operational configuration exists in which one of the two HI cameras is completely unaffected by Venus-induced dynamic straylight. This persistent coupling between planetary location and instrument observation domain confirms the need for dedicated correction strategies to preserve CME detectability throughout the mission lifetime.

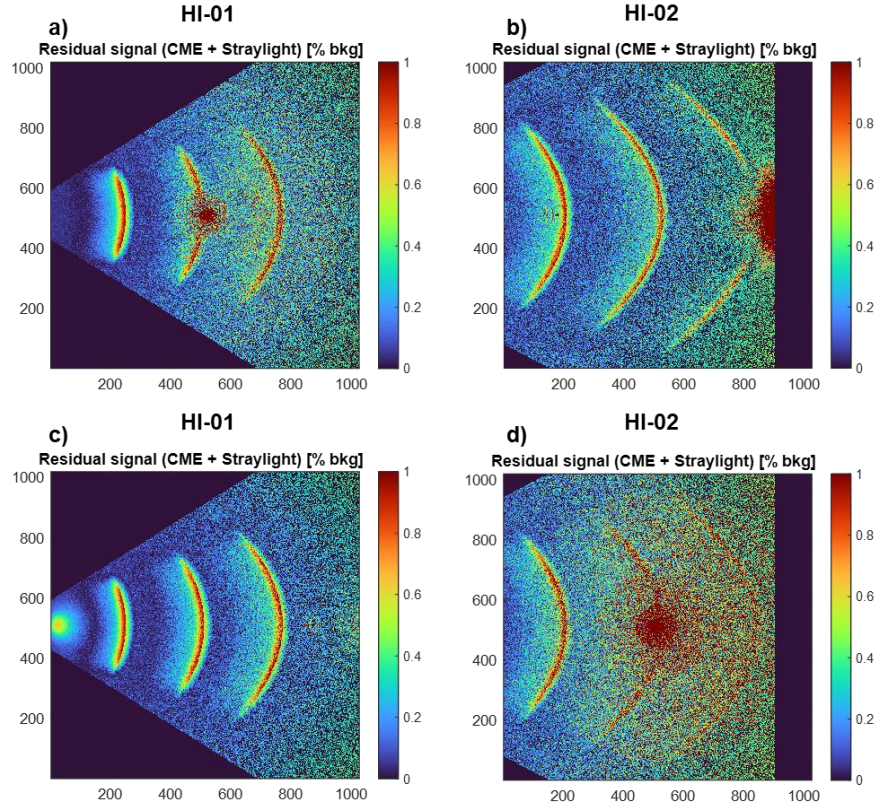


Figure 5 Detectability assessment of synthetic CME signatures in the presence of Venus residual straylight for two limiting observing configurations. The top row, maps a) and b), corresponds to the configuration in which Venus is located on the boresight of HI-01 (20° elongation angle), corresponding to a position approximately 1° outside the HI-02 field of view. The bottom row, maps c) and d), corresponds to the opposite configuration, with Venus located on the boresight of HI-02 (37° elongation angle), corresponding to a position approximately 1° outside the HI-01 field of view. Left and right columns refer to HI-01 and HI-02, respectively.

4. PRELIMINARY ASSESSMENT USING HERITAGE STEREO/HI DATA

To validate results reported in previous section, a dedicated analysis about instrument radiometric stability (for which HI requirement is set to 0.1% of the heliospheric background) using heritage data from the STEREO/SECCHI HI-01 and HI-02 cameras was performed. Such analysis was considered mandatory to provide a realistic baseline of the performance achievable in space.

Experimental Design

The analysis evaluates radiometric stability using stellar point sources with signal levels representative of CME observations. Only stars with background-subtracted integrated signals comparable to typical CME intensities are selected, specifically between 0.5% and 1.5% of the background intensity.

Following aperture photometry method, instead of tracking a single-pixel peak value, the stellar flux is integrated over a 3×3 pixel window to reduce sensitivity to sub-pixel pointing jitter.

Selected stars are then tracked over a 24-hour sequence of 12 frames, and the relative standard deviation of their background-normalized signals is measured.

Step-by-Step Procedure

The raw images are downloaded from the NASA repository [7]. For each test case, 12 images acquired at 2-hour intervals are used to cover a full 24-hour period. The analysis is performed for both HI-01 and HI-02, considering cases where Venus is present in the field of view, Figure 6 a), and cases where it is absent, Figure 6 b). The raw images, see example in Figure 6 c), are dominated by a strong diffuse gradient from the F-corona, while stars appear only as small fluctuations above the background. As a first preprocessing step, saturated pixels are identified and masked or corrected before further analysis.

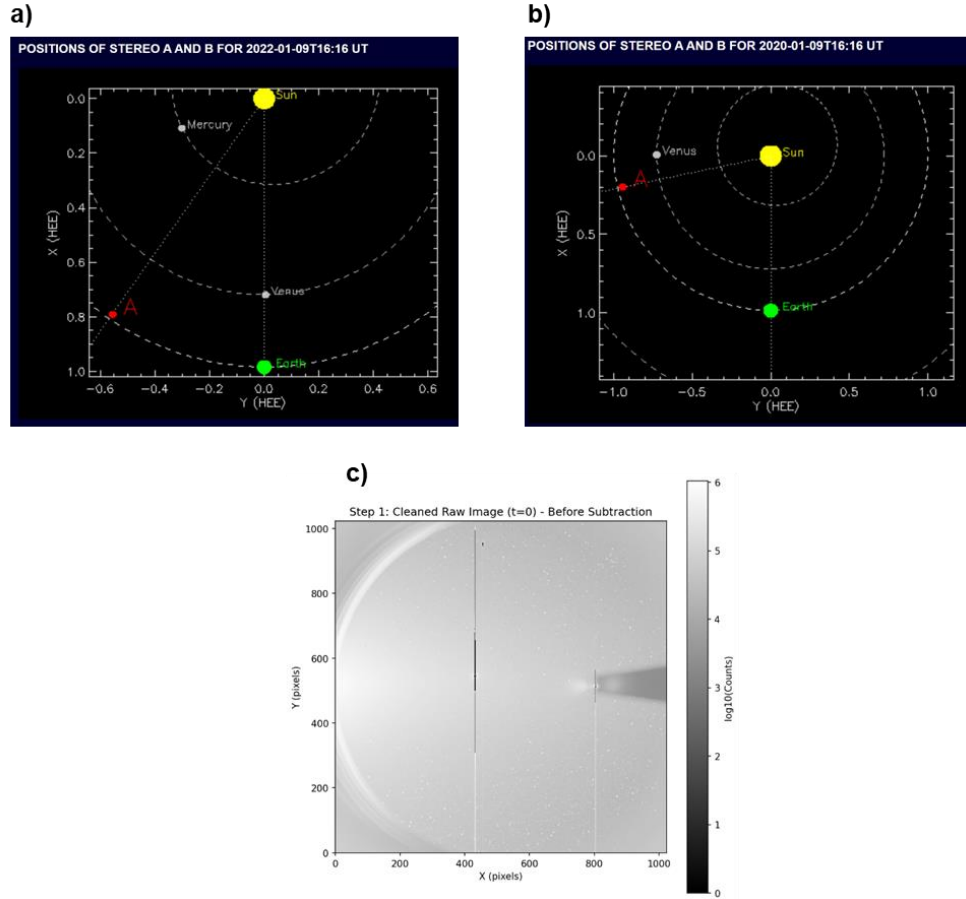


Figure 6 Test case with Venus in the field of view of STEREO HI-02 (a) and test case with no bright planet in the field of view (b). In (c), example of STEREO HI-02 raw image

Heliospheric images are dominated by the diffuse F-corona background, which is orders of magnitude brighter than both stellar signals and CME-like features. A robust background-removal process is therefore required before faint signals can be extracted. For both HI-01 and HI-02, the background image is generated by taking the pixel-by-pixel minimum of the 12 images acquired during the 24-hour period. This is used as a simple first-order background estimate: it is effective for suppressing slowly varying diffuse emission, but it can retain residual stars, moving objects, or artefacts if they remain fixed or evolve slowly over the sequence.

The generated background image is subtracted from each raw image, revealing the stellar field and enabling subsequent radiometric analysis, as in Figure 7.

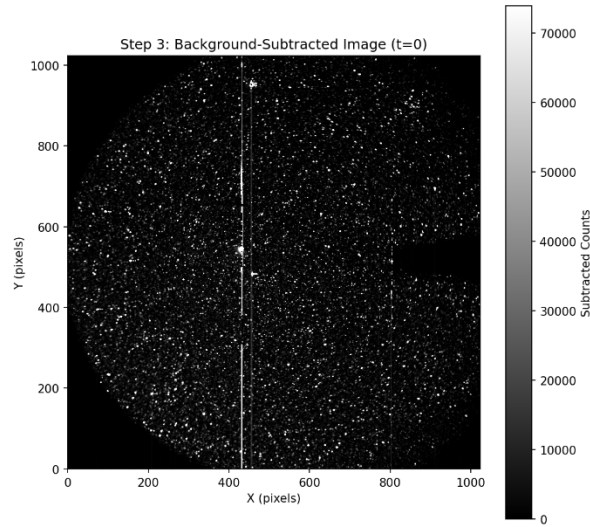


Figure 7 Image after background subtraction

Stars with signals comparable to representative CME signal levels are identified using the DAOStarFinder class from the Photutils/Astropy package, which detects stars and point sources in astronomical images using the DAOFIND algorithm. The selected stars are then tracked across the 12 images covering the full day.

Stability evaluation results

We analyzed the stability of the tracked stars across HI-01 and HI-02 FOVs considering the signal over a 3x3 window centered on the centroid of the star.

Regarding HI-01 radiometric stability, for stars selected in the 0.5%–1.5% background range the mean relative standard deviation of the tracked 3x3 aperture signals over the 24-hour period results approximately 1.3% under nominal conditions. This results above VIGIL HI requested stability of 0.1%.

Regarding HI-02, characterized by a wider FOV and lower spatial resolution, applying the same 0.5%–1.5% signal-selection criterion gives an average relative standard deviation of approximately 0.58% when no bright planets are present in the field of view.

This analysis is currently limited to only a small number of test cases. To improve confidence in the results, the study should be extended including a broader set of dates covering different levels of solar activity and varying planetary geometries.

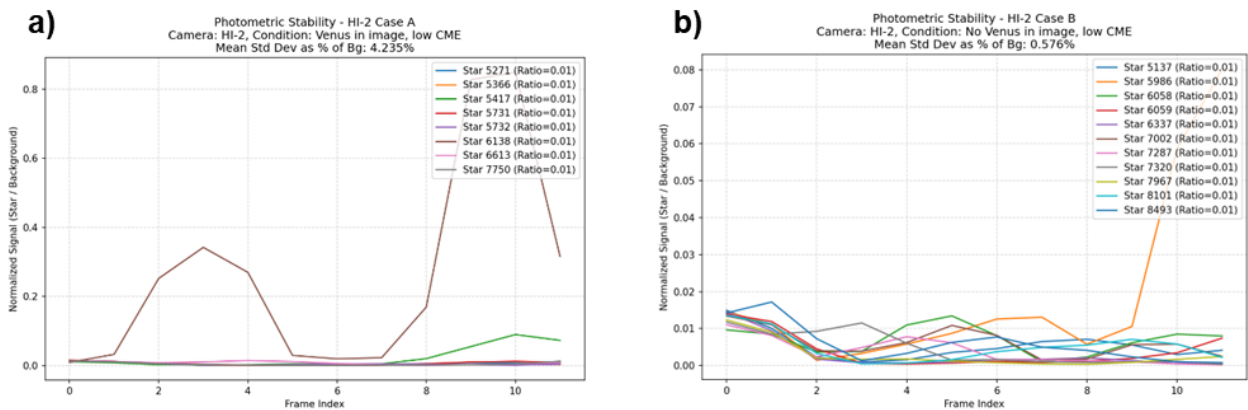


Figure 8 Examples of star signal fluctuations for STEREO HI-02

Conclusions

The STEREO/SECCHI heritage data indicate that sub-percent radiometric stability, in the range of approximately 0.5%–1.3%, is achievable using a simple background-subtraction approach and aperture photometry on stellar point sources. These results do not directly satisfy the more stringent 0.1% Vigil HI requirement, but they provide a useful in-flight benchmark for identifying the dominant contributors to residual signal variability.

For Vigil, compliance with the 0.1% target implies required improvements in thermal control, pointing stability, detector calibration and finally straylight mitigation or correction. Recommended next steps are to extend the analysis to a larger set of dates, separate instrumental effects from processing artefacts, assess cases with different planetary geometries and solar activity levels, and compare alternative background-removal methods against the current minimum-image approach.

The most relevant result emerging from the preliminary heritage analysis is the significant increase in the observed radiometric variability when Venus is present within the field of view. In the analysed HI-02 dataset of Figure 8, signal fluctuations increase from sub-percent levels in nominal observing conditions (right graph) to values approaching 4% in the presence of Venus (left graph). Although the dataset considered in this work is limited and does not allow a statistically rigorous assessment, the result suggests that bright planetary sources may contribute to measurable scene-dependent radiometric variations in heliospheric imaging observations.

A more extensive statistical analysis covering additional temporal intervals and different planetary geometries is planned in future work to further investigate this behaviour and quantify its occurrence across the historical STEREO dataset. While preliminary, the present results provide an encouraging indication that the signal regime investigated in this study is representative of effects that can be encountered in flight data.

5. DYNAMIC STRAYLIGHT MITIGATION PERSPECTIVES

Analyses presented in the previous sections indicate that Venus-induced dynamic straylight can locally reach signal levels comparable to, or exceeding, the brightness of faint CME signatures targeted by Vigil HI. At the same time, the dominant straylight source is not associated with an unknown or rapidly varying scene, but with the apparent motion of a bright planetary object. Unlike typical Earth Observation scenarios involving clouds, oceans or land surfaces, both the position and brightness of Venus are accurately predictable. As a consequence, the associated straylight contribution is largely deterministic and represents a particularly suitable case for modelling, calibration and correction.

The objective of this section is not to present a full operational correction chain, which is currently under development, but rather to assess whether realistic straylight mitigation factors can reduce the Venus-induced contamination to levels compatible with HI radiometric stability requirements and with CME signatures characterized by intensities of the order of 1% of the local heliospheric background.

Heritage from the 3MI Straylight Correction Activities

The MetOp-SG 3MI instrument [8] provides a particularly relevant heritage for the present study, as it relies on a straylight correction approach based on the calibration of SPST maps and on the reconstruction of the straylight contribution through a linear combination of calibrated kernels weighted by the observed scene. The correction algorithm uses an iterative approach combined with SPST interpolation and was specifically developed to compensate complex ghost patterns distributed across the detector. The methodology and its theoretical performance assessment are described in detail in [9].

Prior to instrument calibration, performance predictions based on ray-tracing simulations indicated that the 3MI straylight correction algorithm would need to achieve correction factors of approximately 60 at 2σ level (and up to about 120 at 1σ level) in order to meet the mission radiometric requirements. The predicted performance was obtained while accounting for practical limitations such as finite SPST calibration grids, interpolation errors, detector noise and dynamic range recombination. The analysis demonstrated that correction factors of this magnitude were theoretically achievable using SPST-based modelling, calibration and interpolation techniques [9].

The subsequent PFM and FM2 calibration campaign provided an experimental validation of the correction concept using measured SPST maps [10]. For the VNIR channels, which are the most representative case with respect to the Vigil HI visible-light observations and CCD detector technology, the achieved correction factors were found to range typically between 70 and 90, depending on the spectral channel. These values were obtained on flight hardware and include the effects of real calibration uncertainties and instrument non-idealities [10].

Although 3MI and Vigil HI operate in substantially different observational scenarios, the underlying correction philosophy remains the same: accurate characterization of the instrument SPST response followed by model-based estimation and subtraction of the straylight contribution. The 3MI heritage therefore demonstrates that correction factors significantly larger than one decade can be achieved in practice.

FLORIS straylight calibration and correction

The ESA FLEX/FLORIS instrument [11] provides a second highly relevant heritage case for the present assessment. Similar to the approach envisaged for Vigil HI, FLORIS relies on an SPST-based correction architecture in which instrument straylight is reconstructed from calibrated SPST functions and subsequently removed through model-based processing of the observed scene. The correction chain combines experimentally measured SPSTs, optical model correlation, and scene-dependent straylight reconstruction through convolution techniques.

FLORIS posed particularly demanding requirements because the retrieval of the weak solar-induced chlorophyll fluorescence signal requires straylight levels several orders of magnitude below the observed radiance. The corresponding calibration activities required the characterization of SPST maps over dynamic ranges approaching 9 to 10 orders of magnitude [12]. A major challenge was represented by CCD blooming, which limited the dynamic range achievable with conventional in-field measurements and motivated the development of dedicated Out-Of-Band (OOB) and Out-Of-Field (OOF) characterization techniques. These complementary measurements enabled correlation of the optical model down to straylight levels of the order of 10^{-9} to 10^{-10} relative to the primary signal.

Using the correlated SPST database, the FLORIS correction chain demonstrated a reduction of the correctable straylight contribution by approximately one order of magnitude under the mission worst-case scene configuration. The residual error budget after correction was found to be dominated not by limitations of the SPST-based methodology itself, but primarily by intrinsically non-correctable straylight terms, most notably the Across-Track Out-Of-Field (OOF-ACT) contribution generated by scene radiance outside the instrument field of view, for which no direct measurement is available. Additional residual contributions were associated with contamination changes occurring after ground calibration and therefore not represented in the calibrated SPST database [12].

This distinction is particularly relevant when considering the applicability of the FLORIS heritage to Vigil HI. In Earth observation missions such as FLORIS, important straylight contributions can originate from unknown radiance distributions located outside the instrument field of view. In contrast, the dominant straylight sources expected for Vigil HI are deterministic astronomical objects whose position and brightness can be estimated with high accuracy. Furthermore, the dual-camera configuration provides the possibility of directly observing sources that are outside the field of view of one camera while remaining inside the field of view of the other camera. Consequently, some categories of straylight that are intrinsically non-correctable in Earth-observation missions may be mapped and potentially reconstructed in the Vigil HI dual-camera configuration. While the two missions address substantially different observational scenarios, the FLORIS experience nevertheless demonstrates the practical viability of SPST-based straylight calibration and correction, even in the presence of severe detector blooming and extremely demanding radiometric constraints.

Potential correction performance for VIGIL HI

Based on the available heritage, a correction factor of 10 should not be regarded as a performance target but rather as a conservative working assumption for a preliminary assessment. Recent heritage from 3MI and FLORIS demonstrates that SPST-based correction methodologies can remain effective even when accounting for calibration uncertainties, interpolation errors, detector anomalies and other non-ideal effects associated with real flight hardware and calibration data. In this context, adopting a correction factor of one order of magnitude for Vigil HI represents a reasonably conservative assumption rather than an optimistic performance expectation.

Figure 9 illustrates the effect of applying a representative correction factor of 10 to the Venus-induced dynamic straylight residuals discussed in the previous sections. Results are shown for the worst radiometric case on each camera, corresponding to Venus located in the boresight (top row, a) and b) map). The corrected maps (bottom row, c) and d) map) show a substantial reduction of the dominant ghost structures responsible for the largest local radiometric perturbations. As a consequence, the areas where the residual straylight exceeds the brightness of the reference CME signatures are significantly reduced in both observing configurations.

The improvement is particularly evident for the extended CME structures intersecting the ecliptic region, where the strongest Venus-induced residuals are concentrated. After correction, most of the synthetic CME signatures remain distinguishable from the residual planetary straylight and become detectable over a substantially larger fraction of the

applicable field of view. Although localized residual artefacts are still present in correspondence of the strongest ghosts, their amplitude is reduced to levels comparable with, or below, the adopted CME reference signal.

These results suggest that even a relatively modest mitigation factor of one order of magnitude may be sufficient to recover a significant fraction of HI observational capability that would otherwise be lost because of Venus-induced dynamic straylight. While the actual correction performance achievable in flight remains to be demonstrated, the analysis indicates that the required mitigation level is compatible with correction factors already demonstrated by SPST-based correction schemes on previous space optical instruments [10][12].

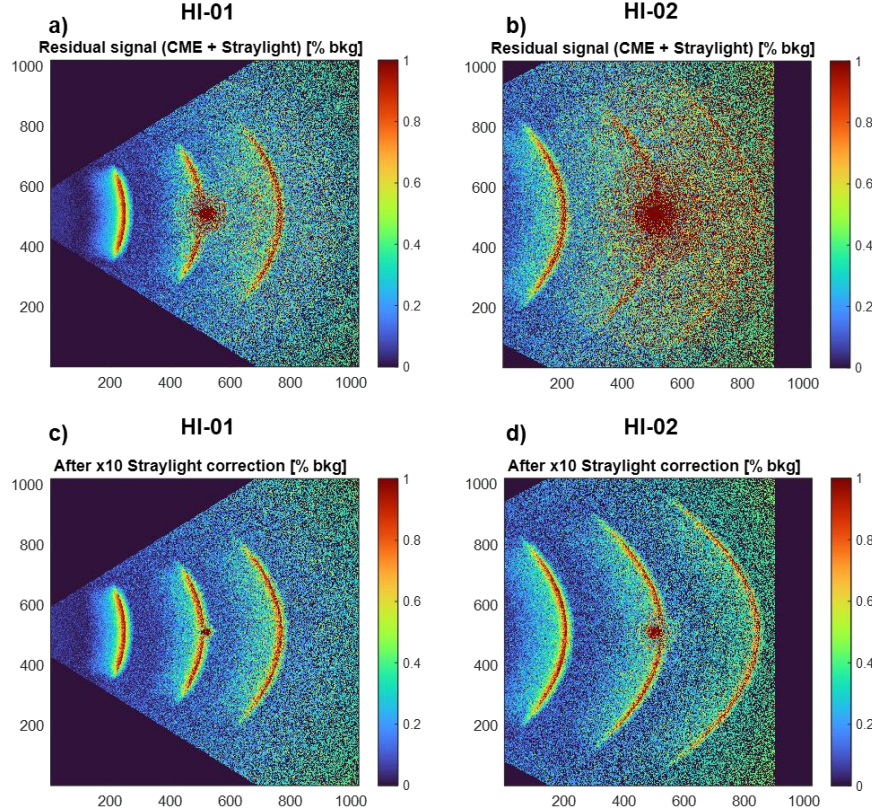


Figure 9 Impact of a representative 10 $\times$ straylight correction on CME detectability for the worst-case observing configurations, corresponding to Venus located on the boresight of HI-01 (left column) and HI-02 (right column). Top row, maps a) and b), reports the predicted imaging including residual Venus-induced straylight, instrument noise and synthetic CME signatures. Bottom row, maps c) and d), shows the corresponding results after applying a correction equivalent to a $\times 10$ reduction of the residual straylight contribution. The correction significantly reduces the contamination generated by the dominant residual ghost structures and restores the visibility of CME signatures over most of the applicable FOV

Preliminary error budget considerations

The correction performance discussed in the previous section assumes that the instrument SPST response can be calibrated with sufficient accuracy and then used to reconstruct the straylight generated by bright planetary sources. Although a complete correction chain is still under development for HI, it is already possible to identify the principal contributors expected to affect the calibration accuracy of the SPST database and therefore the effectiveness of any model-based straylight mitigation approach.

For the purpose of a preliminary assessment, the identified contributors can be grouped into four main categories: random measurement errors, systematic calibration biases, dynamic-range-related reconstruction errors and SPST interpolation errors.

Random measurement errors include contributors such as photon noise, readout noise, smearing noise, residual non-linearity correction uncertainty, dark signal subtraction residuals and other second-order effects. Preliminary analyses

indicate that these contributions are expected to remain comparatively small and are therefore not considered primary drivers of the overall SPST calibration uncertainty.

A second category is represented by systematic calibration biases associated with the Optical Ground Support Equipment (OGSE) and calibration facility. These include source radiometric stability during the calibration campaign, attenuation factor calibration accuracy and possible pupil illumination non-uniformities. Unlike random contributors, systematic effects cannot be reduced by averaging and may therefore introduce biases in the measured SPST amplitude and shape.

Particular attention has also been devoted to estimating the straylight generated by the calibration facility itself. Preliminary analysis performed by CSL indicates that the straylight contribution of the dedicated SPST OGSE is several orders of magnitude below the instrument SPST levels targeted by the calibration campaign, see Figure 10. While these results still require consolidation during the upcoming calibration reviews, they suggest that OGSE straylight is unlikely to become a dominant contributor within the overall calibration uncertainty budget.

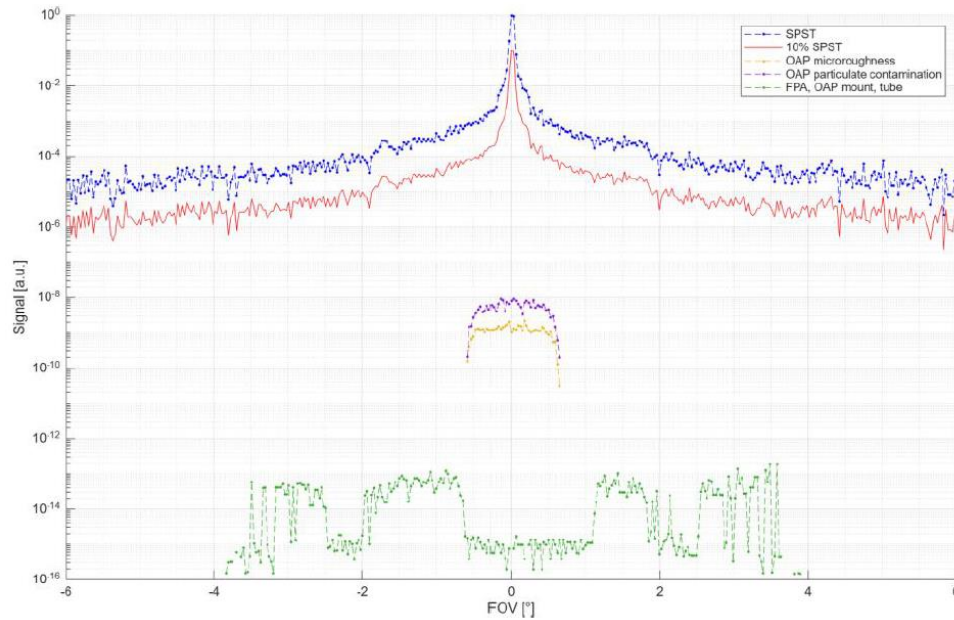


Figure 10 OGSE straylight contributors (OAP microroughness, yellow line, OAP particulate contamination, purple line, FPA+OAP mount and tube, green line) comparison with respect to HI SPST, blue line, and target requirement, red line. Figure courtesy of CSL.

The largest currently identified contribution is associated with the reconstruction of the whole instrument SPST dynamics. In order to characterize straylight levels several orders of magnitude below the primary signal, measurements acquired at different OGSE input fluxes and HI exposure times must be combined through dynamic-range recombination process used to reconstruct the full SPST. A dedicated end-to-end simulation of the acquisition and reconstruction chain has therefore been developed, including detector saturation and quantization, shot noise, readout noise, dark noise, smear signal and SPST levels recombination. In addition, detector blooming occurring under the most severe saturation conditions may further reduce the amount of usable information available in the highest-flux acquisitions. Since this effect is still under investigation, it is discussed separately in the following section. Preliminary results indicate that dynamic-range-limited SPST reconstruction is currently one of the largest identified contributors to the overall calibration uncertainty budget.

An additional contribution arises from the finite angular sampling adopted during SPST calibration. During operations, the correction algorithm requires SPST maps corresponding to arbitrary source positions across the field of view, as planetary sources move across HI focal plane with pixel- and sub-pixel-scale displacements throughout routine operations. Since only a discrete set of source positions can be experimentally calibrated, intermediate SPSTs must be reconstructed through interpolation. The corresponding interpolation error depends on the calibration grid spacing and on the local evolution of the SPST morphology with field angle. At the present stage of the analysis, this contribution remains allocated and requires further consolidation.

Overall, preliminary analyses indicate that dynamic-range-limited SPST reconstruction and SPST interpolation errors are likely to dominate the final calibration uncertainty, whereas classical detector calibration residuals and OGSE-related effects appear to play a secondary role. Future development activities will therefore focus primarily on consolidating the reconstruction of the SPST maps in the whole dynamics, refining the calibration sampling strategy and improving the characterization of detector blooming under highly saturated conditions.

Blooming characterization

Among the contributors discussed above, blooming characterization currently represents the least mature aspect of the analysis and the principal open item in the assessment of the achievable straylight correction performance.

The radiometric analyses presented in this work indicate that Venus may exceed the detector FWC by approximately four orders of magnitude over significant portions of HI operational observation domain. Under such highly saturated conditions, charge redistribution mechanisms within the detector will generate signal structures extending well beyond the nominal Point Spread Function (PSF) response.

This aspect is particularly relevant because the proposed mitigation approach assumes that the instrument response can be represented through calibrated SPST kernels. While optical ghost and scattering contributions are naturally included within the SPST formalism, blooming introduces an additional signal redistribution mechanism originating inside the detector and its associated readout chain. Consequently, any blooming contribution that is not adequately characterized and incorporated into the calibration model may limit the achievable correction performance.

A similar calibration challenge was encountered during the development of the ESA FLEX/FLORIS instrument [12]. In that case, detector blooming represented one of the principal limitations in achieving the dynamic range required for extreme straylight characterization and motivated the development of dedicated calibration methodologies for extending the measurable SPST range. The resulting heritage demonstrates that blooming can become a major driver of SPST reconstruction accuracy whenever very bright sources are involved.

To support Vigil HI development activities, ESA recently performed a dedicated blooming characterization campaign on a CCD230-42 detector representative of the same silicon architecture proposed for the mission. The investigation covered illumination levels ranging from nominal operation up to several times the detector FWC and included dedicated analyses of charge spreading, saturation behaviour, supersaturation and remanence effects. Preliminary results indicate that blooming produces a preferential charge redistribution along the detector row direction, while showing limited sensitivity to variations of the image area clocking levels. Furthermore, the observed blooming signatures appear sufficiently stable and repeatable to suggest that the charge spreading can be characterized experimentally and potentially incorporated within a calibration framework.

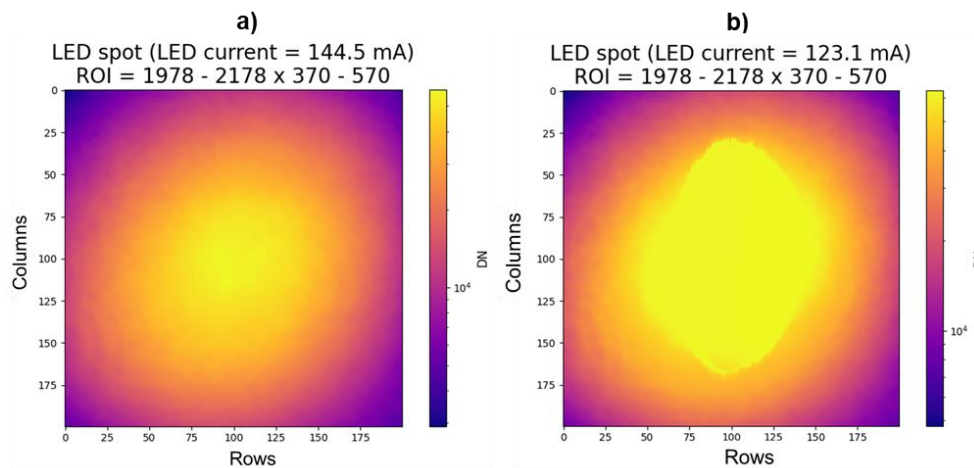


Figure 11 Example of blooming characterization results obtained on Teledyne E2V detector CCD230-42. The measurements illustrate the evolution of the spot morphology under increasing saturation levels and the preferential charge spreading observed after FWC is exceeded. Figure courtesy of ESA.

Although encouraging, ESA investigation was performed on a detector representative of the CCD architecture but not on the final detector and electronics chain selected for Vigil HI. For this reason, a dedicated experimental campaign is planned by Leonardo during the upcoming development phases. The objective of this activity is to characterize the combined response of the selected detector and CEB over several decades of incident flux and to quantify the spatial propagation of charges overspill under saturation conditions representative of the expected Venus signal levels.

The resulting measurements will provide the experimental basis required to refine the current SPST calibration error budget and to assess the extent to which blooming can be modelled and incorporated into the operational straylight correction chain. At the time of writing, these activities are still ongoing and no consolidated blooming model is yet available. Consequently, blooming remains the principal contributor requiring further investigation before a fully representative correction-performance assessment can be established. Nevertheless, heritage provided by 3MI and FLORIS instruments suggests that correction factors significantly larger than one decade can be achieved for well-characterized straylight components.

6. CONCLUSIONS

The operational geometry of Vigil HI makes bright planetary sources, and Venus in particular, a recurrent contributor to the instrument straylight environment. The analyses presented in this work indicate that the residual dynamic straylight generated by Venus can locally reach levels comparable to the brightness of faint CME signatures close to the mission detectability threshold.

Simulations performed using instrument SPST maps show that Venus-induced ghost residuals may significantly affect CME detectability in portions of the applicable FOV, especially along the ecliptic plane where Earth-directed CMEs are expected to propagate. Preliminary analyses of heritage STEREO/HI observations further suggest that bright planetary sources can generate measurable radiometric variability in flight data.

Heritage from the 3MI and FLORIS programmes demonstrates the practical applicability of SPST-based straylight correction approaches. Using a conservative correction factor of 10, the predicted impact of Venus-induced residuals is substantially reduced and CME detectability is recovered over most of the applicable FOV.

Preliminary error-budget analyses indicate that the dominant uncertainties are associated with the SPST dynamics reconstruction, SPST interpolation and detector blooming characterization, whereas classical detector calibration residuals and OGSE-related effects appear to be secondary contributors. Upcoming detector-level blooming measurements on representative Vigil hardware will provide the experimental basis required to further consolidate the present assessment.

Overall, the results indicate that dynamic planetary straylight is a non-negligible contributor for Vigil HI operations, but also suggest that SPST-based correction techniques represent a technically credible mitigation approach capable of preserving the operational performance required by the mission.

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