

Onboard temporal filtering of solar energetic particle artifacts in heliospheric imager data for enhanced CME detectability

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ABSTRACT

The ESA Vigil mission will provide continuous observations of the inner heliosphere from the Sun-Earth L5 Lagrangian point, supporting improved space weather nowcasting and forecasting. Its Heliospheric Imager is designed to detect faint solar wind structures, including Coronal Mass Ejections (CME), whose radiometric signature can be of the order of one percent of the F- and K-corona background. Such sensitivity requires long-exposure visible-light acquisitions and temporal accumulation over observation windows of 30 minutes, making the image data susceptible to transient artifacts induced by Solar Energetic Particles (SEP) and cosmic rays interacting with the CCD detector. This paper presents an onboard-compatible temporal filtering approach for particle artifact mitigation at single-frame level, before frame accumulation. The method operates independently on each pixel, without spatial correlation or pattern recognition, and detects impulsive temporal outliers by comparing each exposure with neighboring exposures. Two configurations are considered: a low-rate algorithm based on the previous and following frames, and a high-rate algorithm using a wider temporal neighborhood to increase robustness under enhanced particle flux. Detected hits are replaced by a temporal estimator prior to summation. The performance assessment focuses on the residual radiometric bias after background subtraction and on the qualitative preservation of CME visibility. Results indicate that early onboard cleaning significantly reduces particle-induced degradation in nominal conditions while preserving slowly varying coronal signals. The analysis also highlights the limitations encountered under severe particle environments and the importance of requirement verification at product levels relevant to CME detection.

Keywords: Solar energetic particles, Heliospheric Imager, Coronal Mass Ejections, onboard processing, temporal filtering, ESA Vigil, space weather, image artifact mitigation.

1. INTRODUCTION

Coronal Mass Ejections (CMEs) are among the main drivers of severe space weather disturbances at Earth. Their early detection and tracking in the inner heliosphere are therefore essential for improving nowcasting and forecasting capabilities. The ESA Vigil mission will operate from the Sun-Earth L5 Lagrangian point, offering a side-view perspective of solar wind structures propagating toward Earth. From this vantage point, heliospheric imaging can support the continuous monitoring of CMEs as they evolve through the interplanetary medium [1].

The Vigil Heliospheric Imager (HI) is conceived as a wide-field visible-light instrument aimed at observing faint solar wind features over a large elongation range. The scientific target is challenging from a radiometric point of view, since CME signatures may correspond to approximately one percent of the F- and K-corona background signal. The opto-electronic design and data processing chain are therefore driven by sensitivity, signal-to-noise ratio, and radiometric stability requirements [2].

A key acquisition characteristic of heliospheric imaging is the use of long exposure times combined with temporal accumulation over an observation window. For the Vigil HI acquisition concept, multiple single-frame exposures are acquired and accumulated to generate the final onboard image product. 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. If not corrected before accumulation, these impulsive events propagate into the summed product and can significantly affect image quality and feature detectability [3].

This paper describes an onboard-compatible particle cleaning algorithm based on temporal filtering of consecutive exposures. The algorithm is intentionally simple from a computational point of view: it operates on each pixel independently and does not rely on spatial pattern recognition. The objective is to identify impulsive high-count events in the temporal evolution of each pixel while preserving the slowly varying heliospheric signal. The proposed approach is

assessed in terms of its impact on the residual radiometric bias after background subtraction and on the qualitative visibility of CME structures.

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2. VIGIL HELIOSPHERIC IMAGER OBSERVATION CONCEPT

2.1 Instrument overview

The Vigil Heliospheric Imager is designed to observe the inner heliosphere from the L5 region in the visible spectral range. Its wide-field optical concept supports the observation of solar wind features over a broad angular domain around the ecliptic plane and across elongations relevant for CME tracking. The instrument is required to detect faint and slowly evolving structures superimposed on the much brighter coronal background.

The radiometric challenge is mainly driven by the small contrast of CME signatures with respect to the F- and K-corona background. The measurement chain must therefore preserve low-amplitude signals over relatively long observation intervals. This requirement directly affects the acquisition strategy, the onboard processing sequence, and the acceptable level of residual contamination after particle cleaning.

2.2 Acquisition sequence and onboard processing chain

The HI acquisition sequence is based on the collection of multiple single-frame exposures within a temporal observation window. The single frames are processed onboard before the generation of the L0 product. The onboard processing chain includes particle cleaning, frame summing, saturation flagging, trimming, and binning. Additional corrections, such as non-linearity, dark current, smearing, flat-field correction, geometrical modeling, and absolute gain calibration, are performed by the on-ground processor at subsequent product levels.

This distribution of processing tasks is important for the particle cleaning strategy. Since particle hits are impulsive events affecting individual exposures, their correction is most effective before temporal summation. Once the frames have been accumulated, particle artifacts become mixed with the useful signal and are more difficult to identify and remove without degrading the faint heliospheric structures.

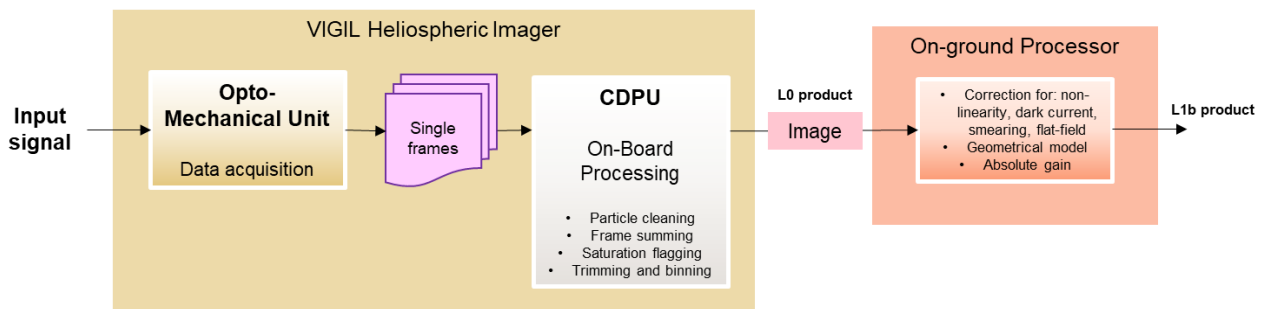


Figure 1. Simplified acquisition and processing chain for VIGIL HI.

2.3 Radiometric challenge for CME detection

The final scientific objective is not simply the reduction of bright particle tracks or individual contaminated pixels, but the preservation of CME detectability after all relevant image formation steps. Since the CME signal is expected to be weak with respect to the background, the residual error introduced by incompletely corrected particle events must be evaluated against the radiometric contrast of the CME itself.

For this reason, the assessment presented in this work considers the residual bias after background subtraction. This is a relevant metric because background subtraction strongly reduces the dominant coronal component and enhances the relative visibility of CME

structures. The residual contribution of uncorrected particle events, or of cleaning-induced errors, is therefore assessed in the same domain in which CME visibility is judged.

3. PARTICLE CONTAMINATION IN LONG-EXPOSURE HI DATA

The HI detector is exposed to charged particle events originating from both nominal galactic cosmic ray conditions and enhanced Solar Energetic Particle (SEP) environments. Particle contamination levels can vary significantly during the mission. Under nominal assumptions, the particle rate is of the order of 10,000 charged particles per frame, while severe space weather conditions can increase the rate up to several million charged particles per frame.

The assessment considers the relevant acquisition parameters for the two HI cameras. HI-1 uses 70 frames with an integration time of 20s and a 2 by 2 binning configuration. HI-2 uses 50 frames with an integration time of 30s and a 3 by 3 binning configuration. The detector is modeled as a 2048 by 2048 CCD with 15 micrometer pixel pitch, and an average affected area of 2.25 pixels per impinging particle is assumed.

A particle interacting with the detector can generate a localized, impulsive signal that is not correlated with the slowly evolving heliospheric scene. In a single exposure, this contribution may appear as a high-value outlier. If not removed, the event is included in the accumulated image. As a result, transient contamination can be amplified by the summation process and may locally modify the radiometric content of the L0 image.

This effect is especially critical for faint CME detection. A residual artifact comparable to a fraction of the coronal background can become significant when the signal of interest is itself approximately one percent of that background. The cleaning algorithm must therefore remove a large fraction of impulsive events while avoiding excessive false detections that would alter the useful signal.

The temporal nature of particle hits makes single-frame cleaning a natural solution. The physical scene observed by the HI evolves slowly over consecutive exposures, while particle events are generally impulsive and affect only a limited number of frames. This difference in temporal behavior can be exploited to detect outliers at the pixel level.

The proposed algorithm, preliminary assessed by RAL Space in phase A/B1, is applied before frame summing. For each pixel, the current exposure is compared with neighboring exposures. If the current value exceeds a temporal estimator by a configurable threshold, a particle hit is detected and the pixel value is replaced by the estimator. This approach avoids the need for spatial filtering and reduces the risk of altering narrow or low-contrast heliospheric features.

4. ONBOARD TEMPORAL FILTERING ALGORITHM

4.1 General detection and correction principle

The particle cleaning algorithm operates on a pixel-by-pixel (i,j) basis. For a given pixel position, the measured value in the current exposure is compared with an estimator derived from temporally adjacent exposures. The algorithm identifies high-count temporal outliers, based on both a significance threshold and an absolute threshold. The significance criterion accounts for the expected noise of the difference between the current value and the estimator, while the absolute criterion prevents excessive flagging in regions where the signal is very low.

Let I be the measured pixel value in the current exposure and E the temporal estimator computed from neighboring exposures. A hit is detected when the difference between I and E exceeds the selected thresholds. If a hit is detected, the corrected value I' is set equal to E . Otherwise, the original value is preserved. The thresholds are parameterized so that they can be tuned if required during operations.

$$I'_{i,j} = \begin{cases} E_{i,j} & \text{if the threshold is exceeded} \\ I_{i,j} & \text{Otherwise} \end{cases}$$

Where $I_{i,j}$ is the pixel value in the current exposure and $I'_{i,j}$ is the corrected pixel value.

The threshold is based on the significance of the difference between the recorded counts and the estimator and on the absolute difference (the latter is required to prevent excessive numbers of hits being flagged in regions where there is little or no signal):

$$H_{i,j} = \frac{I_{i,j} - E_{i,j}}{\sigma(I_{i,j} - E_{i,j})} > S_p \text{ and } I_{i,j} - E_{i,j} > N_p$$

Where: $H_{i,j}$ is a logical condition indicating that a hit is detected, $\sigma(I_{i,j} - E_{i,j})$ is the standard deviation of the difference between I and E , S_p is the significance threshold and N_p is the absolute threshold.

4.2 Low-rate algorithm

The low-rate algorithm is intended for nominal to moderate particle flux conditions. It is designed to provide efficient particle rejection while limiting the generation of false positives. In this configuration, the estimator is computed as the mean of the previous and following exposures for the same pixel location:

$$E_{i,j} = \frac{I_{i,j;-1} + I_{i,j;+1}}{2}$$

This estimator is appropriate when the probability of particle contamination in both neighboring frames is low. Since heliospheric features evolve slowly relative to the frame-to-frame interval, the local temporal mean provides a suitable estimate of the uncontaminated signal. The variance of the difference between the current value and the estimator is then used to define the significance of the detected deviation, taking into account the system gain.

The variance of the difference is then given by:

$$\sigma^2(I_{i,j} - E_{i,j}) = \frac{I_{i,j}}{G} + \frac{E_{i,j}}{2G}$$

where G is the gain of the system in photo-electrons per DN.

4.3 High-rate algorithm

The high-rate algorithm is intended for severe particle environments, where the probability of contamination in neighboring frames increases. In this case, using only the previous and following frames may not be sufficiently robust, since one or both reference frames may themselves be affected by particle hits.

To improve robustness, the high-rate algorithm uses a wider temporal neighborhood composed of the two previous and two following exposures. The estimator is computed as the minimum value among these four neighboring samples:

$$E_{i,j} = \min(I_{i,j;-2}, I_{i,j;-1}, I_{i,j;+1}, I_{i,j;+2})$$

The use of the minimum reduces the probability that the estimator is biased upward by particle contamination in the neighboring frames. This configuration is more conservative and is better suited to enhanced SEP conditions, although it may introduce different behavior in terms of signal preservation and statistical variance.

There does not appear to be an exact expression for the variance of the minimum of a set of values drawn from a Poisson distribution, but by experimentation with random numbers, 1/9 of the variance of the sum is a good approximation for four values, hence:

$$\sigma^2(I_{i,j} - E_{i,j}) = \frac{I_{i,j}}{G} + \frac{I_{i,j;-2} + I_{i,j;-1} + I_{i,j;+1} + I_{i,j;+2}}{9G}$$

where G is the gain of the system in photo-electrons per DN.

4.4 Algorithm transition and tunable parameters

The particle cleaning performance assessment was driven by mission-level requirements expressed in terms of temporarily degraded angular samples. Under nominal operating conditions, the number of temporarily degraded angular samples is required to remain below 2% of the total number of angular samples, while during the 1-in-100-years severe space weather event the number of temporarily degraded samples shall remain below 50%. A degraded angular sample is defined as an angular sample for which the applicable performance, such as the signal-to-noise ratio, is not met. Temporarily degraded samples are those affected by external and recoverable conditions, including severe space weather events or saturation effects due to bright objects crossing the field of view. These requirements provided the starting point for the definition of a verification approach, but they did not directly specify how the degradation induced by residual SEP or cosmic-ray artifacts should be quantified in the final science-oriented image domain. For this reason, a dedicated quantitative metric was introduced, based on the residual radiometric bias after cleaning, frame accumulation, and background subtraction. This metric allows the impact of uncorrected or imperfectly corrected particle events to be

expressed as a percentage of the background signal and to be mapped into a percentage of temporarily degraded pixels. In this way, the cleaning performance can be assessed against a measurable radiometric criterion that is directly linked to the detectability of faint CME signatures.

At the end of the PDR assessment, the quantitative radiometric bias analysis was complemented by a qualitative evaluation of the actual CME visibility in the processed images after background subtraction. This criterion was used as the final guiding element of the analysis, because the ultimate objective of the cleaning function is not only to reduce the number of degraded samples, but to preserve an image quality adequate for detecting the presence and morphology of faint CME structures. Since the CME signal becomes effectively assessable only after subtraction of the dominant coronal background, the visual inspection of the background-subtracted images provided a direct verification of whether the residual particle-induced artifacts were still compatible with the scientific use of the product. The radiometric bias metric was therefore introduced as a quantitative support to the requirement interpretation, while the effective visibility of the CME after background subtraction remained the reference criterion for consolidating the assessment at PDR.

5. PERFORMANCE ASSESSMENT METHODOLOGY

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5.1 Simulation approach

The assessment is based on simulated acquisition windows reproducing the HI frame acquisition, particle contamination, particle cleaning, and frame accumulation sequence. Two types of input scenes are considered. The first contains only the coronal background signal. The second contains the same background with an added CME structure. Both scenes are propagated through the same particle contamination and cleaning pipeline, allowing the residual particle contribution to be evaluated in a differential way. This approach is particularly relevant because CME detectability is assessed after background subtraction. The subtraction strongly suppresses the dominant background component and makes the CME signal more visible. At the same time, residual particle-induced errors can remain in the difference image and may locally interfere with the detection of faint structures.

The radiometric bias metric is evaluated using two residual images. The first residual image is obtained from the simulation including the CME, by subtracting the corresponding reference image without particle contamination. The second residual image is obtained from the background-only simulation, again by subtracting the corresponding uncontaminated reference. The differential residual error is then computed as the absolute difference between these two residuals, normalized to the input background signal.

In conceptual form, the metric can be expressed as:

$$\text{Residual_CME} = \text{CME_image_with_particles_and_cleaning} - \text{CME_reference}$$

$$\text{Residual_NO_CME} = \text{background_image_with_particles_and_cleaning} - \text{background_reference}$$

$$\text{Relative_error} = \text{abs}(\text{Residual_CME} - \text{Residual_NO_CME}) / \text{background_signal}$$

A pixel is considered temporarily degraded when the relative error exceeds a selected radiometric bias threshold. The analysis considers several threshold values expressed as percentages of the background signal. This allows the sensitivity of the results to the selected performance criterion to be investigated.

5.2 Test cases

For nominal conditions, the low-rate algorithm is applied. The HI-1 case considers 70 frames, 20 s integration time, 2 by 2 binning, and 7288 particle events per frame. The HI-2 case considers 50 frames, 30 s integration time, 3 by 3 binning, and 10932 particle events per frame.

For enhanced particle conditions, the high-rate algorithm is applied. A representative high-flux case with 6 million particle events per frame is considered for both HI-1 and HI-2. These cases are used to evaluate the degradation trend under severe particle contamination and to identify the limitations of the current cleaning strategy.

6. RESULTS

6.1 Nominal SEP flux conditions

Under nominal particle conditions, the low-rate algorithm provides effective mitigation of impulsive events for both HI-1 and HI-2. After background subtraction, the percentage of temporarily degraded pixels depends on the selected residual radiometric error threshold. For the HI-1 nominal case, the degraded pixel percentage decreases from 0.81 percent at a 0.2 percent threshold to 0.11 percent at a 0.75 percent threshold. For HI-2, the corresponding values decrease from 0.95 percent to 0.12 percent.

These results indicate that, for nominal particle rates, the residual impact of particle artifacts after cleaning is spatially limited and remains compatible with the objective of preserving CME visibility over most of the image. The behavior is consistent for both cameras, despite the different integration times, number of frames, and binning configurations.

Table 1. Percentage of temporarily degraded pixels after cleaning under nominal conditions for HI-1 and HI-2 as a function of residual radiometric error threshold.

Residual radiometric error [% wrt background signal after subtraction]	Percentage of temporarily degraded pixel in CCD after cleaning HI-1	Percentage of temporarily degraded pixel in CCD after cleaning HI-2
0.2	0.81%	0.95%
0.3	0.31%	0.33%
0.5	0.14%	0.15%
0.75	0.11%	0.12%

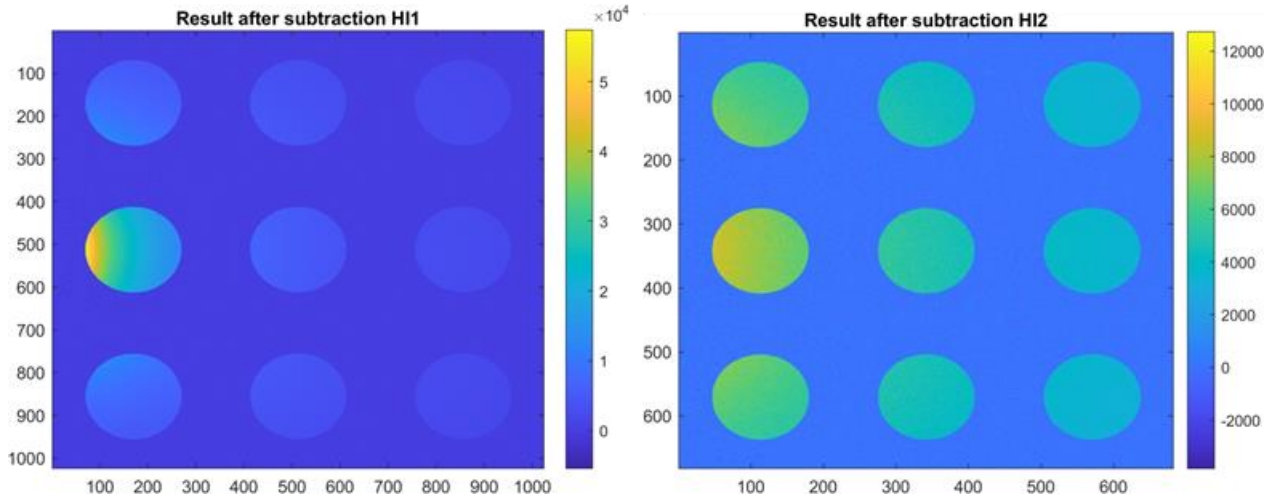


Figure 2. Background-subtracted results in nominal SEP flux conditions for the HI-1 and HI-2 simulated acquisition cases after onboard particle cleaning and frame accumulation. The subtraction of the coronal background enhances the visibility of the CME-like structures and enables a qualitative assessment of the residual particle-induced artifacts with respect to CME detectability.

6.2 High SEP flux conditions

Under high particle flux conditions, the high-rate algorithm is required to increase robustness against contamination of the temporal neighborhood. However, the residual degradation becomes significantly larger. For the 6 million particle per frame case, the HI-1 degraded pixel percentage ranges from 73.2 percent at a 0.2 percent threshold to 37.9 percent at a 0.75 percent threshold. For HI-2, the corresponding range is from 82.6 percent to 47.0 percent.

These results show that, although the high-rate algorithm improves the ability to identify and correct particle hits in severe environments, the residual radiometric degradation remains substantial when the particle flux is extremely high. This is expected because the probability of repeated contamination of the same pixel over neighboring frames increases, reducing the availability of uncontaminated temporal samples for estimator construction.

Table 2. Percentage of temporarily degraded pixels after cleaning under severe space weather conditions for HI-1 and HI-2 as a function of residual radiometric error threshold.

Residual radiometric error [% wrt background signal after subtraction]	Percentage of temporarily degraded pixel in CCD after cleaning HI-1	Percentage of temporarily degraded pixel in CCD after cleaning HI-2
0.2	73.2%	82.6%
0.3	64.5%	75.4%
0.5	50.7%	61.9%
0.75	37.9%	47.0%

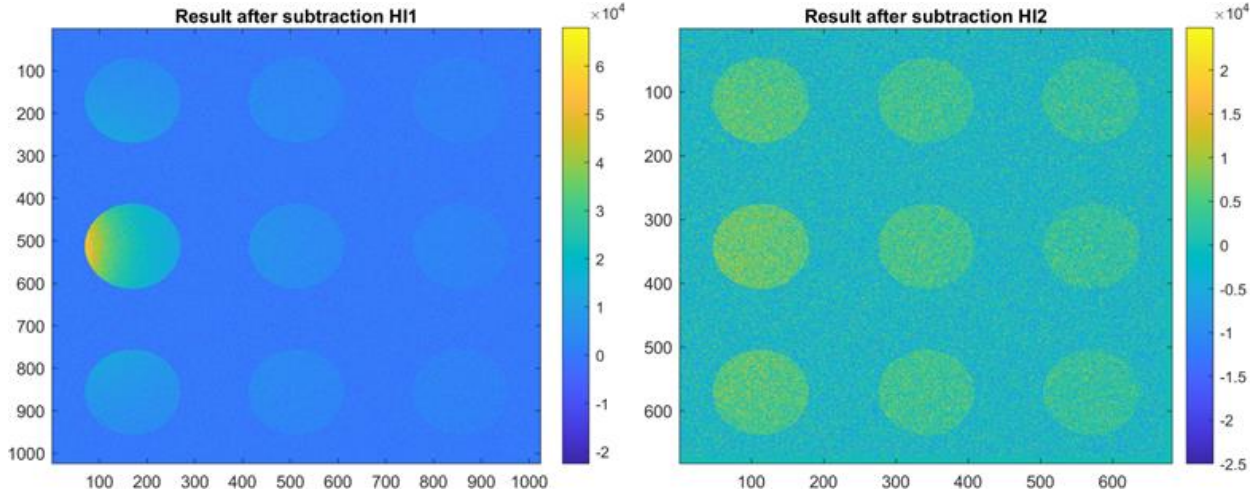


Figure 3. Background-subtracted results in severe space weather SEP flux conditions for the HI-1 and HI-2 simulated acquisition cases after onboard particle cleaning and frame accumulation. The subtraction of the coronal background enhances the visibility of the CME-like structures and enables a qualitative assessment of the residual particle-induced artifacts with respect to CME detectability.

6.3 Impact on CME visibility

The qualitative assessment of CME visibility confirms the importance of evaluating the algorithm after background subtraction. In the accumulated L0 image, the CME signal is superimposed on a dominant background and may be difficult to assess directly. After subtraction of the background-only reference, the CME morphology is enhanced and the residual particle-induced artifacts can be evaluated against the signal of interest.

In nominal conditions, the temporal filtering approach suppresses most of the impulsive contamination while preserving the slowly varying CME structure. The remaining degraded pixels are sparse and do not dominate the visual interpretation of the CME morphology. In high particle flux conditions, residual artifacts become more spatially widespread and may interfere with the reliable identification of faint CME features, particularly when the acceptable radiometric bias threshold is stringent.

7. DISCUSSION

The proposed method is compatible with onboard implementation because it has low algorithmic complexity. It processes each pixel independently, requires only a limited number of neighboring exposures to be stored, and avoids spatial correlation, segmentation, or morphology-based operations. This makes the approach suitable for real-time or near-real-time processing within the constraints of an onboard data handling chain. The algorithm is also configurable. Detection thresholds and transition criteria can be adjusted, allowing the balance between cleaning efficiency and false-positive rate to be tuned. This flexibility is important because the actual in-flight particle environment may differ from pre-launch assumptions, and operational experience may suggest optimized parameter sets.

A key design choice is the use of temporal filtering rather than spatial filtering. In heliospheric images, the useful signal is faint and structured over large angular scales. Spatial filtering could modify low-contrast features or introduce local distortions that affect CME morphology. By exploiting the temporal impulsiveness of particle hits instead, the algorithm better preserves spatial structures that are stable or slowly evolving across consecutive exposures. The low-rate algorithm is particularly well aligned with this objective, since the mean of the previous and following frames provides a smooth estimate of the expected signal. The high-rate algorithm introduces a more conservative estimator, based on the minimum of four neighboring samples, which is advantageous when contamination probability increases but may require careful threshold tuning to avoid excessive correction.

The analysis also shows that requirement verification must be defined with sufficient detail. A generic requirement on residual particle contamination may not be directly representative of CME detectability unless the product level,

background subtraction approach, radiometric threshold, and spatial metric are specified. For this reason, the assessment after background subtraction provides a more meaningful link between algorithm performance and scientific objective. A limitation of the current assessment is that the CME detectability evaluation is primarily qualitative. A more quantitative analysis could be introduced in future work, for example by using spatial frequency analysis, contrast metrics, structural similarity indices, or detection probability estimates. Such metrics would support a more objective evaluation of the effect of residual particle artifacts on CME tracking performance.

8. CONCLUSIONS

An onboard-compatible temporal filtering approach has been presented for the mitigation of SEP and cosmic-ray induced artifacts in Vigil Heliospheric Imager data. The algorithm operates at single-frame level before temporal accumulation and uses pixel-wise temporal comparisons to detect impulsive particle hits. Two configurations are considered: a low-rate algorithm based on the previous and following exposures, and a high-rate algorithm based on a wider temporal neighborhood.

The performance assessment demonstrates the importance of correcting particle artifacts before frame summing, particularly for faint CME detection where the useful signal is of the order of one percent of the coronal background. In nominal particle conditions, the algorithm significantly limits the percentage of temporarily degraded pixels after background subtraction and preserves CME morphology. Under severe particle flux conditions, the residual degradation becomes much larger, highlighting the intrinsic difficulty of maintaining radiometric performance when the probability of repeated temporal contamination is high.

The results support the suitability of temporal filtering as a baseline strategy for onboard particle cleaning in the Vigil HI processing chain. They also emphasize the need to define verification metrics at the appropriate product level and in relation to the final scientific objective, namely the reliable detection and tracking of CMEs in heliospheric image products.

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