

Long-term detector health monitoring of the Metis coronagraph through stellar observations

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ABSTRACT

The Metis coronagraph aboard ESA’s Solar Orbiter images the solar corona simultaneously in visible light (VL, 580-640 nm) and ultraviolet light (UV, H I Ly- α at 121.6 nm), covering the solar atmosphere from 1.7 to approximately 9 solar radii ($R_{\odot}$). As Solar Orbiter completes multiple orbits reaching perihelia down to 0.29 AU, the instrument is exposed to an increasingly intense particle and radiation environment. Ensuring the long-term validity of coronal observations requires continuous tracking of detector health and optical performance. We present a health-monitoring study based on stellar observations acquired between December 2021 and January 2025, drawing from a full-resolution dataset of the Metis visible-light channel (2048×2048 pixels). By pairing observations of the same background star at close spatial proximity on the detector ($\Delta_{\text{pos}} \leq 40$ px), field-dependent aberrations are cancelled, isolating temporal variations in the point-spread-function width and signal-to-noise ratio. After physical filtering, linear regression analysis on seven reference stars (spanning $V = 0.97$ -4.27 mag) initially suggests a statistically significant trend for three of the seven stars, on both the major and minor axis; however, once corrected for the multiple comparisons involved in testing seven stars independently, only one of these trends survives a conservative significance threshold. A per-star decomposition traces the residual signal to a small subset of stars sampled close to the inner edge of the internal occulter, rather than to a genuine, detector-wide degradation.

Keywords: Solar Orbiter, Metis coronagraph, detector health monitoring, point spread function, PSF, in-flight calibration, stellar photometry, CMOS radiation damage

1. INTRODUCTION

Solar Orbiter addresses fundamental questions in solar and heliospheric physics through a combination of in-situ and remote-sensing instruments.¹ Among these, the Metis coronagraph provides simultaneous imaging of the solar corona in visible light (VL, 580-640 nm) and ultraviolet emission (UV, H I Ly- α at 121.6 nm), mapping the solar atmosphere from 1.7 to nearly $9 R_{\odot}$ depending on the instantaneous spacecraft distance². Over its operational lifetime, Metis has delivered critical scientific observations of coronal mass ejections (CMEs), the solar-wind acceleration region, and the thermal and magnetic structure of the coronal plasma.

Because Solar Orbiter executes close perihelion passages down to 0.29 AU, Metis operates in a harsh radiation and thermal environment. Prolonged exposure to high-energy solar particles can degrade the performance of the optical coatings and of the active CMOS detectors over time. Continuous in-flight monitoring of detector health is therefore essential for maintaining photometric accuracy and spatial resolution.

Background stars transiting the Metis field of view serve as ideal, stable photometric references. Because their intrinsic flux is constant on operational timescales, any observed deviation in stellar signal or profile width

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across epochs indicates instrumental artifacting or optical drift rather than astrophysical variability. This study leverages a dataset spanning more than three years of operations (December 2021 - January 2025) to evaluate the long-term health and optical stability of the Metis VL channel.

2. INSTRUMENT AND CALIBRATION

2.1 The Metis coronagraph

Metis^{2,3} is a coronagraph with a distinctive optical design that allows simultaneous observation of the solar corona in two wavelength ranges: a visible broadband channel and an ultraviolet channel. Its annular field of view spans from 1.5° to 2.9° in elongation, enabling observation of dynamic coronal structures close to the Sun.

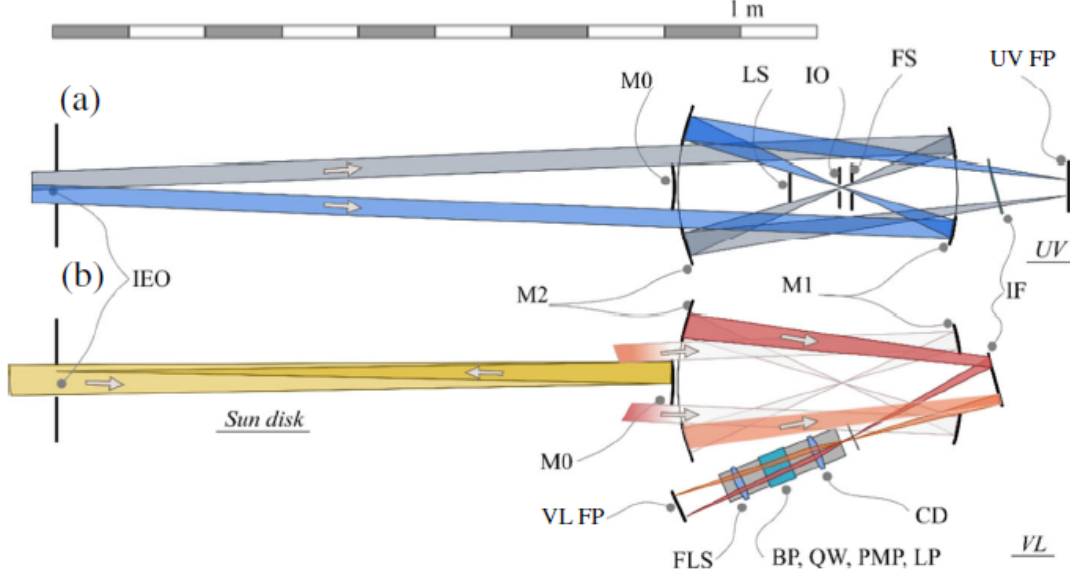


Figure 1. Schematic optical layout of the Metis coronagraph.³ Incoming sunlight is intercepted by the Inverted External Occulter (IEO) and the mirror M0, which also acts as an external occulter; coronal light proceeds to an on-axis Gregorian telescope (M1, M2). Residual stray light is suppressed by an internal occulter (IO) and Lyot stop (LS). A dichroic interference filter (IF) separates the UV beam, sent to the Ultraviolet Detector Assembly (UVDA, 1024×1024 px), from the VL beam, which passes through the Polarization Module Package (PMP) before reaching the Visible-Light Detector Assembly (VLDA, 2048×2048 px). FP, FLS, BP, QW and LP respectively stand for: Focal Plane, Focus Lens System, Band Pass filter, Quarter Wave plate and Linear Polarizer

Operating as close as 0.29 AU from the Sun, Metis is exposed to large and variable thermal loads along its orbit. The inverted external occulter (IEO) design mitigates the stress while suppressing direct sunlight and preserving the optical alignment needed for coronal imaging. Both the UVDA and VLDA are custom: radiation-tolerant CMOS Active Pixel Sensors (APS) have been chosen over the CCD technology traditionally used in space coronagraphs for their lower power consumption, flexible readout, and greater resilience to the proton and electron fluxes encountered during Solar Orbiter’s close perihelion passages. This radiation environment, and its potential long-term impact on detector performance, is precisely what motivates the differential health-monitoring analysis presented in this work. Because the in-flight instrumental response must be characterized quantitatively, background stars transiting the field of view are used, in this and companion studies,^{4–7} as point-source references to probe the point spread function (PSF) across the detector and its evolution with time. A more detailed description of the optical design and of the full stellar dataset used to characterize the Metis PSF across the field of view can be found in Casini et al. (2026).⁸

2.2 Calibration methodology

Directly comparing stellar PSFs across different focal-plane coordinates is complicated by field-dependent optical aberrations inherent to the telescope geometry. To bypass these spatial gradients, observations of the same star obtained at epochs t_1 and t_2 are matched into differential pairs. The separation distance Δ_{pos} between the pair centroids (x_1, y_1) and (x_2, y_2) is defined as

$$\Delta_{\text{pos}} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}. \quad (1)$$

By enforcing a strict spatial threshold of $\Delta_{\text{pos}} \leq 40$ px, both observations sample virtually identical optical paths, effectively cancelling localized astigmatism and coma. A star is retained in the statistical baseline only if it yields at least $N \geq 3$ valid differential pairs.

Raw candidate detections are processed through a multi-stage quality filter to remove non-physical values and fitting degeneracies:

- observations with short integration times ($\text{DIT} < 3$ s) or low signal-to-noise ratio ($\text{SNR} < 10$) are discarded, since short exposures are dominated by read noise, and yield unconstrained Gaussian fits;
- unresolvable numerical artifacts returning $\text{FWHM}_{\text{major}} < 1.5$ px and $\text{FWHM}_{\text{minor}} < 1.5$ px are eliminated;
- pairs exhibiting $|\Delta\text{FWHM}_{\text{major}}| > 1$ px or $|\Delta\text{FWHM}_{\text{minor}}| > 1$ px (such as the extreme residual artifacts observed in isolated frames of the σ Sgr star) are purged as unphysical fitting failures;
- bright targets causing pixel saturation or extended halo contamination (such as α Sco) are manually excluded;

2.3 Reference stars for calibration

Stellar targets are identified in Level-0 VL images by cross-matching local intensity peaks with the SIMBAD⁹ astronomical database. Individual 23×23 pixel cutouts are extracted around each confirmed star and fitted with a two-dimensional Gaussian profile to recover centroid, Full Width Half-Maximum (FWHM) widths on both major and minor axis, and signal-to-noise ratio (SNR). Because four diagonal spider arms supporting the internal occulter introduce diffraction artifacts, the analysis is strictly limited to stellar transits occurring within four clear, unobstructed detector sectors (labelled North, South, East and West, in Table 1) and shown in figure 2.

Table 1. Reference stars used for the differential PSF/SNR pairing analysis. N_{pairs} is the number of differential pairs retained after the quality filtering of Sec. 2.2.

Star	V (mag)	Epoch range	DIT (s)	N_{POL}	Sector(s)	N_{pairs}
α Vir	0.97	2022-11-10 - 2024-10-27	20-30	0	East / West	18
δ Sco	2.32	2022-12-11 - 2024-11-30	20-30	0	South / East	57
σ Sgr	2.07	2023-01-30 - 2025-01-24	5-30	0-4	West	142
τ Sco	2.81	2022-12-22 - 2024-12-11	20-30	0	North	59
σ Sco	2.89	2022-12-15 - 2024-12-08	20-30	0	West / East	33
θ Oph	3.26	2023-07-05 - 2024-12-25	20-30	0	East / South	32
d Oph	4.27	2023-07-05 - 2024-12-26	20-30	0	North	52

This selection and star-identification methodology, together with the complete stellar-transit catalogue (23 stars, 611 individual observations, December 2021 - January 2025), is described in detail in a recent publication;⁸ the present differential health-monitoring study draws from this catalogue the subset of seven stars with a sufficient number of repeated, closely-spaced observations to support the pairing analysis of Sec. 2.2.

Table 1 lists the seven bright field stars that satisfied the pairing and quality-filtering criteria described in Sec. 2.2, together with their visual magnitude, the epoch range spanned by their observations, the range of detector integration times (DIT) and polarizer states (N_{POL}) sampled, the detector sector in which they were observed, and the resulting number of valid differential pairs N_{pairs} .

The sample spans nearly four magnitudes in brightness ($V = 0.97$ -4.27) and covers the full mission baseline considered in this work, providing a robust and independent set of point sources against which to test detector stability across epochs, exposure times, polarization states, and detector sectors. In total, $N_{\text{pairs}} = 393$ differential pairs passed the quality filtering described below.

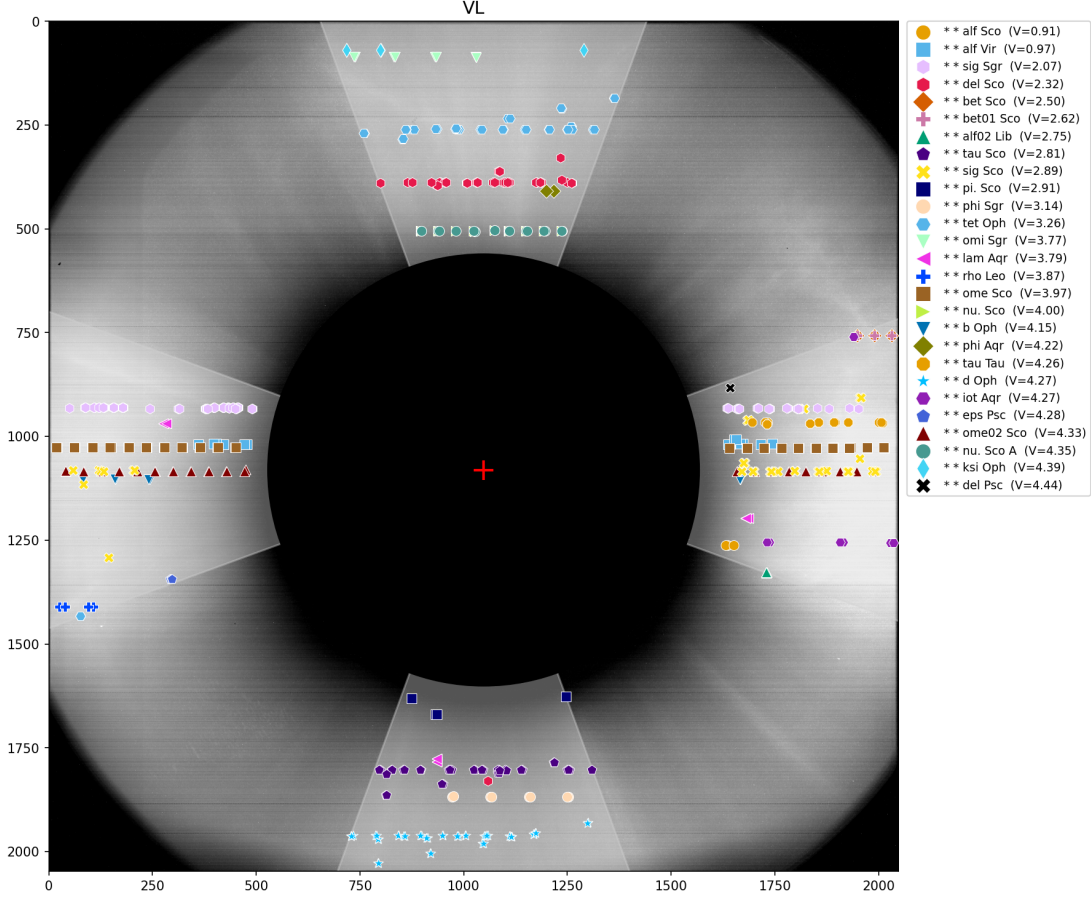


Figure 2. Spatial distribution of stellar observations used in the PSF analysis, overlaid on a Metis VL coronagraph image. The four light gray sectors indicate the regions free from support-structure selected for this study. The red cross marks the optical axis (boresight).⁸

3. STATISTICAL RESULTS AND DETECTOR HEALTH DIAGNOSTICS

We define the pairwise FWHM change between two epochs t_1 and t_2 as

$$\Delta\text{FWHM}_{\text{major,minor}} = \text{FWHM}_{\text{major,minor}}(t_2) - \text{FWHM}_{\text{major,minor}}(t_1), \quad [\text{px}] \quad (2)$$

For each of the $N_{\star} = 7$ reference stars, a linear regression model is then fitted independently to $\Delta\text{FWHM}_{\text{major,minor}}$ as a function of the pair time separation $\Delta t = t_2 - t_1$ (in days):

$$\Delta\text{FWHM}_{\text{major,minor}}(\Delta t) = a_{\star} \cdot \Delta t + b_{\star}, \quad [\text{px}] \quad (3)$$

where a_* and b_* are the star-specific slope and intercept. For each star and each axis, the slope a , its standard error, the coefficient of determination R^2 , and the p -value are obtained from an ordinary least-squares fit of ΔFWHM against Δt , performed with the `scipy.stats.linregress` routine within the Python analysis pipeline used to derive the statistics presented in this paper.

We note that this fit does not use a weighted, χ^2 -based approach (which would require a per-pair uncertainty σ_i on ΔFWHM , propagated from the covariance of the two-dimensional Gaussian fit to each stellar cutout); instead, an ordinary (unweighted) least-squares fit is adopted, with R^2 and p serving as the primary diagnostics of fit quality and significance. Propagating per-point measurement uncertainties into a weighted χ^2 fit is left for future work.

These two numbers, p and R^2 , answer two different questions. The p -value tests the hypothesis that the true slope is exactly zero (no dependence of ΔFWHM on Δt). If that hypothesis were true, p is the probability of observing, purely by chance, a slope as large as (or larger than) the one measured in our data. A small p -value means this would be very unlikely to happen by chance alone, so we conclude the slope is probably not zero, i.e., there probably is a real trend. We adopt the conventional threshold $p < 0.05$ (a less than 5% chance of this being a fluke) to call a slope statistically significant.

The coefficient of determination R^2 answers a different question: how well does it describe the data, once we know there is a trend. It is computed as

$$R^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2}, \quad (4)$$

where y_i are the observed values of ΔFWHM , $\hat{y}_i$ the values predicted by the fitted line, and $\bar{y}$ their mean. R^2 ranges from 0 (the line explains none of the scatter in the data, the points are just as spread out as if you ignored Δt completely) to 1 (every point lies exactly on the line, with no scatter at all). In other words, R^2 tells us how much of the point-to-point variability in ΔFWHM is captured by the straight-line trend, as opposed to being left over as unexplained scatter.

Across the full three-year baseline, the star-by-star regressions yield the slopes, p -values, and R^2 reported in Table 2. At face value, three of the seven reference stars (α Vir, σ Sco, σ Sgr) show a nominally significant trend ($p < 0.05$) on *both* the major and minor axis, while the remaining four (δ Sco, τ Sco, θ Oph, d Oph) are consistent with zero slope on both axes. Of the three significant stars, α Vir, σ Sco and σ Sgr are exactly the three stars identified in Sec. 3.1 as having pairs close to the inner edge of the internal occulter, where residual field-dependent aberration is amplified by imperfect position cancellation.

Table 2. Per-star linear regression of ΔFWHM (px) vs. Δt , major and minor axis.

Star	Major axis			Minor axis		
	a (px/day)	p	R^2	a (px/day)	p	R^2
α Vir	2.39×10^{-3}	0.005	0.42	-1.64×10^{-3}	0.028	0.27
d Oph	7.12×10^{-4}	0.188	0.03	7.75×10^{-5}	0.751	0.00
δ Sco	6.54×10^{-5}	0.572	0.01	2.82×10^{-6}	0.963	0.00
σ Sco	1.02×10^{-3}	0.039	0.13	-5.49×10^{-4}	0.009	0.20
σ Sgr	-3.25×10^{-4}	0.043	0.03	-6.78×10^{-4}	0.001	0.22
τ Sco	-1.02×10^{-4}	0.384	0.01	1.60×10^{-4}	0.378	0.01
θ Oph	-8.15×10^{-5}	0.772	0.00	2.36×10^{-4}	0.353	0.03

Because seven stars are tested independently on each axis, the probability of observing at least one nominally significant $p < 0.05$ purely by chance, even if no star carries a real trend, is substantially higher than the

nominal 5%. Applying a standard correction for this multiple-testing effect shows that only the σ Sgr minor-axis trend ($p = 0.0001$) remains significant once this stricter threshold is applied; the α Vir major-axis ($p = 0.0053$) and σ Sco minor-axis ($p = 0.0101$) trends no longer clear it, and are consistent with the kind of chance fluctuation expected when testing seven independent stars. A genuine, uniform detector-wide degradation would be expected to affect all seven stars comparably; instead, this more conservative statistical picture strengthens the interpretation, developed further in Sec. 3.1, that the residual signal is attributable to localized aberration in a subset of stars sampled near the occulter edge, not to a true temporal degradation of the sensor.

3.1 Localized residual aberration: α Virginis, σ Scorpii, and σ Sagittarii

While for most reference stars the residual disagreement between the two FWHM axes: $\Delta\text{FWHM}_{\text{major}}$ and $\Delta\text{FWHM}_{\text{minor}}$, stays below ~ 0.3 px regardless of Δpos , three stars: α Vir, σ Sco, and σ Sgr show individual pairs in which this residual reaches ~ 1.02 px. Tables 3, 4, and 5 list, for each star, the pairs with the $\Delta\text{FWHM}_{\text{major}}$ and $\Delta\text{FWHM}_{\text{minor}}$, together with Δpos , the pair detector coordinates, and the sector.

Table 3. α Vir pairs with: Δpos , $\Delta\text{FWHM}_{\text{major}}$ and $\Delta\text{FWHM}_{\text{minor}}$, the pair detector coordinates, and the sector

Δpos (px)	ΔFWHM major (px)	ΔFWHM minor (px)	x_1, y_1	x_2, y_2	Sector
36.0	+1.02	−0.63	1673, 1030	1637, 1029	East
31.0	+0.92	−0.53	1673, 1030	1642, 1029	East
30.1	+0.80	−0.65	1667, 1031	1637, 1029	East
25.1	+0.70	−0.55	1667, 1031	1642, 1029	East
22.8	−0.61	+0.59	1637, 1029	1657, 1040	East
18.6	−0.52	+0.49	1642, 1029	1657, 1040	East

Table 4. σ Sco pairs with: Δpos , $\Delta\text{FWHM}_{\text{major}}$ and $\Delta\text{FWHM}_{\text{minor}}$, the pair detector coordinates, and the sector

Δpos (px)	ΔFWHM major (px)	ΔFWHM minor (px)	x_1, y_1	x_2, y_2	Sector
30.0	+1.01	−0.05	1700, 964	1670, 964	East
27.0	+0.97	−0.03	1697, 964	1670, 964	East
32.7	+0.54	−0.34	1700, 964	1675, 985	East
28.0	+0.70	−0.15	1700, 964	1672, 964	East
30.4	+0.50	−0.33	1697, 964	1675, 985	East
25.0	+0.66	−0.14	1697, 964	1672, 964	East

For all three stars, the largest ΔFWHM values are found among the pairs with the largest Δpos , close to the 40 px pairing threshold of Sec. 2.2. These pairs are not scattered across the field of view, but cluster in narrow, $y \approx 1114$ – 1116 px (sector East). Figure 3 shows one example pair for each star, illustrating the visible change in PSF shape between the two epochs.

For σ Sco, the minor axis changes only marginally across all listed pairs ($|\Delta\text{FWHM}_{\text{minor}}| < 0.35$ px), while the major axis reaches +1.01 px; for α Vir and σ Sgr, both axes change by comparable amounts, up to ~ 1.02 px in the most extreme cases. The most extreme fit failures already removed by the $|\Delta\text{FWHM}| > 1$ px filter of Sec. 2.2 (values of tens of pixels, clearly unphysical) also fall predominantly in the immediate neighbourhood of the σ Sgr cluster described above. Rather than being unrelated artifacts, these excluded outliers and the surviving large pairs of Table 5 appear to be different manifestations of the same underlying effect at the same detector location, at increasing severity.

Table 5. σ Sgr pairs with: Δpos , $\Delta\text{FWHM}_{\text{major}}$ and $\Delta\text{FWHM}_{\text{minor}}$, the pair detector coordinates, and the sector

Δpos (px)	ΔFWHM major (px)	ΔFWHM minor (px)	x_1, y_1	x_2, y_2	Sector
34.1	+0.77	−0.58	457, 1117	491, 1114	West
35.1	+0.72	−0.62	456, 1117	491, 1114	West
34.1	+0.67	−0.65	457, 1117	491, 1114	West
35.1	+0.71	−0.60	456, 1117	491, 1114	West
22.1	−0.98	+0.28	1637, 1116	1659, 1114	East
32.1	+0.71	−0.52	457, 1117	489, 1114	West
33.1	+0.65	−0.56	456, 1117	489, 1114	West
32.1	+0.60	−0.59	457, 1117	489, 1114	West
33.1	+0.64	−0.54	456, 1117	489, 1114	West

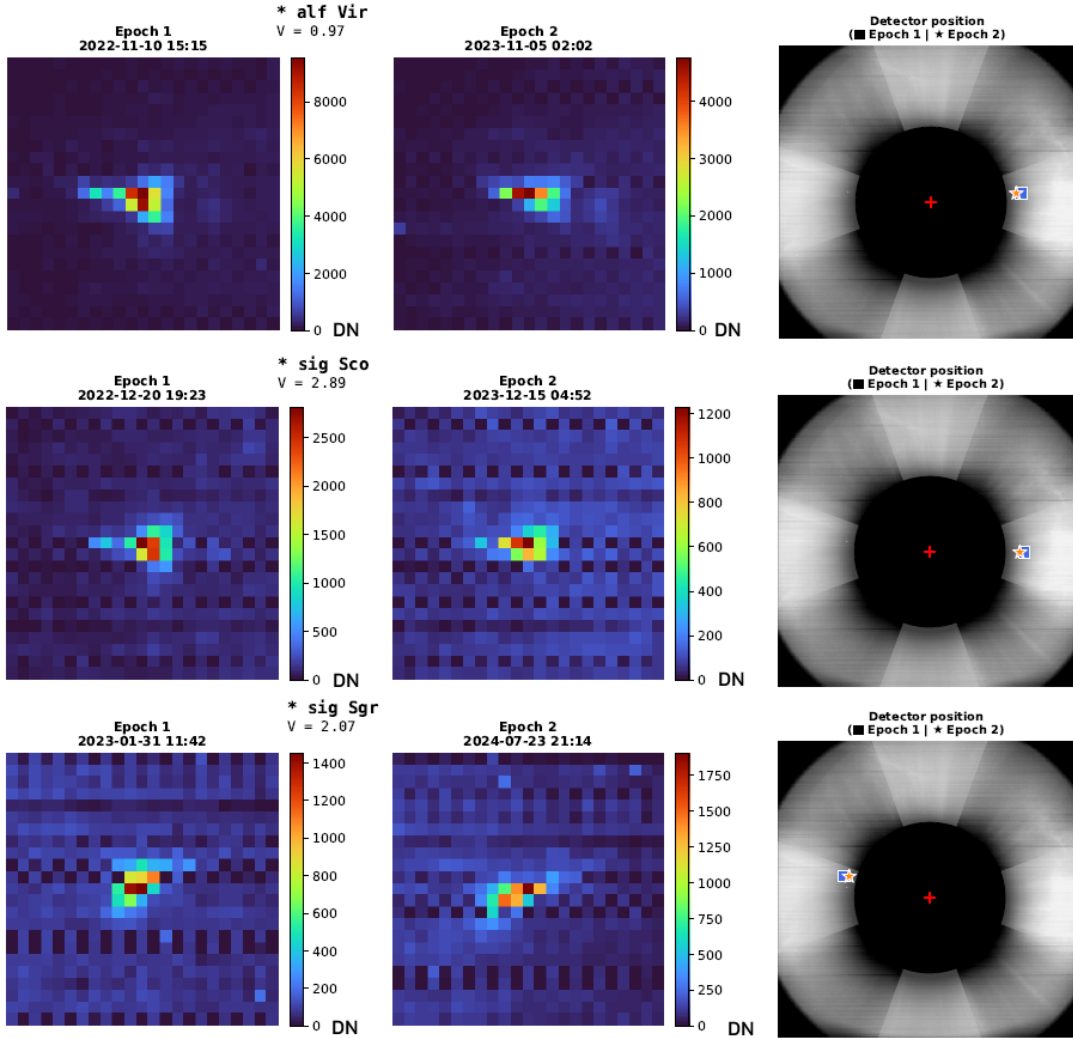


Figure 3. Example pairs with the largest ΔFWHM change for each of the three stars discussed in this section: α Vir (Table 3, $\Delta\text{pos} = 36.0$ px), σ Sco (Table 4, $\Delta\text{pos} = 30.0$ px), and σ Sgr (Table 5, $\Delta\text{pos} = 34.1$ px).

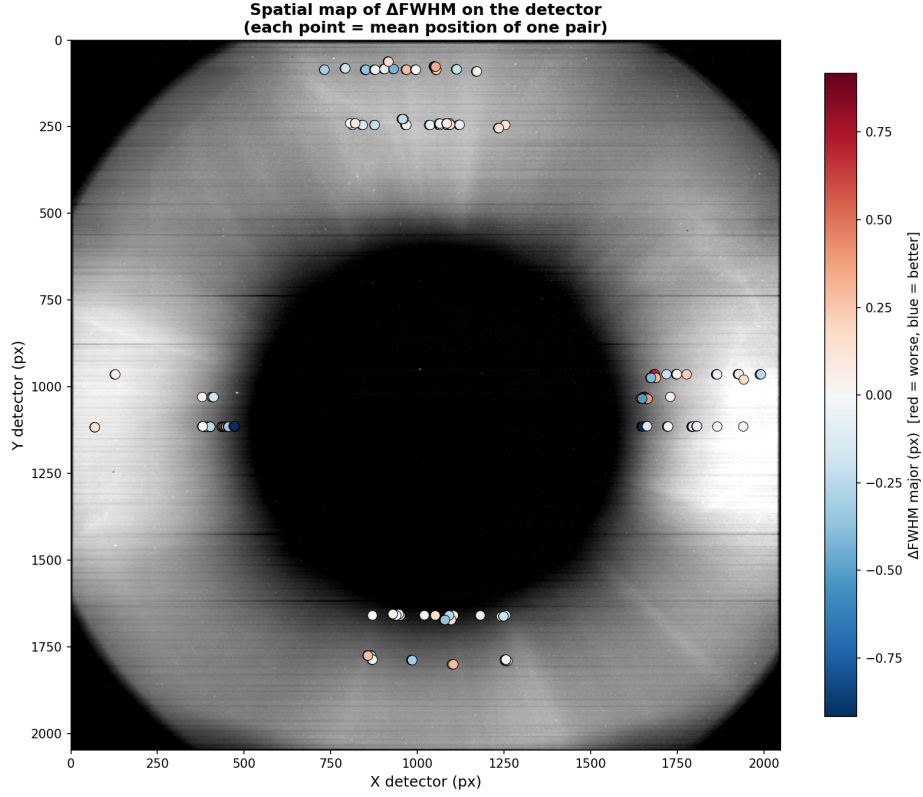


Figure 4. Spatial map of $\Delta\text{FWHM}_{\text{major}}$ (px) at the mean pair coordinates, overlaid on a Metis VL image. Observations are confined to the four clear sectors of the field of view; the largest changes (dark red/blue) are concentrated near the inner edge of the occulter, in the same regions identified above for α Vir, σ Sco and σ Sgr.

A change concentrated at large Δpos and confined to specific detector coordinates, rather than scattered uniformly across the sample, is the expected signature of residual field-dependent optical aberration: not fully cancelled when the two epochs of a pair do not fall at exactly the same focal-plane position, amplified near the inner edge of the internal occulter (IO), where the steep intensity gradient and partial vignetting of the stellar PSF make the fitted FWHM markedly more sensitive to the exact sub-pixel position of the star. This interpretation is directly supported for σ Sco and, more weakly, for σ Sgr, by the tighter-threshold test: restricting the pairing to $\Delta\text{pos} \leq 20$ px removes the significant trend for σ Sco entirely and weakens it for σ Sgr, consistent with a residual pairing effect that a stricter position cut suppresses. For α Vir, however, the trend persists, and does not weaken, under the same tighter threshold, so occulter-edge aberration alone does not fully explain its behaviour; its origin remains open and may be related to signal-to-noise or to coronal stray-light background near the occulter.

4. CONCLUSIONS

The monitoring methodology provides an effective, astrophysics-independent framework for monitoring the Metis visible-light channel aboard Solar Orbiter. Filtering out noise-dominated cutouts ($\text{SNR} < 10$, $\text{DIT} < 3$ s) and unphysical fit degeneracies yields a clean dataset of 393 differential pairs from seven reference stars, spanning over three years of operations (Table 1); after the $|\Delta\text{FWHM}| \leq 1$ px filter, 374 pairs remain for the per-star regression analysis. Differential analysis demonstrates that the major-axis PSF width remains stable over time when all pairs are pooled together. The minor axis shows a highly significant pooled trend; however, decomposing

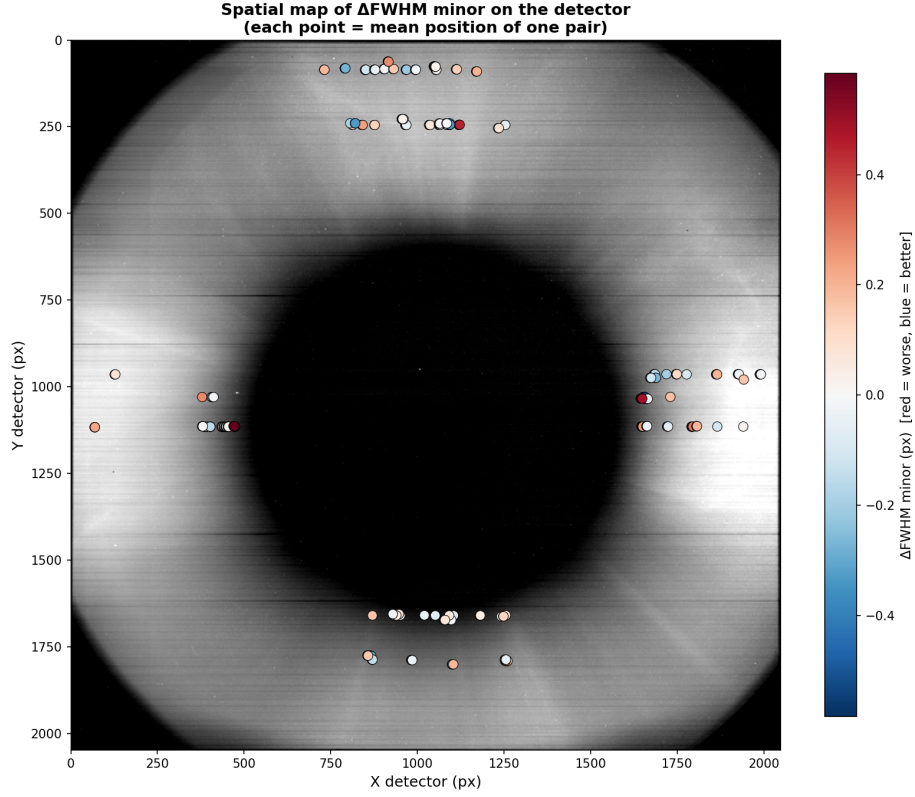


Figure 5. As Fig. 4, for $\Delta\text{FWHM}_{\text{minor}}$ (px). The largest positive and negative changes appear at the same detector locations as in Fig. 4.

the regression star by star (Table 2) shows that only three of the seven stars (α Vir, σ Sco, σ Sgr) individually yield a nominally significant trend, and only the σ Sgr minor-axis trend survives a conservative correction for the multiple comparisons involved in testing seven stars independently; the remaining two nominally significant trends are consistent with the kind of chance fluctuation expected under repeated independent testing. For all three stars, the largest changes in ΔFWHM occur among the pairs with the largest Δpos , close to the 40 px pairing threshold, and remain at or just above one pixel even in the most extreme cases (Sec. 3.1). Repeating the analysis with a tighter pairing threshold ($\Delta\text{pos} \leq 20$ px) confirms that the 40 px criterion is likely too loose to fully cancel field-dependent aberration for σ Sco, whose trend is no longer significant under the stricter cut, and partly for σ Sgr, whose trend weakens; for α Vir, however, the trend persists, and its significance does not decrease, under the tighter threshold, so the pairing criterion alone does not fully explain its behaviour. This overall pattern is inconsistent with a genuine, detector-wide degradation, which would be expected to affect all seven stars comparably; it points instead to residual, position-dependent effects concentrated in a small subset of stars, with α Vir remaining an open case that may warrant a pair-by-pair examination of signal-to-noise ratio and proximity to the internal occulter, where an increased coronal stray-light background could affect the Gaussian PSF fit.

These findings demonstrate that, despite repeated exposure to intense radiation environments during perihelion passages down to 0.29 AU, the Metis visible-light channel maintains excellent optical stability and detector health as Solar Orbiter enters its extended mission phase. Resolving the open question on α Vir, and extending this analysis to the full stellar catalogue of our team,⁸ are identified as natural next steps.

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REFERENCES

- [1] D. Müller, O. C. St. Cyr, I. Zouganelis, et al., “The Solar Orbiter mission: Science overview,” *Astron. Astrophys.* **642**, A1 (2020).
- [2] E. Antonucci, M. Romoli, S. Andretta, et al., “Metis: the Solar Orbiter visible light and ultraviolet coronal imager,” *Astron. Astrophys.* **642**, A10 (2020).
- [3] S. Fineschi, G. Naletto, et al., “Optical design of the Multi Element Telescope for Imaging and Spectroscopy (Metis) coronagraph,” *Exp. Astron.* **49**(3), 239 (2020).
- [4] De Leo, Y., Burtovoi, A., Teriaca, L., et al. 2023, A&A, 697, A73, doi:10.1051/0004-6361/202450759
- [5] De Leo, Y., Burtovoi, A., Teriaca, L., et al. A&A, 676, A45, doi: 10.1051/0004-6361/202345979
- [6] Casini, C., Chioetto, P., Comisso, A., et al. 2024, Aerotecnica Missili & Spazio, doi:10.1007/s42496-024-00219-3
- [7] Casini, C., Chioetto, P., De Leo, Y., et al. 2025, Proc. SPIE, 13699, International Conference on Space Optics ICSO 2024, 136995I, doi:10.1117/12.3071290
- [8] C. Casini, P. Chioetto, F. Frassetto, A. J. Corso, S. Fineschi, A. Herald, F. Landini, M. Romoli, P. Zuppella, and V. Da Deppo, “Long-term characterization of the Metis visible light point spread function,” *Proc. SPIE* **14145**, (2026); doi:10.1117/12.3104455.
- [9] M. Wenger, F. Ochsenbein, D. Egret, et al., “The SIMBAD astronomical database,” *Astron. Astrophys. Suppl. Ser.* **143**, 9-22 (2000).
- [10] W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical Recipes: The Art of Scientific Computing*, 3rd ed., Sec. 14.5 and Sec. 15.2, Cambridge University Press, Cambridge (2007).