



SVOM/VT: Preliminary Calibration Analysis

Zhu-Heng Yao¹, Yu-Lei Qiu¹, Jin-Song Deng^{1,2}, Li-Ping Xin¹, Chao Wu¹, Hua-Li Li¹, Jing Wang¹,
Yi-Nuo Ma^{1,3,4}, Hong-Bo Cai¹, Xu-Hui Han¹, Jian-Yan Wei^{1,2}, and Bertrand Cordier⁵

¹ National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China; zhyao@bao.ac.cn, qiuyl@nao.cas.cn, jsdeng@nao.cas.cn

² School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 101408, China

³ Institute for Frontier in Astronomy and Astrophysics, Beijing Normal University, Beijing 102206, China

⁴ School of Physics and Astronomy, Beijing Normal University, Beijing 100875, China

⁵ CEA/Paris-Saclay, Irfu/Département d'Astrophysique, 91191 Gif-sur-Yvette, France

Received 2026 January 19; revised 2026 March 17; accepted 2026 March 31; published 2026 October 5

Abstract

We present the in-orbit calibration of the Visible Telescope (VT), one of the key instruments aboard the Space-based multi-band Variable Objects Monitor (SVOM) mission for gamma-ray burst (GRB) studies. Using Gaia Data Release 3 (DR3) as a reference, the VT achieves an astrometric precision better than $0''.03$ for bright stars, degrading to $\sim 0''.25$ for faint targets. Shortly after launch, contamination was detected, reducing system transmission by $\sim 40\%$. An initial bake-out successfully restored performance, but gradual recontamination caused transmission to decline by $\sim 20\%$ over the following 100 days before stabilizing. Despite this effect, routine standard star observations maintain precise zero-point calibration, ensuring photometric stability at the 0.02 mag level. Using synthetic stellar spectra, we derived photometric transformations to the Gaia, Sloan Digital Sky Survey, and Johnson–Cousins systems with typical residuals of 0.03 mag. These results demonstrate the VT system's capability and reliability in calibrating observations of GRBs and other transients.

Key words: space vehicles: instruments – telescopes – (stars:) gamma-ray burst: general – methods: observational – techniques: image processing – methods: data analysis

1. Introduction

The Space-based multi-band Variable Objects Monitor (SVOM) is a Chinese–French joint mission dedicated to the study of gamma-ray bursts (GRBs) and other transient phenomena in the high-energy universe (Wei et al. 2016; Cordier et al. 2026). The Visible Telescope (VT) onboard SVOM is a 44 cm Ritchey–Chrétien optical telescope designed to provide rapid and sensitive follow-up observations of GRBs detected and localized by the SVOM/ECLAIRs (Godet et al. 2026). Using a dichroic beam splitter, VT simultaneously observes in the blue band ($0.40\text{--}0.65\ \mu\text{m}$; hereafter VT_B) and the red band ($0.65\text{--}1.00\ \mu\text{m}$; hereafter VT_R), enabling prompt two-color photometry over a $26' \times 26'$ field of view (FOV). Each band is equipped with a $2\text{k} \times 2\text{k}$ e2V CCD detector and is required to reach a limiting magnitude of ~ 22.5 in a 300 s exposure (Qiu et al. 2026).

A central objective of VT within the SVOM mission is to refine GRB localization to subarcsecond levels in celestial coordinates to facilitate timely redshift measurements by ground-based large telescopes, necessitating precise astrometric calibration. In addition, VT aims to construct a homogeneous and well-sampled dataset of optical light curves of GRB afterglows, capturing detailed temporal features such as early brightenings, plateaus, flares, late breaks and rebrightenings. These temporal features provide key insights

into the nature of GRB central engines, radiation mechanisms, and shock physics (Zhang 2007). Furthermore, the color information derived from the two VT bands, particularly deep upper limits in instances of non-detection, may serve as a preliminary indicator of high-redshift GRBs (Wang et al. 2020; Qiu et al. 2026). All of these scientific objectives critically rely on accurate and stable astrometric and photometric calibration.

To mitigate atmospheric turbulence and gravitational flexure, current ground-based wide-field surveys such as DES (Abbott et al. 2018), Pan-STARRS (Magnier et al. 2020), and LSST (Ivezić et al. 2019) rely on Gaia-based reference catalogs (Gaia Collaboration et al. 2016) to establish astrometric solutions at the level of tens of milli-arcseconds (mas). Furthermore, nightly observations of standard stars are performed to maintain photometric zero-points with accuracies of a few percent.

For a space-borne optical telescope like the VT, although atmospheric turbulence and terrestrial gravitational flexure are absent, regular onboard calibrations are necessary to compensate for the low-frequency evolution of thermoelastic deformations, ongoing degradation of optical coatings and detectors due to radiation damage, and accumulated outgassing contamination on sensitive optical surfaces (Poole et al. 2008; Massey et al. 2010; Euclid Collaboration et al. 2023;

Gardner et al. 2023). For example, the Hubble Space Telescope (HST; Holtzman et al. 1995; Sirianni et al. 2005) utilizes a mature geometric distortion model calibrated through repeated observations of dense stellar fields, achieving sub-10 mas astrometric precision. The Swift/UVOT instrument (Poole et al. 2008) applies a stable distortion map and uses UV spectrophotometric standard stars to maintain its long-term photometric accuracy. More recently, the Euclid mission (Euclid Collaboration et al. 2025) anchors its global astrometric solution directly to the Gaia DR3 catalog and employs a large set of high-quality standard stars for absolute flux calibration, achieving mas-level internal consistency.

The VT_B and VT_R bands are calibrated to the AB magnitude system. They have similar bandwidths and cross-over wavelengths to those of Gaia’s BP and RP bands, but differ significantly from either the Sloan or Johnson–Cousins photometric systems widely used in ground-based GRB follow-up observations. To enable coherent multi-instrument analyses of optical light curves from VT and other facilities, establishing reliable photometric transformations between the VT system and other standard systems (in particular, Sloan and Johnson–Cousins) is critical. Moreover, a precise determination of the effective wavelength for each band is essential for constructing broadband GRB spectral energy distributions (SEDs).

The structure of this paper is as follows. Section 2 describes the astrometric calibration procedure and the accuracy achieved. Section 3 presents the photometric calibration framework, detailing system response curves (Section 3.1), photometric zero-points (Section 3.2), long-term stability monitoring using standard spectrophotometric stars (Section 3.3), and photometric system transformations (Section 3.4). Section 4 discusses potential contamination effects and the red and blue leakages in both bands. Finally, Section 5 summarizes the main results of this work.

2. Astrometric Calibration

2.1. Astrometric Calibration Procedure

The astrometric calibration establishes the transformation between detector pixel coordinates and the International Celestial Reference System. An initial pointing solution is obtained from the onboard spacecraft attitude information and subsequently refined using reference stars from Gaia DR3 to achieve high-precision astrometry.

The calibrated spacecraft attitude is represented by a quaternion that describes the orientation of the VT optical axis, which is aligned with the FOV center of the red channel. This information yields the nominal pointing coordinates (R.A.₀, Decl.₀) and the roll angle ϕ_0 . Combined with the detector pixel scale, these parameters define an initial approximate World Coordinate System (WCS) for each VT image, which enables the projection of proper-motion-corrected

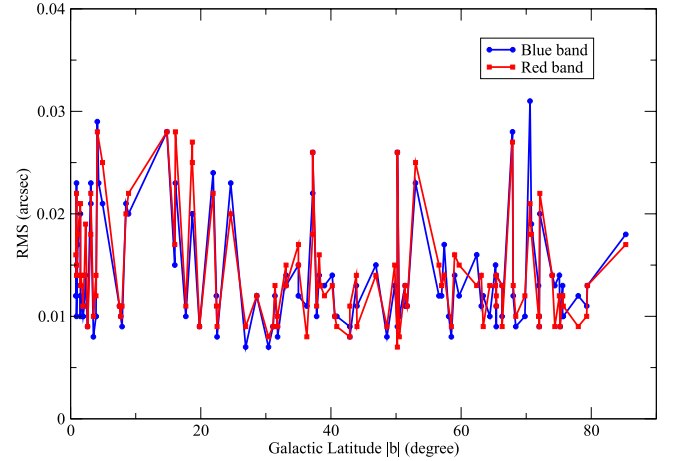


Figure 1. VT astrometric calibration residuals (rms) versus Galactic latitude in the 110 GRB fields.

Gaia DR3 reference stars onto the detector plane. The accuracy of this initial WCS is constrained by that of the attitude calibration (performed between the VT and star trackers), which is $\sim 15''$ at 90% confidence level (Qiu et al. 2026).

The initial WCS solution is refined by matching bright VT sources with well-determined centroids to the projected Gaia DR3 positions using a search radius of 20 pixels. An intermediate astrometric solution is derived with the IRAF (Tody 1986, 1993) task `ccmap`, using typically 20–30 anchor stars (see Figure 2 of Wu et al. 2026 for the geometric schematic) selected as the brightest unsaturated sources in each exposure. A second- or third-order polynomial model is adopted to correct for large-scale field-dependent distortions, and the fitting is performed iteratively with outlier rejection until a stable subarcsecond solution is achieved. Based on this intermediate solution, the fitting procedure is repeated using an expanded sample of more than 100 bright sources and a tighter matching tolerance at the subarcsecond level. A fourth-order or higher polynomial model is then applied to reduce residual systematics and correct small-scale geometric distortions. The resulting optimized solution achieves an astrometric accuracy of approximately $0''.01$.

In rare cases (e.g., crowded fields) where the initial attitude-based WCS fails to yield good alignment with Gaia projections, a blind astrometric solution is derived using ASTROMETRY.NET (Lang et al. 2010). However, ASTROMETRY.NET is employed only as a backup option in our procedure, taking computational costs into account.

2.2. In-orbit Performance of Astrometric Calibration

The in-orbit astrometric performance of VT is evaluated using 110 GRB fields observed during routine operations. As shown in Figure 1, more than 90% of the analyzed fields achieve an astrometric precision better than $0''.03$, fully

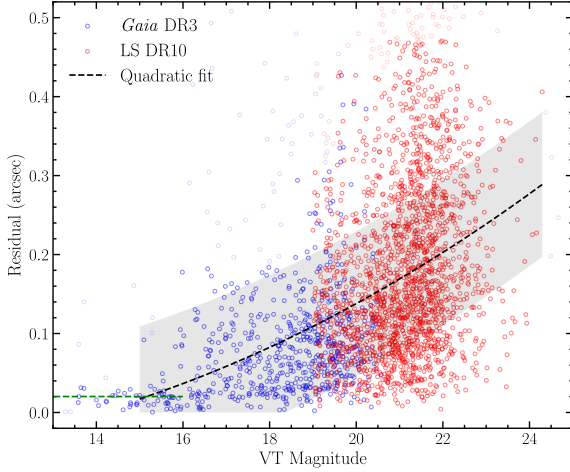


Figure 2. Relationship between stellar magnitude and astrometric residuals (blue circles for Gaia DR3 stars and red circles for LS DR10 stars). The green horizontal dashed line indicates the astrometric residual $0''.02$ measured for bright stars. The black dashed curve represents the best-fitting second-order polynomial to the data, and the gray shaded region indicates the corresponding 1σ uncertainty range.

satisfying the requirements for rapid detections of GRB counterparts and follow-up observations. The rms of astrometric residuals shows no significant correlation with Galactic latitude, despite localized variations ($\sim 0''.01$ – $0''.03$). Both bands exhibit consistent systematic trends, with only minor discrepancies. Considering that the two bands operate independently, their synchronous variations cannot be attributed to noise but likely arise from a common systematic source: either stellar density or pointing stability. However, the absence of a correlation between Galactic latitude (a proxy for stellar density) and astrometric accuracy excludes stellar density as the cause. We therefore conclude that variations in astrometric accuracy are most likely driven by spacecraft pointing stability.

Furthermore, to extend our assessment of VT astrometric performance to fainter sources, we analyze the dependence of positional residuals on stellar brightness using a representative VT image. We additionally employ the Legacy Survey DR10 (LS DR10; Dey et al. 2019) catalog as an independent reference, which offers substantially deeper magnitude coverage.

The results are illustrated in Figure 2. For bright stars, the astrometric residuals (rms) are $\sim 0''.02$. The astrometric residuals increase gradually toward fainter magnitudes. To quantitatively describe this trend, we fit the residual–magnitude relationship with a second-order polynomial function. Within the magnitude range effectively sampled by LS DR10, down to approximately 23 mag, the positional accuracy (rms) of VT remains at a mean value of $0''.25$. These results demonstrate that VT maintains reliable astrometric performance even for faint sources, ensuring accurate localization of GRB optical counterparts and other faint transients.

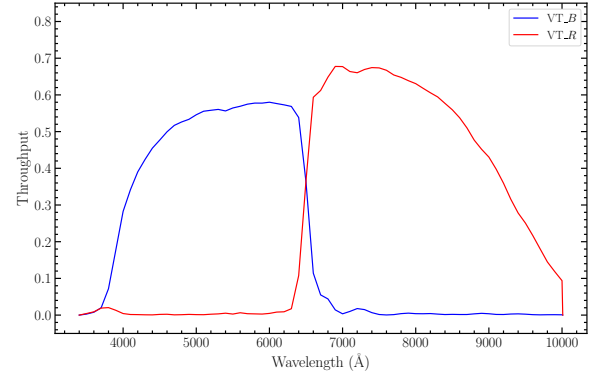


Figure 3. The total system response curves of the VT_B and VT_R bands.

Table 1
Filter Parameters for the VT_B and VT_R Bands

Parameter	VT_B	VT_R	Unit
λ_{eff}	539.48	794.73	nm
λ_{cent}	533.67	789.09	nm
FWHM	251.66	275.76	nm
$\Delta\lambda_{\text{eff}}$	249.91	284.96	nm
σ_{λ}	78.78	93.78	nm
$S(\lambda_{\text{eff}})$	0.557	0.635	...
S_{peak}	0.580	0.678	...

3. Photometric Calibration

3.1. Spectral Characteristics of VT Bands

The wavelength-dependent system response curves, $S(\lambda)$, for the VT_B and VT_R bands represent the full optical throughput of the instrument. They are constructed by combining the detector quantum efficiency provided by the manufacturer, the reflectivities of the mirrors, the transmission efficiency of the dichroic beam splitter, and other optical efficiency factors (e.g., obscuration and optical losses) along the light path (see Qiu et al. 2026; Zhang et al. 2026). The resulting response curves are shown in Figure 3. Key system parameters, defined below from $S(\lambda)$ and summarized in Table 1, are used in the subsequent analyses.

The effective wavelength, λ_{eff} , defined as the photon-weighted mean wavelength following (Schneider et al. 1983; Fukugita et al. 1996), is given by:

$$\lambda_{\text{eff}} = \exp \left[\frac{\int \lambda \ln \lambda S(\lambda) d\lambda}{\int \lambda S(\lambda) d\lambda} \right]. \quad (1)$$

The central wavelength defined in this work is consistent with Euclid Collaboration et al. (2022):

$$\lambda_{\text{cent}} = \frac{\int \lambda S(\lambda) d\lambda}{\int S(\lambda) d\lambda}. \quad (2)$$

The equivalent bandwidth, $\Delta\lambda_{\text{eff}}$, corresponds to the width of a rectangular bandpass that transmits the same total flux when multiplied by the throughput at the effective wavelength:

$$\Delta\lambda_{\text{eff}} = \frac{\int S(\lambda) d\lambda}{S(\lambda_{\text{eff}})}, \quad (3)$$

where $S(\lambda_{\text{eff}})$ is the system response at the effective wavelength. The rms bandwidth is calculated by:

$$\sigma_\lambda = \sqrt{\frac{\int (\lambda - \lambda_{\text{eff}})^2 S(\lambda) d\lambda}{\int S(\lambda) d\lambda}}, \quad (4)$$

which quantifies the dispersion of the filter transmission profile around its effective wavelength.

As summarized in Table 1, the VT_B and VT_R bands have $\lambda_{\text{eff}} = 539.48$ nm and 794.73 nm, with central wavelength $\lambda_{\text{cent}} = 533.67$ nm and 789.09 nm, respectively. In both bands, λ_{eff} is shifted to slightly longer wavelengths than λ_{cent} (by ~ 5 –6 nm), indicating that the long-wavelength side of the bandpass contributes marginally more to the response-weighted representative wavelength. The two filters are broad, with FWHM = 251.66 nm (VT_B) and 275.76 nm (VT_R); the effective bandwidths are 249.91 nm (VT_B) and 284.96 nm (VT_R). The close agreement between $\Delta\lambda_{\text{eff}}$ and FWHM for VT_B suggests a relatively regular single-peaked passband, whereas the slightly larger $\Delta\lambda_{\text{eff}}$ than FWHM for VT_R implies a greater contribution from the low-throughput wings. The rms bandwidths are $\sigma_\lambda = 78.78$ nm for VT_B and 93.78 nm for VT_R, indicating that VT_R has a broader wavelength spread around λ_{eff} than VT_B in the rms sense. Finally, the response evaluated at the effective wavelength is close to the peak response, with $S(\lambda_{\text{eff}})/S_{\text{peak}} \approx 0.96$ (VT_B) and ≈ 0.94 (VT_R), showing that λ_{eff} lies near the high-throughput region of each passband.

3.2. Pre-launch Photometric Zero-points

The VT photometric system is defined in the AB magnitude system, following the standard AB magnitude formalism (Schneider et al. 1983; Fukugita et al. 1996):

$$m_{\text{AB}} = -2.5 \log_{10} \left[\frac{\int d(\ln \nu) f_\nu S(\nu)}{\int d(\ln \nu) S(\nu)} \right] - 48.60, \quad (5)$$

where f_ν is the flux density in units of $\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$ and $S(\nu)$ denotes the dimensionless system response in the frequency domain.

In practical observations, the AB magnitude corresponds to the measured photon count rate CR as:

$$m_{\text{AB}} = -2.5 \log_{10}(\text{CR}) + \text{ZP}, \quad (6)$$

where ZP is the zero-point of the system defined as the corresponding magnitude for 1 photoelectron per second and CR is determined by the incident photon flux and the system

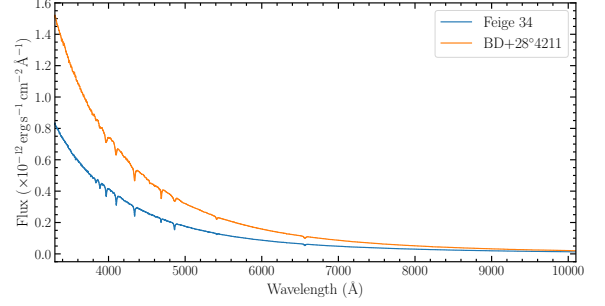


Figure 4. Spectra of the two spectrophotometric standard stars BD+28°4211 and Feige 34.

response:

$$\text{CR} = A \int F_\lambda^{\text{phot}} S(\lambda) d\lambda, \quad (7)$$

where $A = \pi(D/2)^2$ is the collecting area of the telescope, and $F_\lambda^{\text{phot}} = f_\lambda / (h\nu)$ is the photon flux density, with h denoting the Planck constant. Under these definitions, ZP can be expressed as:

$$\text{ZP} = 2.5 \log_{10} \left[A \int S(\lambda) d(\ln \lambda) \right] + 16.85. \quad (8)$$

Using the system response presented above and adopting a telescope diameter of $D = 44$ cm, we derive the AB zero-points: 23.37 mag for VT_B and 23.22 mag for VT_R. These values are derived from the ground-based calibration.

3.3. Zero-point Monitoring in Orbit

To track the temporal evolution of the VT zero-point, we conducted long-term monitoring of standard stars. Two bright and stable spectrophotometric standards, BD+28°4211 and Feige 34, were selected for this purpose. Both stars are hot subdwarfs of spectral type sdO (Massey & Gronwall 1990), with $T_{\text{eff}} \approx 82,000$ K for BD+28°4211 (Latour et al. 2013) and $T_{\text{eff}} \approx 62,550$ K for Feige 34 (Latour et al. 2018). Their spectra (see Figure 4) are drawn from the CALSPEC database⁶ (Bohlin et al. 2014, 2020), and when combined with the VT system response curves, they provide reference magnitudes for calibration (see Table 2).

Standard stars were observed with fixed exposure times and identical CCD readout modes, at a cadence ranging from daily to monthly, ensuring that measurements across different epochs are directly comparable. Raw images were first corrected for instrumental effects, including bias subtraction, dark current correction, and flat-fielding, to ensure a uniform detector response. Aperture photometry was then performed to extract stellar fluxes, using a full aperture with a fixed radius of 10 pixels (7''6), while the sky background was estimated

⁶ <https://www.stsci.edu/hst/instrumentation/reference-data-for-calibration-and-tools/astronomical-catalogs/calspec>

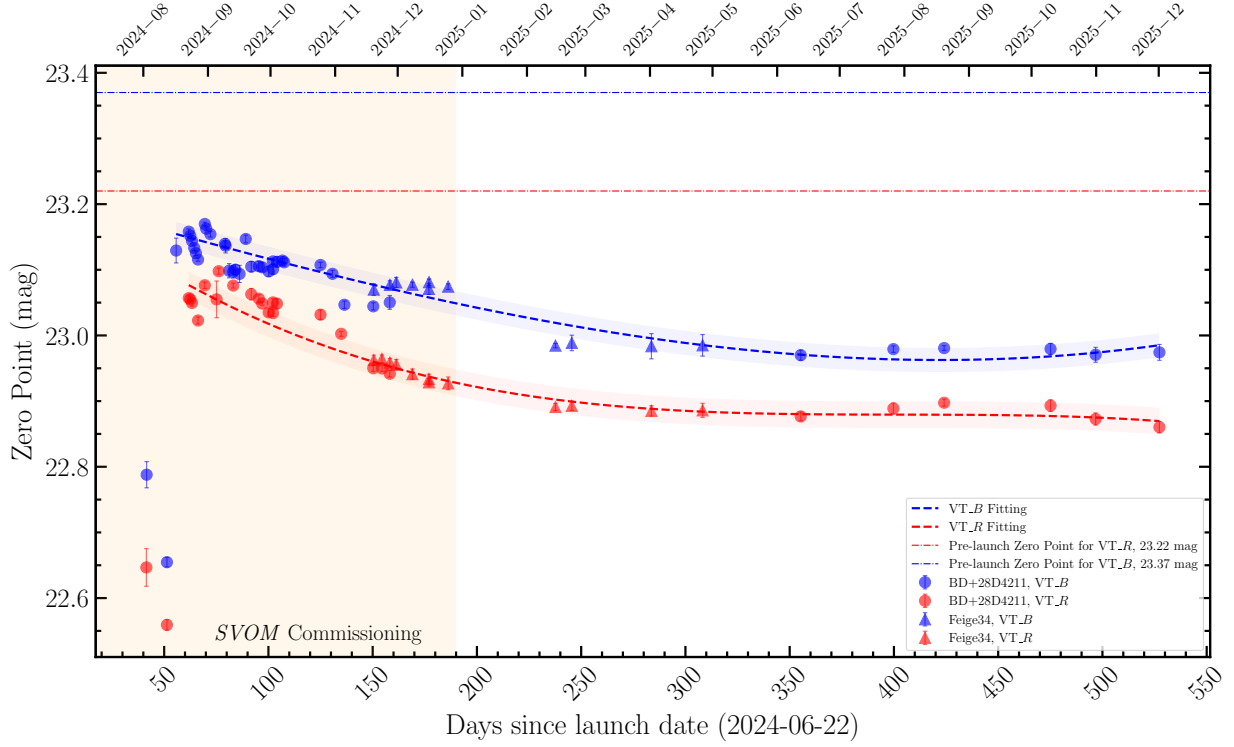


Figure 5. Long-term monitoring of the VT_R (red) and VT_B (blue) zero-points measured from the two standard stars BD+28°4211 (circles) and Feige 34 (triangles). The horizontal lines indicate the ground-based calibration zero-points (23.37 mag for VT_B, 23.22 mag for VT_R). The dashed lines with error bars show a third-order fit to the zero-point evolution. The orange-shaded region marks the SVOM commissioning phase, while the period before it corresponds to the initial pre-launch phase when contamination was most severe. After commissioning, the zero-points remain largely stable, varying by only $\sim 2\%$.

Table 2
Parameters for Two Standard Stars

Object Name	R.A. (J2000.0)	Decl. (J2000.0)	Stellar Type	Mag (VT_B)	Mag (VT_R)
BD+28°4211	21:51:11.02	+28:51:50.37	sdO	10.37	11.19
Feige 34	10:39:36.74	+43:06:09.21	sdO	11.02	11.78

from an annulus spanning 15–20 pixels ($11''4$ – $15''2$) around each source (see Li et al. 2026 for VT-specific details). Given the stable point-spread function in VT images (Qiu et al. 2026), this uniform reduction procedure ensures that the measured flux variations reflect genuine instrumental throughput changes rather than data-processing artifacts.

Figure 5 presents the long-term evolution of the VT photometric zero-points derived from regular monitoring of two spectrophotometric standard stars. Shortly after launch, a significant degradation of the photometric zero-point was detected in both bands, accompanied by notable halos around the bright objects in the VT images, which is likely related to instrumental contamination. To mitigate this effect, CCD bake-out operations were immediately performed, which proved highly effective: the

first bake-out restored the system transmission by approximately 40%, corresponding to a zero-point shift of $\Delta m \sim 0.4$. Despite this recovery, the post-bake-out zero-points remain systematically lower than those measured during pre-launch ground calibration by $\sim 10\%$ – 20% . During the subsequent four months of 2024, the measured zero-points exhibited a gradually degrading of approximately 0.2 mag, indicating a renewed contamination. Since early 2025, the photometric zero-points have remained largely stable, showing only minor fluctuations at the $\pm 2\%$ level in both bands. A detailed discussion of the evolution of contamination is presented in Section 4.1. In the future, the zero-point will continue to be tracked through regular observations of spectrophotometric standard stars to maintain the reliability of VT’s scientific measurements.

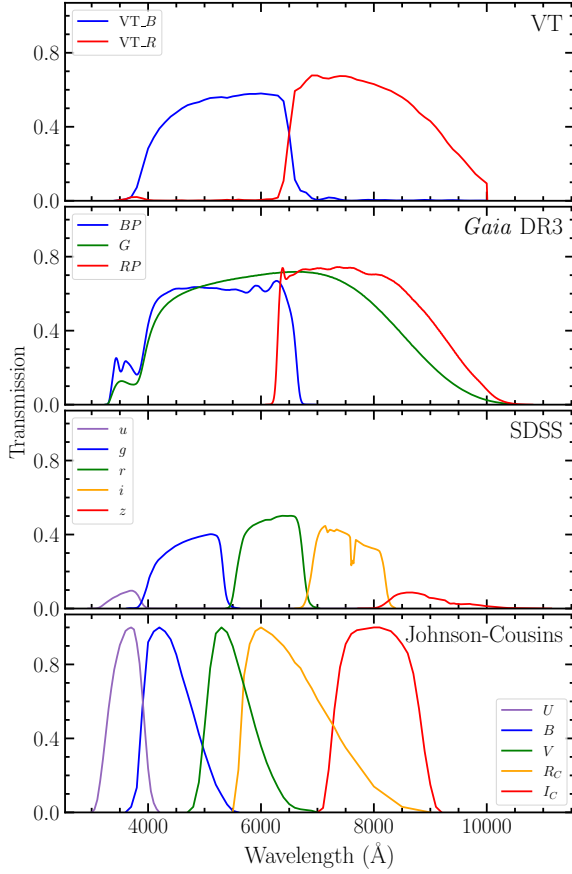


Figure 6. Comparison between the VT response curves and those of the Gaia, SDSS and Johnson–Cousins systems.

3.4. Transformation of the VT Photometric System to External Systems

Reliable transformations between the VT photometric system and widely used external systems are essential for combining VT measurements with existing survey data and for interpreting VT photometry within a broader astrophysical context. In particular, expressing VT magnitudes in the Gaia, Sloan Digital Sky Survey (SDSS), and Johnson–Cousins systems enables direct comparison with archival catalogs and places VT observations on a well-established photometric scale.

Figure 6 compares the VT passbands with those of Gaia, SDSS, and Johnson–Cousins. The VT_B band largely overlaps with Johnson *B* and SDSS *g*, while VT_R closely follows Cousins *R* (*R_C*) and Gaia *RP*, and is wider than the SDSS *r* and *i* filters.

To derive these transformations, we employed the ISAAC Spectroscopic Library provided by ESO,⁷ which covers stars from early-O to late-M spectral types. This ensures that the

resulting relations are applicable over the main-sequence color range and for moderately evolved stars. Synthetic photometry was performed using the PYTHON package *synphot* (Lim et al. 2025). For each stellar spectrum, synthetic magnitudes were computed in the VT and external systems by convolving the flux distributions with the corresponding total system response curves.

To quantify the transformations, we modeled the magnitude differences for each comparison system as a function of appropriate color indices. The resulting transformation relations were fitted using polynomials of the general form

$$X - Y = \sum_{i=0}^N a_i C^i, \quad (9)$$

where X and Y denote magnitude in the VT or external photometric system, and C is a color index sensitive to the stellar effective temperature (e.g., $B - V$, $VT_B - VT_R$). For transformations from external systems to VT, color indices native to the external system (e.g., $BP - RP$, $g - r$, $B - V$) were adopted. For inverse transformations from VT to external systems, the color index was chosen as $VT_B - VT_R$, which provides a self-consistent and directly observable color within the VT system. Here, N denotes the maximum polynomial order. In most cases, third-order polynomials ($N = 3$) were adopted to capture nonlinear trends across the full color range, while lower-order ($N = 2$) fits were used when they provided comparably good representations of the data. Higher-order polynomials were tested but provided only marginal improvements while introducing instability at the color boundaries. Therefore, third-order fits were selected as a balance between flexibility and robustness. The best-fitting coefficients for all transformation relations are summarized in Table 3, and the corresponding fitting curves with residuals are shown in Figures 7–9.

3.4.1. Transformation between the VT and Gaia DR3 Systems

A comparison of the response curves (Figure 6) shows that VT_R closely resembles the Gaia *RP* band, whereas VT_B lies between Gaia *BP* and SDSS *g*. These similarities suggest that relatively simple color-dependent transformations may be expected, particularly for VT_R.

We derived bidirectional transformation relations between the VT and Gaia DR3 systems (Riello et al. 2021) using synthetic photometry of stellar spectra. For transformations from Gaia to VT, the color index ($BP - RP$) was adopted, while for inverse transformations from VT to Gaia, the color index $VT_B - VT_R$ was used to ensure internal consistency within the VT system (Table 3). The results are shown in Figure 7.

For VT_R, the quantity $VT_R - RP$ as a function of $(BP - RP)$ exhibits only weak color dependence over the range $-1.5 \lesssim (BP - RP) \lesssim 3$. A third-order polynomial was adopted to account for subtle nonlinear trends across the full color range.

⁷ <https://www.eso.org/sci/facilities/paranal/decommissioned/isaac/tools/lib.html>

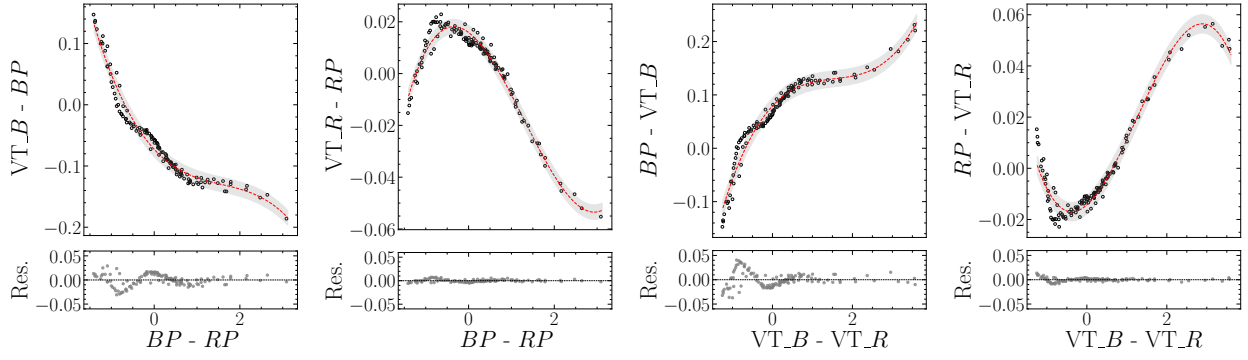


Figure 7. Magnitude differences between the VT bands and the Gaia photometric system as a function of color indices, derived from synthetic photometry of stellar spectra. In each panel, black circles represent the synthetic photometric data points, the red dashed line shows the best-fit transformation relation, and the gray shaded region indicates the 1σ uncertainty of the fit. The lower subpanels display the residuals relative to the best-fit relation.

Table 3

Photometric Transformation Relations between the VT System and the Gaia, SDSS, and Johnson–Cousins Systems, Derived from Synthetic Photometry of Stellar Spectra

X	Y	C	a_0	$a_{0, \text{err}}$	a_1	$a_{1, \text{err}}$	a_2	$a_{2, \text{err}}$	a_3	$a_{3, \text{err}}$
VT—Gaia Transformations										
VT_B	BP	BP – RP	–7.278	0.151	–7.639	0.186	3.795	0.171	–0.800	0.079
VT_R	RP	BP – RP	1.586	0.035	–1.246	0.044	–1.570	0.040	0.405	0.018
BP	VT_B	VT_B – VT_R	7.912	0.184	8.106	0.204	–4.650	0.225	1.000	0.073
RP	VT_R	VT_B – VT_R	–1.430	0.040	1.379	0.045	1.591	0.051	–0.422	0.016
VT—SDSS Transformations										
VT_B	g	$g - r$	0.350	0.039	–37.585	0.050	–10.924	0.075	...	...
VT_R	r	$r - i$	3.086	0.118	–105.703	0.315	–7.757	0.279	...	...
VT_R	z	$i - z$	2.066	0.093	85.782	0.263	–22.937	0.504	...	...
u	VT_B	VT_B – VT_R	146.228	4.137	168.495	4.591	–20.131	5.066	–8.663	1.635
g	VT_B	VT_B – VT_R	8.507	0.316	41.371	0.454	6.663	0.484	–4.478	0.166
r	VT_R	VT_B – VT_R	–13.128	0.370	47.215	0.439	10.510	0.487	0.992	0.163
i	VT_R	VT_B – VT_R	–4.202	0.087	2.398	0.116	3.633	0.121	0.484	0.051
z	VT_R	VT_B – VT_R	10.511	0.385	–26.352	0.427	0.549	0.472	–0.468	0.152
VT—Johnson–Cousins Transformations										
VT_B	B	$B - V$	1.019	0.067	–70.821	0.118	–11.841	0.157	...	...
VT_R	R_C	$R_C - I_C$	0.933	0.077	–77.310	0.189	–7.574	0.234	...	...
U	VT_B	VT_B – VT_R	142.971	4.079	171.401	4.526	–18.269	4.994	–9.298	1.612
B	VT_B	VT_B – VT_R	25.985	0.837	66.297	0.980	–0.348	1.088	–4.186	0.348
V	VT_B	VT_B – VT_R	–8.811	0.204	–17.627	0.225	8.035	0.249	–0.646	0.080
R_C	VT_R	VT_B – VT_R	–10.780	0.239	35.570	0.300	7.204	0.136	...	...
I_C	VT_R	VT_B – VT_R	1.995	0.243	–12.737	0.271	0.251	0.304	1.082	0.097

Note. For readability, all listed coefficients and their uncertainties have been multiplied by 10^2 .

The residual scatter remains at the ~ 0.01 mag level for most spectral types, indicating that VT_R is closely matched to Gaia RP, with only minor color-dependent corrections required.

The transformation between VT_B and Gaia BP shows more pronounced curvature. Because VT_B is narrower and slightly redder than BP, the difference VT_B – BP varies systematically with stellar color. This relation is well described by a third-order polynomial, with residuals typically within

~ 0.03 mag across the main-sequence color range. The remaining low-level structure at the ~ 0.01 mag level likely reflects differences in detailed passband shapes and the influence of spectral features.

In addition, all the Gaia-based transformation relations show noticeably larger dispersion toward the blue end, and stars with $(BP - RP) \approx -1$ should be treated with particular caution, as the fits become less reliable in this regime due to the limited

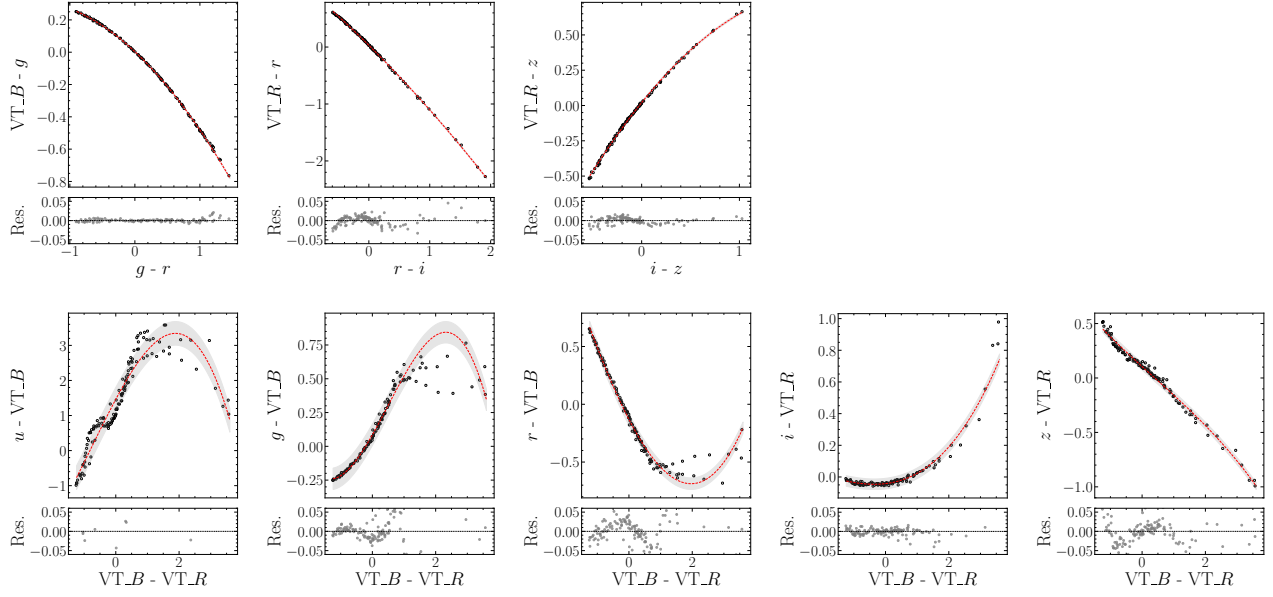


Figure 8. Magnitude differences between the VT bands and the SDSS photometric system as a function of color indices, derived from synthetic photometry of stellar spectra. The symbols, lines, and shaded regions have the same meaning as in Figure 7.

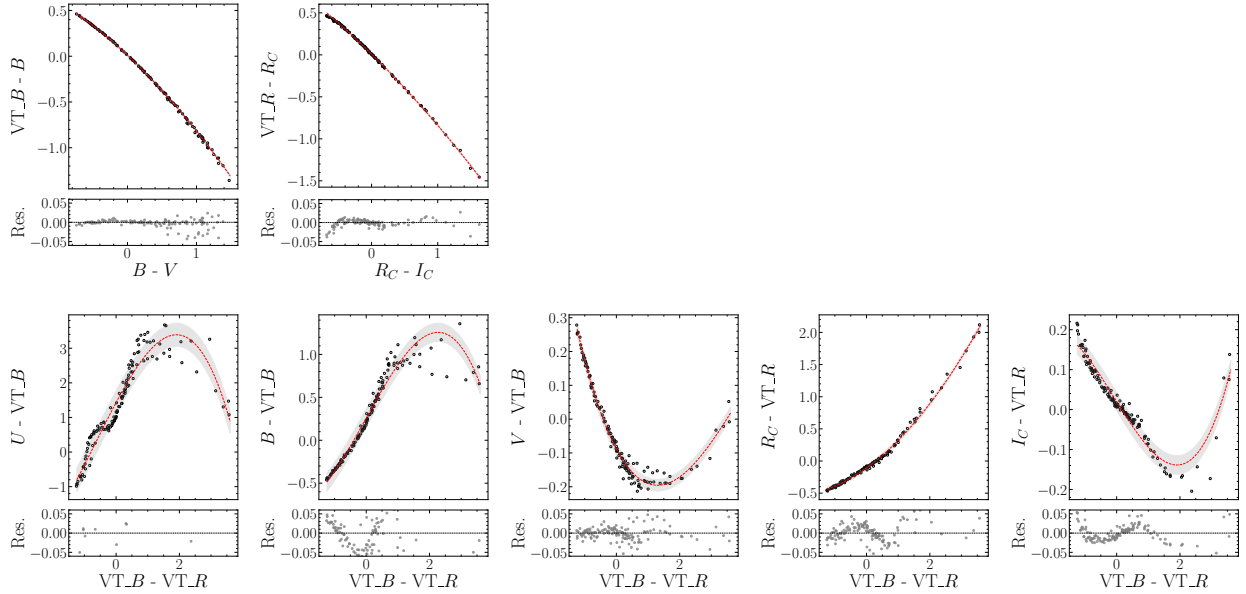


Figure 9. Magnitude differences between the VT bands and the Johnson-Cousins photometric system as a function of color indices, derived from synthetic photometry of stellar spectra. The symbols, lines, and shaded regions have the same meaning as in Figure 7.

number of calibration spectra and the increasing mismatch between the VT and Gaia passbands. The inverse transformations (BP and RP expressed as functions of $VT_B - VT_R$) exhibit comparable residual levels, confirming the internal consistency of the bidirectional fitting.

3.4.2. Transformation between the VT and SDSS Systems

Figure 8 presents the bidirectional transformation relations between the VT and SDSS systems (Doi et al. 2010), derived

from synthetic stellar photometry. The upper panels show the transformations from SDSS to VT, while the lower panels display the inverse relations. For transformations from SDSS to VT, native SDSS color indices (e.g., $g - r$, $r - i$, $i - z$) were adopted. For inverse transformations from VT to SDSS, the internal VT color $VT_B - VT_R$ was used to ensure practical applicability when only VT measurements are available (Table 3).

For VT_B , the most relevant SDSS comparisons involve the g band. The relations $VT_B - g$ and $VT_B - r$ as functions of

$(g - r)$ show clear nonlinear trends and are therefore modeled with third-order polynomials. We tested higher-order fits (fourth order and above), which yield marginal reductions in rms scatter but introduce increased oscillatory behavior at the color boundaries without significant improvement in predictive accuracy. A cubic formulation was therefore adopted as a compromise between flexibility and stability.

The VT_R band most closely resembles the SDSS r and partially overlaps with z . The relations $VT_R - r$ as a function of $(r - i)$ and $VT_R - z$ as a function of $(i - z)$ exhibit smooth curvature and are well represented by quadratic polynomials over the color ranges $-0.5 \lesssim (r - i) \lesssim 2.0$ and $-0.5 \lesssim (i - z) \lesssim 2.0$. Typical residuals remain within ~ 0.03 mag across the main-sequence regime. A moderate increase in scatter is observed toward the reddest colors, which is primarily attributable to the reduced number of late-type calibration spectra and the increasing sensitivity of red passbands to molecular absorption features.

The inverse relations (e.g., g, r, i, z expressed as functions of $VT_B - VT_R$) show comparable residual levels and confirm the internal consistency of the bidirectional fitting procedure. For very red stars ($VT_B - VT_R \gtrsim 1.0$), the transformation relations show noticeably larger dispersion and deviate from a simple polynomial description. This behavior is primarily driven by late-type (M-type) stars, for which broadband colors become increasingly degenerate due to strong molecular absorption features and the limited sensitivity of $VT_B - VT_R$ to spectral subtype. The derived relations should therefore be applied with caution in this color regime.

Overall, within the primary stellar color range $-1.0 \lesssim (g - r) \lesssim 1.0$, the VT magnitudes can be transformed into the SDSS system with typical uncertainties of ~ 0.03 mag. The relations remain stable and monotonic over this interval, with no evidence of strong pathological behavior. In contrast, applications involving $VT_B - VT_R \gtrsim 1.0$ should be treated with caution, as the transformation relations become increasingly uncertain in this regime.

3.4.3. Transformation between the VT and Johnson–Cousins Systems

The Johnson–Cousins photometric system remains widely used in the literature, particularly for long-term stellar monitoring and historical photometric data. We therefore derived transformation relations between the VT system and the standard Johnson–Cousins $UBV(RI)_C$ system (Bessell 1990).

For transformations from Johnson–Cousins to VT, the color indices $(B - V)$ and $(R_C - I_C)$ were adopted for the VT_B and VT_R relations, respectively. For the inverse transformations, the internal VT color $VT_B - VT_R$ was used to express U, B, V, R_C , and I_C magnitudes (Table 3).

The relation $VT_B - B$ as a function of $(B - V)$ exhibits smooth nonlinear behavior and is well represented by a low-

order polynomial across the color range $-0.9 \lesssim (B - V) \lesssim 1.5$. Typical residuals remain within ~ 0.03 mag for most main-sequence and moderately evolved stars. Similarly, $VT_R - R_C$ as a function of $(R_C - I_C)$ shows stable behavior over $-0.9 \lesssim (R_C - I_C) \lesssim 1.5$, with comparable residual levels.

At the edges of the calibration range, some increased dispersion is observed. For the VT_B transformation, red stars with $(B - V) \gtrsim 0.5$ exhibit larger scatter, while for the VT_R transformation the bluest stars with $(R_C - I_C) \lesssim -0.5$ show a noticeable increase in residuals. In particular, for very red stars with $VT_B - VT_R \gtrsim 1.0$ (as discussed in Section 3.4.2), the polynomial representation becomes less accurate and the scatter increases noticeably. Applications in this color regime should therefore be treated with caution. Despite these edge effects, the transformations remain stable and well behaved within the primary stellar color ranges, with typical uncertainties of ~ 0.03 mag.

Because the Johnson–Cousins system is traditionally tied to the Vega magnitude scale, whereas the SDSS system is defined on an AB-like scale, some care is required when combining measurements across different photometric systems. However, our synthetic-photometry approach treats all systems in a fully consistent manner, such that differences in absolute zero-point definitions are naturally absorbed into the fitted coefficients. The resulting transformations therefore implicitly include the effective zero-point offsets between the VT and Johnson–Cousins magnitudes implied by the adopted flux calibration.

4. Discussion

4.1. Contamination and Effects on Photometric Zero-points

As described in Section 3.3, the long-term monitoring of spectrophotometric standard stars reveals significant temporal variations in the VT photometric zero-point. Shortly after launch, the zero-point exhibited a rapid and substantial decline, which cannot be attributed to intrinsic variability of the standard stars or to statistical measurement uncertainties, but instead points to an instrumental origin.

A natural explanation for these behaviors is optical contamination within the VT system. For space-borne instruments, outgassed material (e.g., H_2O molecules) from the spacecraft platform and onboard components can deposit on sensitive optical surfaces. At the typically low operating temperatures, such contaminants may accumulate and undergo photochemical processing, leading to a gradual reduction in system throughput. In addition, contaminant-induced scattering can introduce stray light and short-term fluctuations in the instrumental response. For example, the Euclid mission has implemented dedicated cleanliness and contamination-control programs to mitigate water ice and other molecular contaminants (Euclid Collaboration et al. 2023), while the James

Webb Space Telescope enforces extremely stringent molecular contamination limits for its optical surfaces. These examples demonstrate that contamination by volatile species is a well-established cause of long-term throughput loss in space telescopes.

The VT CCD detectors operate at low temperatures to suppress dark current, making them particularly susceptible to optical contamination, unlike the VT main body and other optical components, which operate at room temperature. To test the hypothesis of contamination, CCD bake-out operations were performed during the early commissioning phase. During bake-out, the detector temperature was significantly elevated, which could partially mitigate contamination effects.

Following the first CCD bake-out on 2024 August 14, the photometric zero-point showed a substantial recovery, corresponding to an approximate 40% increase in throughput. At the same time, noticeable changes were observed in the flat-field structures (Qiu et al. 2026), indicating a redistribution of material within the optical system. The strong and immediate photometric response to bake-out provides compelling evidence that the dominant contaminant is volatile in nature, most likely water ice.

In principle, a contamination layer could introduce wavelength-dependent absorption or scattering, leading not only to a gray throughput loss but also to color-dependent photometric effects. To assess this possibility, we performed a preliminary analysis using Gaia XP spectra of stars and examined the correlation between stellar color and zero-point variations after correcting for the long-term evolution. Within the current photometric precision, no significant color-dependent trend is found for either VT_B or VT_R, indicating that the throughput degradation is consistent with a gray response change at the present accuracy level. A more detailed spectrophotometric analysis, incorporating full time-dependent modeling, will be presented in a future dedicated calibration study.

Although a later bake-out (on 2025 November 15) continued to induce measurable responses in the zero-point, its effectiveness diminished with time, producing only transient improvements that dissipated within a few days. This behavior suggests that the contaminant was not fully removed but rather redistributed or re-condensed on other cold surfaces, eventually reaching a quasi-stable configuration.

Although the contamination remains a concern, our analysis shows that it can be adequately controlled (Figure 5). Encouragingly, since early 2025, the VT zero-points have reached a stable equilibrium, remaining consistent to within $\sim 2\%$ over long timescales. Nevertheless, continuous standard-star monitoring and regular calibration updates are still necessary to accurately track and correct any residual effects, ensuring that the scientific performance of VT is not significantly compromised.

4.2. Filter System Performance: Red and Blue Leakages

The performance of a broadband photometric system can be affected by out-of-band spectral leakage, whereby light outside the nominal passband is transmitted through the filter and contributes to the measured flux. For blue filters, so-called “red leak,” contamination by long-wavelength photons, is of particular concern for intrinsically red sources. Conversely, “blue leak” refers to short-wavelength contamination in red filters. Such leakages introduce systematic photometric biases that depend on the SED of the observed source.

For the VT instrument, inspection of the synthetic transformations in Figures 7–9 suggests small but non-negligible responses outside the nominal wavelength ranges of both filters, implying the presence of out-of-band leakage. Quantifying the red leak in VT_B and the blue leak in VT_R is therefore essential for assessing the robustness of the broadband photometry.

To evaluate the leakage properties, we adopted the same synthetic-photometry framework described in Section 3.2. A grid of stellar spectra spanning a wide range of effective temperatures, from hot O-type to cool M-type main-sequence stars, was used to compute synthetic fluxes based on the full VT response curves. For each spectrum, we calculated the fractional leakage by:

$$f_{\text{leak}} = \frac{F_{\text{leak}}}{F_{\text{total}}} \times 100\%, \quad (10)$$

where F_{total} is the integrated flux over the full response range (3400–10000 Å), and F_{leak} represents the flux transmitted outside the primary bandpass. For VT_B, the red leak was defined as flux at $\lambda \geq 7000$ Å, while for VT_R, the blue leak was quantified as flux at $\lambda \leq 6000$ Å.

Figure 10 shows the resulting leakage fractions as a function of the synthetic color (VT_B – VT_R), which serves as a proxy for stellar temperature. The red-leak fraction of VT_B (blue circles) shows a strong dependence on color. For hot, blue stars the leakage is negligible ($f_{\text{leak}} \lesssim 0.2\%$), whereas for increasingly red stars the fraction rises rapidly, reaching $\sim 5\%$ at (VT_B – VT_R) ≈ 2.5 and exceeding 10%–15% for extremely cool stars. This behavior indicates that the VT_B band remains effectively clean for most stellar types, but the red leak becomes non-negligible for late-K and M-type stars.

In contrast, the blue-leak fraction of VT_R remains very small for the majority of spectral types. For stars with (VT_B – VT_R) $\gtrsim 0$, the leakage fraction is below 1% and typically at the $\sim 0.1\%$ level, consistent with the designed red-band cutoff of VT_R. Toward the blue end of the sample, where (VT_B – VT_R) ≈ -1 , the blue leak increases modestly to 2%–7%, reflecting enhanced transmission in the short-wavelength wing of the VT_R response. Although this effect is much weaker than the red leak observed in VT_B, it

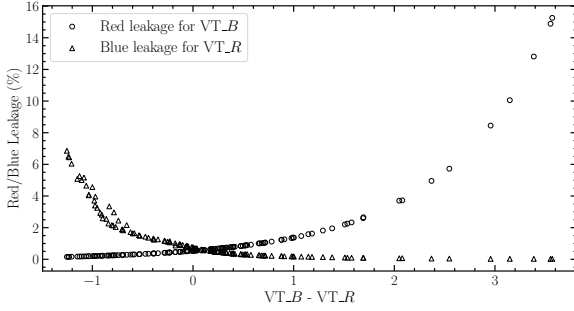


Figure 10. Fractional red leakage in VT_B (circles) and blue leakage in VT_R (triangles) as a function of synthetic color (VT_B – VT_R).

indicates that photometry of very hot stars may experience a small but measurable bias in VT_R.

Overall, the leakage characteristics of the VT filters are well within acceptable limits for broadband photometry. Red leak in VT_B becomes significant only for very cool stars, while blue leak in VT_R remains at the $\lesssim 1\%$ level for most sources and exceeds a few percent only for extremely blue stars. Consequently, leakage-induced photometric biases are expected to be smaller than the typical VT measurement uncertainties for the vast majority of astrophysical targets.

In a broader context, comparisons with other space-based photometric systems indicate that the VT filters perform competitively. Several instruments, such as HST/WFC3 (Brown 2008) and Swift/UVOT (Poole et al. 2008; Breeveld et al. 2011), are known to exhibit noticeable red leak in their UV and blue filters, with contamination levels ranging from a few tenths of a percent up to 5%–10% for very red sources (e.g., WFC3/UVIS F225W and Swift UVW2). Compared to these systems, the VT_B red leak is of similar magnitude to the UV/blue filter leaks on HST and Swift when applied to extremely cool stars, yet remains negligible for hotter stars. The VT_R blue leak, in contrast, is substantially smaller than that observed in many UV-optimized space-based filters, remaining below 1% for most sources. These comparisons reinforce the conclusion that the VT filter system achieves excellent overall performance, with leakage effects expected to be minor for typical scientific applications.

5. Conclusion

We present a comprehensive analysis of SVOM/VT’s in-orbit calibration, characterizing its astrometric performance, photometric system stability, and transformation relations with other photometric systems. The main results of this work can be summarized as follows:

1. *Astrometric performance.* Using Gaia DR3 as the astrometric reference, VT achieves positional residuals better than $0''.03$ for bright sources. For faint sources, the expected astrometric accuracy of $\sim 0''.25$ remains

sufficient for reliable localization of GRB optical counterparts and transient sources.

2. *Photometric response and zero-points.* The effective wavelengths, bandwidths, and AB zero-points of the VT_B and VT_R bands were determined based on ground-based measurements and synthetic photometry. The derived pre-launch AB zero-points are 23.37 mag for VT_B and 23.22 mag for VT_R.
3. *Photometric stability.* Continuous monitoring of spectro-photometric standard stars demonstrates that the VT photometric system has remained stable in orbit at the 0.02 mag level since early 2025. Short-term sensitivity variations associated with CCD bake-out operations are detected but are transient, with the zero-points returning to their pre-bake-out levels within a few days.
4. *Transformations with external photometric systems.* Based on synthetic photometry using a broad stellar spectral library, we derived color-dependent transformations between the VT system and the Gaia DR3, SDSS, and Johnson–Cousins photometric systems. Within the calibrated color ranges, the typical uncertainties of these transformations are ~ 0.03 mag, enabling reliable cross-comparisons between VT data and existing photometric catalogs.
5. *Out-of-band leakages.* An assessment of out-of-band leakage shows that VT_B exhibits measurable red leak for very cool stars, while VT_R shows modest blue leak only for the bluest spectral types. For the vast majority of astrophysical sources, the leakage-induced photometric biases are below the typical VT measurement uncertainties and therefore negligible for routine broadband applications.

Taken together, these results demonstrate that VT delivers stable and well-calibrated astrometric and photometric performance in orbit. The established calibration framework ensures that VT data can be robustly integrated with multi-wavelength observations and fully supports the time-domain and transient science objectives of the SVOM mission.

Acknowledgments

The Space-based multi-band Variable Objects Monitor (SVOM) is a joint Chinese–French mission led by the Chinese National Space Administration (CNSA), the French Space Agency (CNES), and the Chinese Academy of Sciences (CAS). We gratefully acknowledge the unwavering support of NSSC, IAMCAS, XIOPM, NAOC, IHEP, CNES, CEA, and CNRS. This work is supported by the National Key R&D Program of China (grant Nos. 2024YFA161170* and 2024YFA1611700) and by the National Natural Science Foundation of China (grant Nos. 12494571, 12494570, 12494573 and 12133003). The authors are thankful for support from the Strategic Priority Research Program of the CAS (grant No. XDB0550401).

ORCID iDs

Zhu-Heng Yao  <https://orcid.org/0009-0000-1228-2373>
 Yu-Lei Qiu  <https://orcid.org/0009-0007-7207-4884>
 Jin-Song Deng  <https://orcid.org/0000-0001-5646-8583>
 Li-Ping Xin  <https://orcid.org/0000-0002-9422-3437>
 Chao Wu  <https://orcid.org/0009-0001-7024-3863>
 Hua-Li Li  <https://orcid.org/0000-0002-7457-4192>
 Yi-Nuo Ma  <https://orcid.org/0009-0007-1390-7575>
 Xu-Hui Han  <https://orcid.org/0000-0002-6107-0147>

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