



SVOM/VT: Overview of Data Processing and GRB Identifications with X-band Data

Hua-Li Li^{1,6} , Yu-Lei Qiu^{1,6} , Li-Ping Xin^{1,6} , Chao Wu^{1,2}, Zhu-Heng Yao¹, Yi-Nuo Ma^{1,3,4}, Yang Xu¹ , Pin-Pin Zhang¹,
 Xu-Hui Han¹, Jing Wang¹, Hong-Bo Cai¹, Da-Wei Xu^{1,2}, Jesse T. Palmerio⁵, Mao-Hai Huang¹, Jia-Li Zhu¹, Mo Zhang¹,
 Jin-Song Deng^{1,2}, Bertrand Cordier⁵, and Jian-Yan Wei^{1,2}

¹ National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China; lhl@nao.cas.cn, qiuyi@nao.cas.cn, xlp@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 18; revised 2026 March 9; accepted 2026 March 15; published 2026 October 6

Abstract

The Visible Telescope (VT) is an optical telescope onboard the Space-based multi-band Variable Objects Monitor (SVOM) mission, specifically designed to detect optical counterparts of gamma-ray bursts (GRBs), study their afterglows, and select high-redshift candidates. It performs rapid follow-up observations simultaneously in two channels either via autonomous platform slewing or Target of Opportunity (ToO) observations. The science images acquired by VT and transmitted via the X-band downlink system are designated as VT X-band data. This paper provides an overview of GRB optical afterglow identifications with VT and describes the ground-based processing pipeline for VT X-band data, including preprocessing, astrometric calibration, and photometry. Up to 2025 December 3, VT has followed up 111 GRBs triggered by SVOM or external missions. The overall detection rate of optical counterparts is approximately 75%. Specifically, for bursts detected by SVOM/ECLAIRs, the detection rate is 77% when observed by VT within 30 minutes after the burst. A slightly higher detection rate of 81% is achieved for GRBs triggered by external missions through rapid ToO observations with a mid-time of less than 3 hr.

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

1. Introduction

The Chinese-French collaborative satellite Space-based multi-band Variable Objects Monitor (SVOM; Wei et al. 2016; Cordier et al. 2026a) was launched on 2024 June 22. Its primary scientific objective is to detect and study various types of gamma-ray bursts (GRBs). The satellite carries four payloads: ECLAIRs (Godet et al. 2026) and GRM (Sun et al. 2026) are responsible for burst triggering and alert generation, while MXT (Götz et al. 2026) and Visible Telescope (VT; Qiu et al. 2026) perform X-ray and optical follow-up observations. The main scientific goal of VT is to identify and confirm the optical counterparts of GRBs through rapid follow-up observations, and to provide localizations with subarcsecond accuracy. This serves as a bridge to enable large ground-based telescopes to perform deep photometric or spectroscopic observations, leading to redshift determination and subsequent studies of the properties of GRB host galaxies.

When ECLAIRs detects a GRB and generates a high signal-to-noise alert (Schanne et al. 2026), it can trigger the satellite platform to slew rapidly, and guide MXT and VT to conduct immediate follow-up observations (Chen et al. 2026). If the signal-to-noise ratio (S/N) is insufficient or if an external alert is triggered, the SVOM system can also schedule Target of Opportunity (ToO) observations uplinked via the BeiDou Navigation Satellite System or the S-band (Bai et al. 2026; Han et al. 2026) to search for the optical counterpart or to construct the long-term light curve.

Over the past few decades, particularly during the successful 20 yr operation of the Swift satellite (Gehrels et al. 2004), research on the multi-band afterglows of GRBs has significantly advanced our understanding of these extreme astrophysical phenomena (e.g., Zhang 2007; Liang et al. 2013; Dai et al. 2017; Burns et al. 2023; Saccardi et al. 2023; Gao et al. 2025). In particular, a detection rate of about 96% for the X-ray afterglow (Burrows et al. 2007) has enabled the establishment of a rich sample of canonical X-ray light curves (e.g., Nousek et al. 2006). However, in the optical band, the overall detection rate remains roughly 50%, which limited by

⁶ These authors contributed equally to this work.

factors such as geographic location, time zone coverage, weather conditions, wavelength coverage and detection capability. For instance, Swift/UVOT achieves a detection rate of approximately 48% (Oates 2023).

Even with the relatively low detection rate, all these efforts have yielded a large sample of optical light curves for GRBs (Kann et al. 2011), as well as associated supernovae (Dong et al. 2025) and kilonovae (e.g., Tanvir et al. 2017; Levan et al. 2023). Supernova associations support theoretical models that some GRBs originate from the collapse of massive stars (Galama et al. 1998; Hjorth et al. 2003; Stanek et al. 2003). Such bursts can theoretically be detected from the nearby cosmos to the very early universe at redshifts exceeding 20 (Lamb & Reichart 2000).

Benefiting from the featureless spectral properties of gamma-rays, high-redshift GRBs act as beacons traversing the universe, providing a unique probe for studies of the physical conditions of the very early universe (Cucchiara et al. 2011; Wang 2013). However, when the redshift exceeds 7, identification must rely on the near-infrared band, while very early and deep upper limits in the optical could be a good indicator for selecting high redshift candidates (Cordier et al. 2025). This is one of the scientific potential contributions from VT (Qiu et al. 2026). VT operates within an observational wavelength range extending to $1\ \mu\text{m}$. It can initiate observations within 5 minutes after satellite slewing, achieving a detection depth of 23 mag in the early observational phase after the bursts. This significantly increases the possibility of high-redshift candidates once nondetection is determined, although optically faint or heavily extinguished GRBs cannot be fully excluded.

On the other hand, scientific images obtained from space-based optical observations are highly susceptible to interference from cosmic rays, hot pixels, and other effects. In particular, when the localization accuracy of the high-energy trigger is at the arcminute level, many optical candidates will fall within the error region, further complicating to identify the true counterpart. To address this, a robust strategy is to employ a combination of methods, including referencing the properties of X-ray counterparts, cross-matching with deep catalogs, utilizing data from two channels simultaneously, removing cosmic rays via image stacking, filtering using hot pixel lists, checking asteroid databases to exclude moving objects, and analyzing the light-curve behavior and color features of candidates. Through this multi-dimensional approach, the identification of reliable optical counterparts to GRBs becomes feasible.

Two types of VT data are used to identify the optical counterparts. One comprises the VT products generated onboard (Cai et al. 2026), downlinked via the Very High Frequency (VHF) network with low latency and processed on the ground (Cordier et al. 2026b; Wu et al. 2026). This approach enables the identification of optical counterparts for

approximately 60% of bursts. The other consists of the science images transmitted via the X-band downlink system (Liu et al. 2026), which are designated as VT X-band data.

This paper presents astrometric and photometric processing of VT X-band data, focusing on the identification of GRB counterparts using VT X-band data. Since the launch of SVOM, VT has conducted follow-up observations for 111 gamma-ray bursts up to 2025 December 3, achieving an overall detection rate of 75% with X-band data, and has identified several high-redshift GRB candidates. One of these has been confirmed through ground-based near-infrared photometry and spectroscopy, with a measured redshift of 7.3 (GRB 250314A, Cordier et al. 2025; Levan et al. 2025).

This paper is organized as follows. Section 2 introduces the observations of VT for the GRB program. Section 3 describes the pre-processing, astrometric calibration and photometry for the GRB afterglow. Section 4 presents the strategy for identification of afterglow with VT X-band data. The performance of the detection and identification of GRB optical counterparts with VT X-band is discussed in Section 5. A summary is given in Section 6.

2. VT Observation and Data Link

2.1. VT Observations

VT is an optical telescope with a diameter of 44 cm and a field of view of $26 \times 26\ \text{arcminute}^2$. The pixel scale is $0''.76$. It is equipped with two $2\text{K} \times 2\text{K}$ e2v frame-transfer CCDs in the VT_B and VT_R channels. The two channels work simultaneously, covering the wavelength ranges of 400–650 nm and 650–1000 nm respectively. Detailed information on VT could be found in Qiu et al. (2026) and Yao et al. (2026). Given the anti-solar pointing constraints (Cordier et al. 2026a) and earthshine-induced stray-light limitations, high-quality VT observations are only feasible during Earth eclipse, with each orbital pass providing a 30–40 minute observing window.

2.2. Observations for SVOM/ECLAIRs Bursts with Automatic Slew

When a GRB is detected by ECLAIRs and meets the automatic slew threshold, both MXT and VT automatically initiate follow-up observation within 5 minutes of the burst and continue for approximately 8 hr, covering about five orbits. During the slew and prior to platform stabilization, VT operates in chance mode with a short exposure time of 15 s. Subsequently, exposure times of 50 s are adopted to balance readout rate, noise, detection capability and the optical brightness of GRB afterglow in the early phase. In the initial two orbits, VT acquires full-frame images. For subsequent orbits, an exposure time for each frame is increased to 100 s. The image size might be adjusted to window-frame centered on the MXT position, large enough to cover the MXT error

region, once MXT detects the X-ray counterpart onboard. Otherwise, full-frame images are acquired with some drops (Qiu et al. 2026), owing to data budget constraints. Throughout the observations, the high-stability mode is employed to enable rapid stabilization after slewing and to enhance VT detection performance. The Finding Guide System (FGS) operates continuously, enabling the platform to maintain a stability of $1\sigma \sim 0''.85$ over 100 s intervals (Li et al. 2026).

2.3. Observations for Bursts with ToO

ToO observations are executed via telecommand through either the S-band antenna or BeiDou short-message uplink channels. They are performed if no automatic slew is triggered by SVOM/ECLAIRs owing to a low S/N, or if the bursts are detected by other satellites (e.g., Swift or Einstein Probe (EP)), or during follow-up revisits of bursts detected by SVOM.

The high-stability mode is optional, while the normal-stability mode with the FGS inactive is recommended for most cases. In this mode, the platform pointing exhibits a drift of approximately $10''$ per 30 minutes. The gradual pointing drift between consecutive images can help effectively reduce thermal hot pixels and cosmic rays. An exposure time of 50–70 s is also recommended by taking into account the read noise, background levels, and the impact of platform drift on VT image quality.

2.4. X-band Data Link and Format

All science images are downlinked via X-band passes, with typically eight passes per day. All data are initially transferred from each pass to the SVOM Mission Center, located at the National Space Science Center in China (NSSC; Liu et al. 2026). The data are decoded into L0 data by verifying the continuous quality and other parameters, and then promptly transmitted to the SVOM Chinese Science Center located at National Astronomical Observatories, Chinese Academy of Sciences (NAOC), where L1 and L2 products are generated.

For the L1 level, all science data are images in FITS format. The central 2048×2048 area is the exposure region, while the left and right sides each contain 50 blank columns and 50 overscan reference pixel columns, neither of which are exposed. Similarly, above and below the exposure area, there are 20 dark current reference pixel rows each. The final product of L1 level data is defined as L1X. For this type of data, all header information is fully decoded and translated to facilitate better understanding for users. Additionally, the L1X image header includes information that characterizes image quality, such as energy concentration and background brightness. These parameters are useful for image selection, as discussed in Section 3.3.1.

The images after pre-processing and astrometric calibration are classified as L2 images (see Section 3 for details of the pre-processing). For L2 images, only the effective exposure region

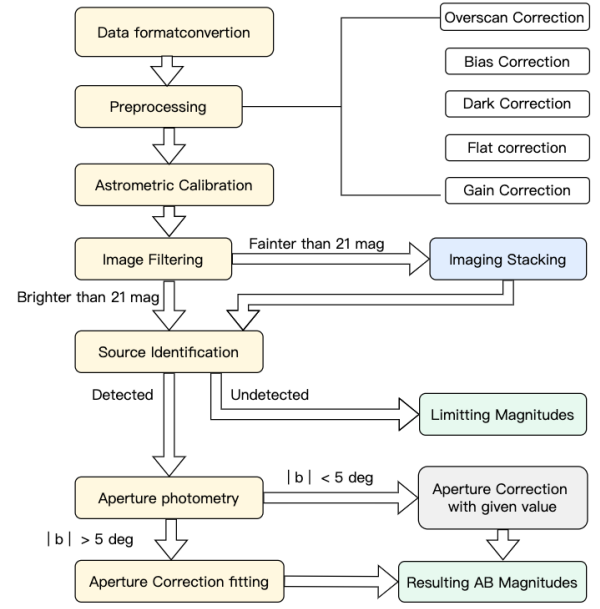


Figure 1. Flow-chart of VT X-band data processing for the GRB afterglow.

(e.g., 2048×2048 pixels) is retained. All the reference pixels are removed after instrument calibrations. VT also supports the configurations for windowed observations. It means that only the sub-window centered on the images would be obtained without any reference pixels presented above. The minimum window size is 300×300 pixels.

3. Pre-processing, Calibration and Photometry

Before identifying the optical counterparts of GRBs, data processing is required, including pre-processing, astrometric calibration, and photometric measurements. The main process is shown in Figure 1. The methods for pre-processing and photometric calibration are identical to those applied to non-GRB scientific targets in VT images. During the identification process, it is sometimes necessary to analyze the light curve behavior of candidates. This section provides a description on these procedures.

3.1. Pre-processing

All L2 images are processed with instrumental effect correction of L1X images in a standard manner, including overscan correction, bias correction, dark correction, and LED flat-field correction. If the readout is performed in both channels, a gain-matching correction for the background is applied, based on the assumption of a uniform background around the interface between the two channels during readout.

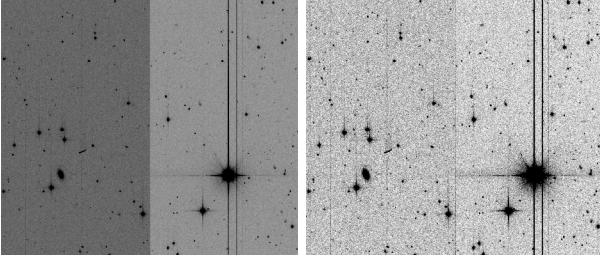


Figure 2. The comparison for the overscan correction. Left: the original image; Right: the same image after the overscan correction.

3.1.1. Overscan Correction

For overscan correction, temporal drift in the bias level can cause the image background to be either overestimated or underestimated. The resulting uneven background across left and right channels would generate spurious sources near the interface region and lead to missing stars or inaccurate photometry when the background is overestimated. Figure 2 shows the images before (left) and after (right) overscan correction. This correction is applied to all the images prior to other corrections.

3.1.2. Bias Correction

VT acquires in-orbit bias images with zero exposure time, after the shutter in front of the two detectors is closed. All observations are scheduled to occur while the platform is in Earth's shadow. During the processing, the bias images are first examined based on their background levels, and any images contaminated by stray light from Earth are rejected. After the filtering all individual images were performed for the overscan correction. The master bias image is generated using the IRAF zerocombine package. This step is also to filter out the effects from the cosmic rays in each image. The bias correction for each science image is performed with IRAF⁷ CCDPROC package.

3.1.3. Dark Correction

Similarly to the bias images, VT also acquires in-orbit dark images with the shutter closed. The exposure time is set to 100 s, which is similar to the typical exposure used for science observations. During the processing, all dark images are filtered according to their background levels, and subsequently corrected for overscan effects. The master dark image is generated using the IRAF darkcombine package. During preprocessing for the science images, the master dark image is normalized to the exposure time of the corresponding

science image and the IRAF.CCDPROC package is then used to perform dark correction.

3.1.4. LED Flat-field Correction

A total of 18 LEDs covering six colors are placed in front of the two detectors. Their central wavelengths are 470 nm, 527 nm, 640 nm, 670 nm, 740 nm, and 870 nm. The blue LEDs (470 nm, 527 nm, 640 nm) are used for the VT_B channel, while the remaining LEDs are used for the VT_R channel (Qiu et al. 2026). All flat-field images are pre-filtered using the same procedure applied to bias and dark-field images. Flat-field images are then grouped by color and combined into a master flat-field image. Gain correction ensures uniform background from left to right across the interface as described in Section 3.1.5. Owing to the short distance between LEDs and detectors, the backgrounds of the flat-field images exhibit non-uniform distribution. The master flat-field image is normalized using background values derived from large-scale fitting. The normalized master LED flat-field image is used to correct pixel-to-pixel non-uniformity in the science images.

3.1.5. Gain Correction

For images obtained in readout mode of “both channels” (Qiu et al. 2026), the gain values of the two channels differ slightly due to electronic effects. This leads to a background difference of up to 4% for the left and right parts of images. In order to eliminate or reduce this effect, gain matching is applied for the images. The algorithm calculates the ratio of the background values for the central left and central right regions.

3.2. Astrometric Calibration

Astrometric calibration aims to determine the transformation between detector coordinates (X , Y) and the celestial coordinates (R.A. and Decl). A custom pipeline based on the IRAF CMAP package was developed and applied to VT images, matching the brightest stars extracted from each image with the Gaia DR2 catalog (Gaia Collaboration et al. 2018) as reference. Detailed information is provided in Yao et al. (2026). In addition ASTROMETRY.NET (Lang et al. 2010) is also used if our custom-developed pipeline fails particularly for those images with high stellar density. All WCS solutions are then written into the image headers. The resulting astrometric accuracy is 0".01 for bright sources and 0".5 for faint sources or sources in crowded fields (Yao et al. 2026).

3.3. Photometry

3.3.1. Image Selection

The initial step in performing photometry is to select images of acceptable quality. For VT, images of good quality are defined as those in which the background level and the point-source enclosed

⁷ IRAF is distributed by the National Optical Astronomical Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

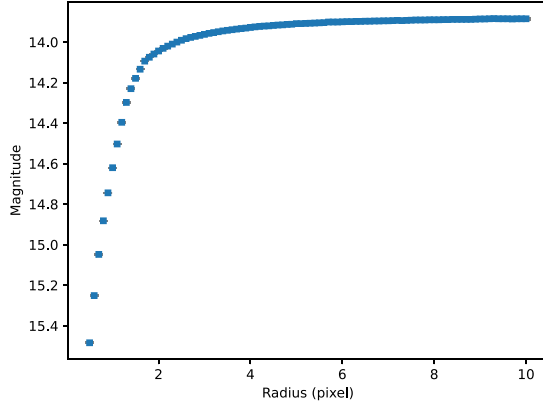


Figure 3. Growing curve in magnitude with radius for a bright source in a VT_R band image.

energy concentration meet the expected criteria, and the observing configuration matches the requested setup.

Typically, the background should be less than one electron per second per pixel. This holds for most observations at high Galactic latitudes. Note that this threshold may vary slightly depending on the satellite's pointing direction and orbital position. For instance, the threshold must be increased for observations where the target is close to the Moon or Earth, or lies within the Galactic plane.

The concentration of enclosed energy for point sources has remained highly stable in orbit over the long term since launch. However, image quality can be degraded by factors such as short-term platform instability or stray light from the Earth or the Moon. This quality check can be performed by inspecting the STAB_CNT keyword in the headers of VT L2 FITS images, which records the counts per second measured by the PDPU onboard SVOM during exposure. An image of good quality should have a STAB_CNT value of at least 80% of the exposure duration.

It is important to note that images with zero-second exposure time, which are generated during orbital gaps when VT switches configurations, are considered invalid observations and should be filtered out at this step.

3.3.2. Aperture Photometry

GRBs triggered by SVOM/ECLAIRs are mostly located at high Galactic latitudes. The stellar density is sufficiently low that most sources are unaffected by crosstalk. Therefore, aperture photometry is applied once the targets are identified in single or stacked VT images.

Photometry is performed in a standard manner. The first step is the determination of the photometric radius. Figure 3 shows the growth curve of a bright star with the photometric radius and corresponding magnitudes in a VT_R image. One can see that the magnitudes peaks at approximately 2–3 pixels from the source center. Therefore, in most cases, a radius of $r = 3$

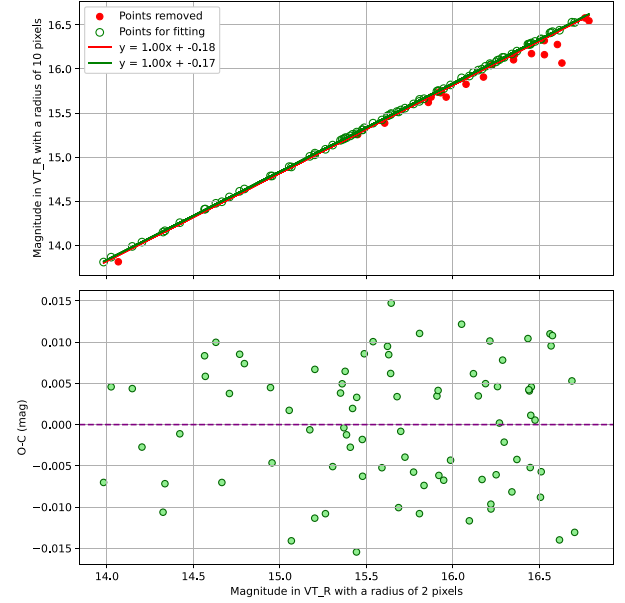


Figure 4. Aperture corrections (upper) and the precision of aperture corrections after iteration (bottom).

pixels is adopted for bright sources, and 2 pixels for faint sources.

Aperture correction is applied, since the aperture radius used for photometry is insufficient to encompass the total flux of bright sources. The aperture correction can be determined using more than ten bright but unsaturated sources within the same image. As shown by the growth curve in Figure 3, a radius of $r = 10$ pixels captures over 99% of the flux, which is adopted as the full aperture radius for this photometric measurement.

Figure 4 illustrates the performance to determine the value of the aperture correction through small-aperture photometry and the full-aperture radius. The fitting effectively eliminates contamination from galaxies, crosstalk from bright sources, and other unexpected effects. As shown in the lower panel of Figure 4, the precision of the aperture correction value reaches to the order of 0.6%.

We define mag_{VT} as the instrument magnitude, given by :

$$\text{mag}_{\text{VT}} = -2.5 * \log(\text{flux} * \text{gain}/\text{exptime}) \quad (1)$$

The resulting magnitude after the aperture correction is then converted to AB magnitude (Oke 1974) with Equation (2).

$$\text{mag}_{\text{AB}} = \text{mag}_{\text{VT}} + \text{Zero}_{\text{VT}} + \text{Cor} \quad (2)$$

Zero_{VT} and Cor are zero magnitudes for VT in both channels with a definition of magnitude per electron (Yao et al. 2026) and magnitude correction for given aperture radius, respectively. All measurements given in this work are in AB magnitude.

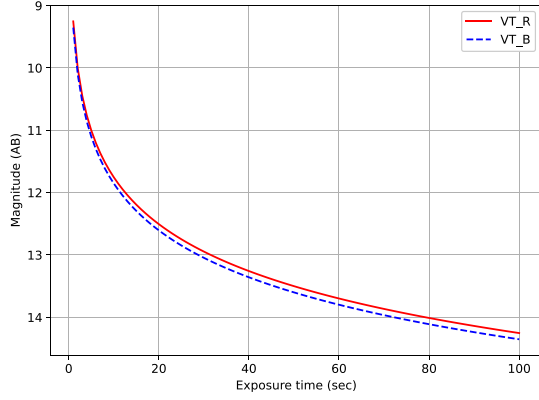


Figure 5. Saturated magnitude curves for *SVOM*/VT with different exposure times.

3.3.3. Photometry for Saturated Sources

The exposure time for GRBs triggered by *SVOM*/ECLAIRs is set to 50 s per frame during the initial two orbits and 100 s for the subsequent three orbits. For ToO observations, the typical exposure time is 70 s for ECLAIRs off-line triggers and bursts triggered by external missions if the brightness in optical is unpredictable. However, if the optical counterpart is too bright, it will lead to saturation in the acquired observations. Figure 5 presents the calculated saturated magnitude curves with different exposure times for VT. Notably, with an exposure time of 3 s, the saturated magnitudes are calculated to be 10.4 mag in VT_R and 10.5 mag in VT_B. When the exposure time is increased to 50 s, the saturated magnitudes rise to approximately 13.5 mag in VT_R and 13.6 mag in VT_B.

For the photometry, we assume that the tail part of the contour profiles for the saturated star and the unsaturated bright stars in the same field follow the same trend, except for the central saturated regions. This assumption is reasonable for the uniformity of Point-Spread Function (PSF) in VT images. For the saturated star, the flux in the annulus between the inner and outer radii is measured, as illustrated in Figure 6. Unsaturated bright stars in the same field of view are measured in the same way. The calculation of the magnitude for a saturated target is then given by Equation (3),

$$\text{Mag}_S = \text{Mag}_C - 2.5 \times \log \frac{\text{Flux}_S}{\text{Flux}_C} \quad (3)$$

where Mag_C denotes the magnitude of the unsaturated bright star measured in VT images, and Mag_S denotes the magnitude derived for the saturated star. Flux_C and Flux_S refer to the fluxes in the annuli for the bright star and the saturated star respectively. This method has been successfully applied to the measure the optical flares from M dwarf star V* UV Cet (sb25083102, W.-J. Xie et al. 2026, in preparation) and 1RXS J020013.6-084106 (sb25091517, H.-L. Li et al. 2026, in preparation) detected by *SVOM*/VT (Li et al. 2025a, 2025b),

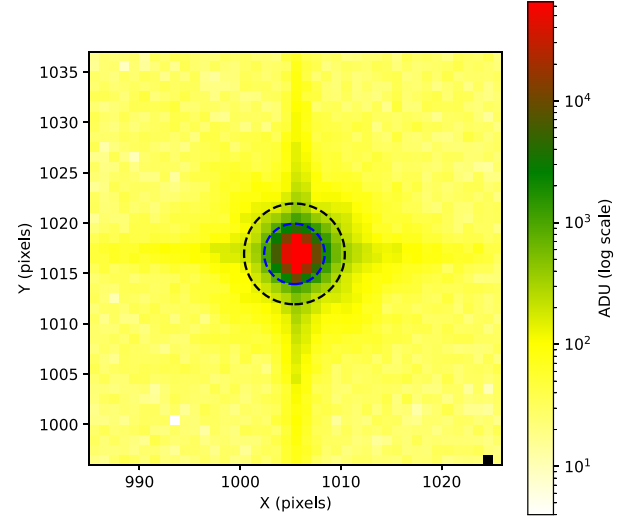


Figure 6. Illustration of radius selection for photometry of a saturated star in a VT image.

which were both initially triggered by *SVOM*/ECLAIRs (Julakanti et al. 2025; Xie et al. 2025a).

3.3.4. Build the Light Curve

The optical light curves of GRBs typically exhibit a decaying trend, often described by a single or broken power-law model. This decay is frequently superimposed with early-time rises or flares, which are generally attributed to the onset of the afterglow emission, passage of the peak radiation frequency through the observed band, re-activity of the central engine, or other underlying physical processes. The distribution of the brightness can span more than several orders of magnitude at the same time post the burst (Kann et al. 2011).

For bright cases, the photometry is performed in individual frames in order to achieve high temporal resolution, enabling the detection of afterglow onset signatures and flare activity. However, it should be noted that some measurements exhibit a sharp flux increase in only one band, which may be due to cosmic ray hits within the aperture region. Such cases require more refined analysis. Conversely, simultaneous flux drops observed in both channels within VT images should also be carefully examined. This may indicate poor image quality not adequately flagged during the initial quality checks, and such frames should be verified or excluded in subsequent analysis.

For faint cases, image stacking is performed. The stacking strategy primarily follows the $\Delta T/T \sim 1$ approach, where ΔT denotes the effective exposure time for the image stacking, and T represents the delay time post the burst. Given the constraints of in-orbit observations, each effective observing window lasts approximately 30–40 minutes per orbit. For images obtained during the early phase of GRB afterglow observations, the stacked time span can be as short as one orbit or even less, depending on the source brightness and specific

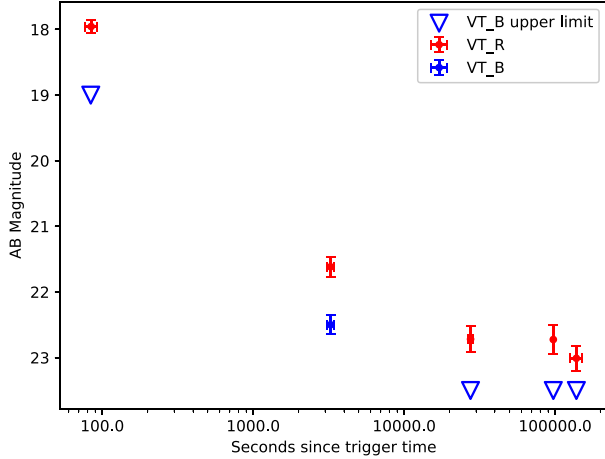


Figure 7. Optical afterglow light curve of GRB 241209B obtained by SVOM/VT.

scientific objectives. In the later afterglow phases, stacking data from 2–3 consecutive orbits may be adopted to improve observational depth.

Figure 7 presents the optical light curve of GRB 241209B derived from VT observations. This burst was triggered by SVOM/ECLAIRS (Xie et al. 2024). Thanks to the slew-onboard strategy, VT initiated observations at 76.5 s post trigger (Qiu et al. 2024). The first data point in Figure 7 was measured from a single frame with 15 s exposure time in VT_R at 84 s post trigger, while subsequent data points were generated via image stacking.

4. Identification of Optical GRB Counterparts

In the VT X-band data, the identification of GRB optical counterparts relies on three factors: the observational data sequence, the time delay relative to the trigger time, and the rapid fading behavior of the transients. The following discussion addresses three specific observational scenarios: SVOM triggers with platform slew automatically, ToO follow-ups observations, and the detection of high-redshift GRBs.

4.1. Identification for SVOM/ECLAIRS Bursts with Automatic Slew

VT performs observations from about 5 minutes after the bursts and lasting for five orbits (about 8 hr) if there are no interruptions from higher-priority observations. Considering the long-duration observations from very early time, there is a high chance to detect the reverse-shock emission or the onset of afterglows, or even prompt optical emissions in VT images. The subsequent behavior may show the diversity with the normal decay phase, a single power-law decay with an index of $\alpha \sim 1.0$ ($f \sim t^{-\alpha}$), a jet break with more rapid fading ($\alpha \sim 2.0$) (Gao et al. 2013) or some flares (Yi et al. 2017) due to the long lasting central energy activities, the fluctuation of the external medium or

other mechanisms. The optical counterparts of GRB will have the following basic characteristics:

1. It is an uncataloged source compared to existing catalogs with comparable depth, except for the host galaxy, which may overlap with the afterglow position. For VT, the DESI catalog (Dey et al. 2019) is ideal as a reference in most cases. If an uncataloged source is detected in both VT channels, the detection is highly reliable. However, there is a small chance ($\sim 5\%$) that the source lies in a region affected by blooming from a very bright nearby object in VT_R, which can hinder identification or measurement in the red channel. In such cases, the counterpart may be detectable only in VT_B. On the other hand, for some GRBs the counterpart may be detected only in VT_R or undetectable in both bands, likely due to optical faintness, line-of-sight extinction (Levan et al. 2006), or high-redshift (blue-dropout) effects (Greiner et al. 2010).
2. The position is consistent with the trigger and the X-ray afterglow. The counterpart should be coincident within the error box of the gamma-ray emission and the X-ray afterglow. For GRBs detected by SVOM/ECLAIRS, the positional uncertainty is from $2'$ to $10'$. The positional error of the corresponding X-ray counterpart is typically $0.5\text{--}3'$ for MXT (Götz et al. 2026), $10''\text{--}20''$ for EP/FXT (Chen et al. 2025), and $3''\text{--}10''$ for Swift/XRT (Burrows et al. 2007). The slow-moving objects also need to be taken into account especially when the field lies near the ecliptic plane. Some asteroids may be detected in VT images and can be verified using the Minor Planet Center (MPC⁸).
3. The brightness generally declines over time. While early-time behavior may exhibit complex features such as flares, plateaus, or rebrightenings, the overall trend of GRB optical afterglows at later phases (hours to days) is a decay in brightness. This property is particularly useful in regions without DESI coverage, or where the depth of existing reference catalogs is insufficient. Constructing light curves for all sources within the error box of the trigger or the X-ray counterpart is a practical method to identify the most promising candidates.

There are some false positives in the VT images which might contaminate the candidates in the case of error box with an order of several arcminutes. The first effect arises from cosmic rays. An uncataloged source detected in multiple single frames or in the stacked image is only considered to be a candidate of interest. The second effect is from hot pixels. The dark correction has been applied prior to the procedure of identification. However some new hot pixels may still emerge or the brightness of the existing hot pixels may intensify, owing to the radiation damage

⁸ <https://www.minorplanetcenter.net/>

from cosmic rays in space. In the first year, internal calibration observations to acquire the dark calibration frames were performed with a frequency of once per month. During the gaps between consecutive calibration observations, we found some new hot pixels present in the calibrated images. These hot pixels could be removed by the image stacking in the normal-stability mode, thanks to the drift between the images. PSF and the hot pixels table are utilized for filtering, particularly when a candidate is detected only in one channel.

There is a wide distribution in the brightness of optical afterglows even at similar epochs after the bursts (Kann et al. 2011). Bright afterglows can be identified in single frames. However, optical counterparts fainter than 22 mag can only be detected in stacked images. The differential imaging method is also used to detect the faint afterglow in cases that it overlaps with a bright host galaxy. For bright counterparts, the first and second halves of the initial orbit can be separated and stacked independently to generate a differential image. For faint afterglows, templates for differential imaging are obtained by stacking images from the final orbits, which could introduce a long time gap between the image pairs used for differencing. However, in this latter case, the identification requires more time owing to the long delay needed for all science images to be downlinked via X-band passes.

Given the complexity of GRB optical light curves at the early phase, which can arise from reverse shocks, forward shocks, central engine activities, together with the wide distribution of optical afterglows, multiple methods must be employed synergistically to characterize the afterglows.

4.2. Identification for Bursts from ToO Observations

For bursts triggered by external missions or confirmed SVOM/ECLAIRs triggers on the ground that do not automatically initiate a platform slew, ToO observations are scheduled. In most cases, the observation duration will be two orbits. Image stacking can achieve a depth of 23–24 mag. The configuration with the normal-stability mode of platform is suggested. The removal of hot pixels and cosmic rays is effectively accomplished in stacked images, owing to the shift during the observations in the normal-stability mode. The typical downlink delay for ToO data is several hours. Better localization of X-ray counterparts reported by Swift/XRT or EP/FXT greatly benefits the identification of candidate counterparts, if no optical counterpart is reported in GRB community.⁹

4.3. Identification for High-*z* GRB Candidates

One of the primary scientific objectives of VT is to select high-redshift GRB candidates through early, deep in-orbit optical observations covering the wavelength range up to

1 μm . As the Ly α line is redshifted to longer wavelengths, emission from sources at redshifts greater than 7 will be shifted beyond the wavelength coverage of VT's red channel.

However, other scenarios may also produce optically dark bursts. One is intrinsically faint optical bursts with unusual microphysical parameters, for example those residing in a very low-density external medium. The other is heavy line-of-sight absorption, as in the case of GRB 070306 (Jaunsen et al. 2008), GRB 080607 (Perley et al. 2011), and GRB 090417B (Holland et al. 2010).

Two conditions must be satisfied to ensure the effectiveness of this selection method: first, observations must begin within minutes of the GRB and reach sufficient depth to avoid missing rapidly fading afterglows. Second, relatively accurate localizations of the X-ray counterparts are required, at the level of a few arcseconds, as achieved by Swift/XRT or EP/FXT. Since onboard images are easily affected by cosmic rays and other instrumental factors, the rapid and effective removal of these contaminants is crucial. Improving positioning accuracy can significantly reduce such artifacts, thereby enhancing the confidence level of the results. One successful application of this method is the identification of GRB 250314A (Cordier et al. 2025).

On the other hand, once an optical counterpart is detected in VT_R or in both bands, its VT color can be used to estimate the redshift (Wang et al. 2020). The VT color redder than 2 can serve as an indicator for the redshift larger than 4, as performed and later confirmed by the spectroscopic observation in GRB 250215A (Sanchez-Ramirez et al. 2025; Xie et al. 2025b).

5. Performance of Identification and Detection

Up to 2025 December 3, 111 GRBs had been followed up by SVOM/VT, in which 63 were triggered by SVOM/ECLAIRs and 48 by external missions, including SVOM/GRM (Sun et al. 2026), EP (Yuan et al. 2022), the Neil Gehrels Swift Observatory (Gehrels et al. 2004), Fermi/GBM (Meegan et al. 2009), INTEGRAL (Winkler et al. 2003), etc. Overall, optical counterpart detection rate from VT X-band data is 75%. The detailed detection rates for all GRBs that VT observed, as well as for each subgroup, are also shown in Figure 8 for comparison.

5.1. SVOM/ECLAIRs Bursts with Automatic Slew

By 2025 December 3, VT had observed 43 ECLAIRs-triggered bursts with automatic slew of the platform, as shown in Figure 9 and Table 1. Here we only present the VT_R brightness for clarity. All detections are shown in red, while the upper limits are shown in black triangles.

The brightnesses in VT_R for ECLAIRs bursts with automatic slew range from 14.0 to >23.4 mag, with a median of VT_R $\sim$ 18.9 mag. The mid-time of the observations ranges

⁹ <https://gen.nasa.gov/circulars>

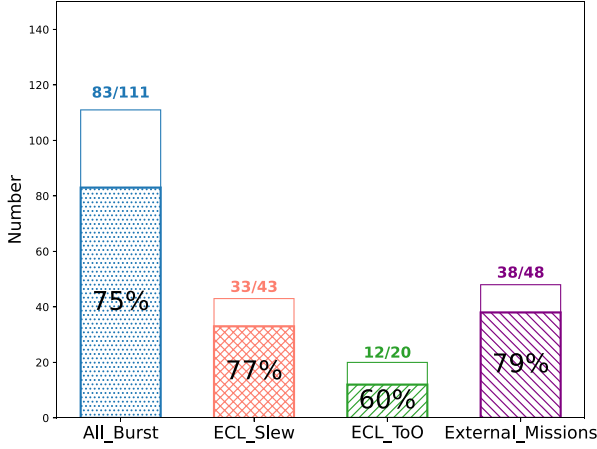


Figure 8. The detection rate in the VT X-band images for all the 111 GRBs observed by VT up to 2025 December 3, including ECLAIRs bursts with automatic slew (ECL_Slew, see also Figure 9 and Table 1), ECLAIRs bursts with ToO observation (ECL_ToO, see also Figure 10 and Table 2), and the bursts triggered by external missions (see also Figure 11 and Table 3).

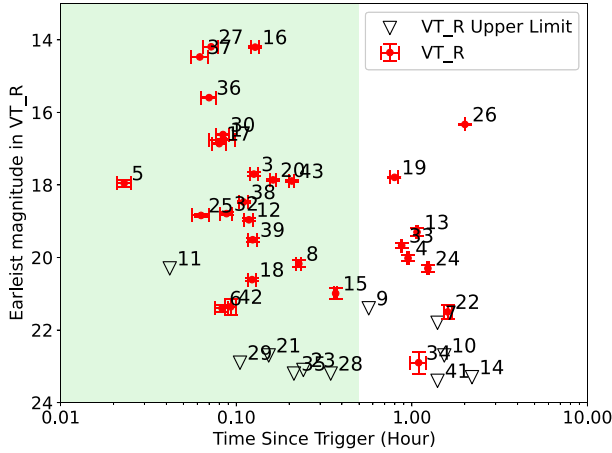


Figure 9. The earliest VT_R magnitudes of the optical counterparts for 43 SVOM/ECLAIRs bursts with automatic slew onboard up to 2025 December 3. Numerical labels adjacent to the data points correspond to the IDs presented in Table 1. The shaded region on the left corresponds to observations with a mid-time of 30 minutes post trigger.

from 84 s to 2 hr, with a median value of 583.2 s (i.e., 9.72 minutes). For VT, the starting time (T_{start}) of images with good quality post trigger is influenced by the angle between the GRB and the platform pointing at that epoch, as well as by the time required for the platform to stabilize. Notably the start time could be delayed by more than one hour, mostly due to Earth occultation, since some bursts are triggered near the end of the best observing window in an orbit.

Among the 43 ECLAIRs-triggered bursts with automatic slew that VT had observed, optical counterparts were detected for 33 GRBs, corresponding to a detection rate of about 77%. Specifically, 27 ECLAIRs bursts were observed within the mid-time of 30 minutes post triggers, as shown in the shaded

Table 1
Earliest Magnitude in VT_R for the Optical Counterparts of 43 SVOM/ECLAIRs Bursts with Automatic Slew up to 2025 December 3 (See also Figure 9)

ID	Burst	Mid-Time (hr)	VT_R (mag)
1	GRB 241018A	0.084	16.75 ± 0.02
2	GRB 241030B	0.106	-
3	GRB 241112B	0.126	17.70 ± 0.05
4	GRB 241212A	0.951	20.02 ± 0.09
5	GRB 241209B	0.023	17.95 ± 0.10
6	GRB 241217A	0.083	21.40 ± 0.10
7	GRB 241229A	1.400	>21.8
8	GRB 250103A	0.227	20.17 ± 0.09
9	GRB 250106A	0.568	>21.4
10	GRB 250108A	1.530	22.1 ± 0.2
11	GRB 250127A	0.042	>20.3
12	GRB 250205A	0.118	18.96 ± 0.04
13	GRB 250215A	1.070	19.30 ± 0.10
14	GRB 250314A	2.200	>23.3
15	GRB 250317B	0.368	20.99 ± 0.15
16	GRB 250327B	0.128	14.20 ± 0.03
17	GRB 250329A	0.080	16.86 ± 0.02
18	GRB 250402A	0.123	20.61 ± 0.05
19	GRB 250419A	0.796	17.79 ± 0.02
20	GRB 250502A	0.162	17.86 ± 0.02
21	GRB 250507A	0.153	>22.7
22	GRB 250512B	1.600	21.50 ± 0.20
23	GRB 250530A	0.241	>23.1
24	GRB 250610B	1.234	20.30 ± 0.10
25	GRB 250612D	0.063	18.84 ± 0.03
26	GRB 250704A	2.005	16.33 ± 0.02
27	GRB 250706B	0.072	14.19 ± 0.01
28	GRB 250713A	0.345	>23.2
29	GRB 250806A	0.105	>22.9
30	GRB 250813B	0.084	16.61 ± 0.02
31	GRB 250818B	0.076	17.3 ± 0.1
32	GRB 250901A	0.088	18.79 ± 0.04
33	GRB 250903A	0.875	19.67 ± 0.07
34	GRB 250910A	1.093	22.90 ± 0.30
35	GRB 250912A	0.213	>23.2
36	GRB 251002A	0.070	15.59 ± 0.02
37	GRB 251013C	0.062	14.47 ± 0.01
38	GRB 251025B	0.110	18.47 ± 0.03
39	GRB 251026A	0.124	19.51 ± 0.05
40	GRB 251111A	1.340	22.3 ± 0.2
41	GRB 251116C	1.400	>23.4
42	GRB 251122A	0.093	21.36 ± 0.22
43	GRB 251129A	0.207	17.89 ± 0.03

Note. For nondetections, 3σ limit magnitude in VT_R is given. For GRB 241030B, “-” indicates that no measurement in VT_R is available since the high background during the observations prevented the images from passing filtering criteria. But it was detected in VT_B with the brightness of 19.47 ± 0.05 mag at a mid-time of 382 s post trigger, as reported in GCN 37999.

region on the left side of Figure 9. Of these, 21 GRBs had optical counterparts, resulting in a 77% detection rate.

We also note that 10 bursts had no optical counterpart detected in VT X-band data, as shown in Figure 9 with black

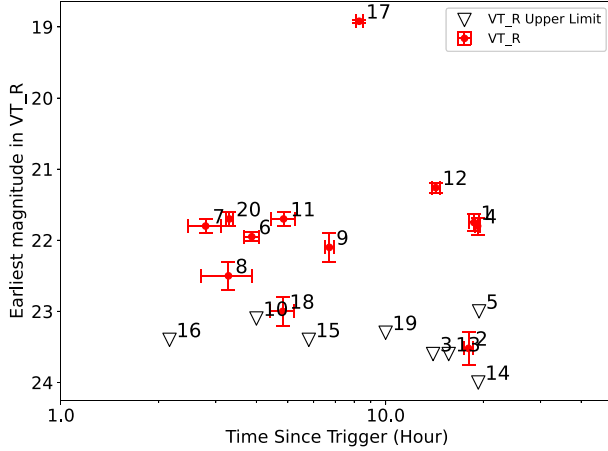


Figure 10. The earliest VT_R magnitudes of the optical counterparts for 20 SVOM/ECLAIRs bursts with ToO observations up to 2025 December 3. Numerical labels adjacent to the data points correspond to the IDs presented in Table 2.

inverted triangles. The VT_R upper-limits of these bursts are listed in Table 1. The possible explanations for these optical nondetections include intrinsic optical faintness in optical, heavy extinction, or high-redshift GRBs. Early nondetections from VT X-band data could help to identify high-redshift GRB candidates. One successful application of this method is GRB 250314A ($z = 7.3$). A detailed identification process through VT observation can be found in Cordier et al. (2025) and Qiu et al. (2026).

5.2. SVOM/ECLAIRs Bursts with ToO Observations

For ECLAIRs bursts that do not meet the onboard slewing criteria (Schanne et al. 2026), observations are performed in the ToO mode. Up to 2025 December 3, 20 ECLAIRs bursts had been observed in the ToO mode, as shown in Figure 10 and Table 2. Most of these bursts were detected from ECLAIRs onboard triggers, except for two events from offline ground-based triggers, which are marked with “*” in Table 2. All these 20 bursts had X-ray counterparts in SVOM/MXT, Swift/XRT, or EP/FXT. Five ECLAIRs ToO bursts were also detected by SVOM/GRM instruments, which are marked with “◇” in Table 2.

The observing times range from 2.16 hr to 19.20 hr, with a median of 5 hr post trigger. About 50% of them were followed up by VT within 5 hr. The VT_R magnitudes for the ECLAIRs ToO bursts range from 18.0 to >23.5 mag, with the median of $VT_R \sim 18.9$ mag. About 90% of the counterparts of ECLAIRs ToO bursts are fainter than 21 mag in VT_R.

Of the 20 bursts, 12 had optical counterparts detected by VT, corresponding to a detection rate of only 60%. The relatively low detection rate for these bursts via ToO observations can be attributed to at least two factors. First, the longer response delay via ToO observation, even though

Table 2
The Earliest Magnitudes in VT_R for the Optical Counterparts of 20 SVOM/ECLAIRs Bursts with ToO Observations up to 2025 December 3 (See also Figure 10)

ID	Burst	Mid-time (hr)	VT_R (Mag)
1	GRB 240821A ◇	18.700	21.75 ± 0.12
2	GRB 241001A	18.000	23.52 ± 0.23
3	GRB 241017A	14.000	>23.6
4	GRB 241029A ◇	19.200	21.80 ± 0.12
5	GRB 241104A ◇*	19.400	>23.0
6	GRB 241113B ◇	3.870	21.95 ± 0.06
7	GRB 250103B	2.790	21.80 ± 0.10
8	GRB 250213A	3.280	22.50 ± 0.20
9	GRB 250219A	6.710	22.10 ± 0.20
10	GRB 250329B	4.000	>23.0
11	GRB 250328A	4.850	21.70 ± 0.10
12	GRB 250403A	14.260	21.26 ± 0.07
13	GRB 250506A ◇	15.640	>23.6
14	GRB 250521B *	19.290	>24.0
15	GRB 250628B	5.800	>23.4
16	GRB 250727A	2.160	>23.4
17	GRB 250812A	8.290	18.92 ± 0.02
18	GRB 251007B	4.820	23.00 ± 0.20
19	GRB 251116B	10.000	>23.3
20	GRB 251203C	3.300	21.70 ± 0.10

Note. “◇” refers to the detection by both SVOM/ECLAIRs and SVOM/GRM. “*” refers to the bursts from SVOM/ECLAIRs offline ground-based triggers.

the BeiDou Navigation Satellite System typically responds to requests within approximately 50 minutes. Second, most of these bursts have relatively low S/Ns, which may be associated with fainter optical counterparts.

5.3. GRBs Triggered by External Missions

For GRBs triggered by external missions that are followed up via VT ToO observations, two constraints must be satisfied: (1) Galactic latitude $>15^\circ$ (Configurable); (2) Sun avoidance angle $>90^\circ$. The typical start time for ToO observations for these bursts is approximately 50 minutes post trigger. Up to 2025 December 3, VT has performed follow-up observations for 48 GRBs triggered by external missions, as illustrated in Figure 11 and listed in Table 3.

The observing time ranges from 0.6 hr to 159.8 hr with a median of about 8.0 hr. The VT_R magnitudes range from 16.25 to >23.8 mag, with a median of $VT_R \sim 21.0$ mag for these bursts. The optical counterparts of 38 GRBs were detected by VT, corresponding to a detection rate of 79%, which is comparable to the VT detection rate for SVOM/ECLAIRs observed with automatic slew onboard and very short delays. This rate is at least 10% higher than that for ECLAIRs triggers with ToO observations, which may be related to the different energy ranges of the respective

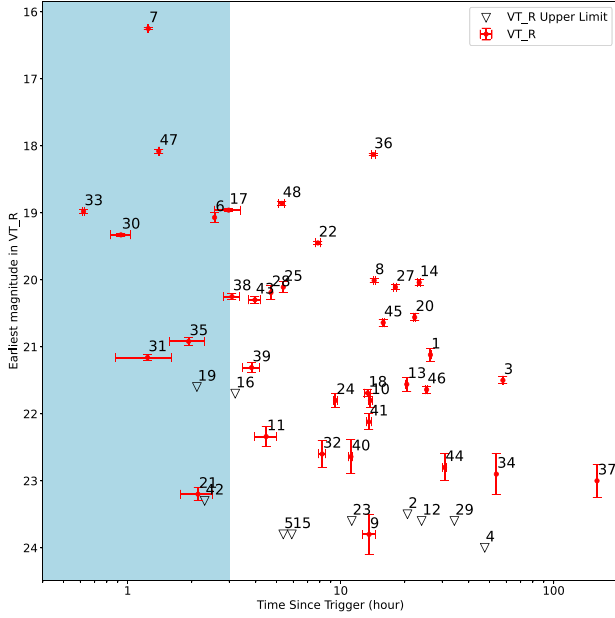


Figure 11. The earliest VT_R magnitudes of the optical counterparts for 48 bursts triggered by external missions with ToO observations up to 2025 December 3. Numerical labels adjacent to the data points correspond to the IDs presented in Table 3. The shaded region on the left corresponds to observations with a mid-time of 3 hr post trigger.

instruments. This trend will be further investigated in the coming years with more observations.

Since 2025 May, automatic ToO observations have been performed through the BeiDou system for triggers that meet the constraints mentioned above. No human intervention is required during this process (Bai et al. 2026; Han et al. 2026). If we consider only the GRBs with a mid-time of less than 3 hr, as shown in the shaded region on the left side of Figure 11, 9 out of 11 have detected optical counterparts, giving a higher detection rate of 81%. This improvement of detection is attributed to the rapid response of the BeiDou uplink system.

6. Summary and Improvements in the Future

In this paper, we present the data processing of VT X-band data, mainly focusing on the GRB science, including the identification of GRB optical counterparts. Up to 2025 December 3, SVOM/VT had performed observations for 111 GRBs mainly from SVOM, Swift and EP missions. Among them, 63 bursts were triggered by ECLAIRs, including 43 ones with onboard automatic slew, and 48 GRBs were triggered by external missions.

The overall VT detection rate of the optical counterparts of these GRBs is approximately 75%. For SVOM/ECLAIRs bursts observed within 30 minutes post trigger, the detection

Table 3

The Earliest Magnitudes in VT_R for the Optical Counterparts for 48 GRBs Triggered by External Missions up to 2025 December 3 (See also Figure 11)

ID	Burst	Mid-time (hr)	VT_R (mag)
1	GRB 240825A	26.400	21.12 ± 0.10
2	GRB 240905E	20.600	>23.5
3	GRB 240910A	57.800	21.50 ± 0.05
4	GRB 240919A/EP240919a	47.500	>24.0
5	GRB 241006A	5.380	>23.8
6	GRB 241025A	2.560	19.07 ± 0.07
7	GRB 241030A	1.250	16.25 ± 0.01
8	GRB 241105A	14.366	20.01 ± 0.03
9	GRB 241213A	13.600	23.80 ± 0.30
10	GRB 241229B	13.800	21.80 ± 0.10
11	GRB 250109A/EP250109a	4.470	22.34 ± 0.15
12	GRB 250114B	24.000	>23.6
13	GRB 250226A/EP250226a	20.450	21.56 ± 0.10
14	GRB 250309B/ZTF25aaitvjt	23.376	20.04 ± 0.04
15	GRB 250327A	5.900	>23.8
16	GRB 250330A	3.200	>21.7
17	GRB 250424A	2.980	18.96 ± 0.02
18	GRB 250430A	13.390	21.69 ± 0.05
19	GRB 250504A	2.780	>23.0
20	GRB 250515A/GOTO25cqo	22.270	20.56 ± 0.05
21	GRB 250520A	2.140	23.2 ± 0.1
22	GRB 250521D	7.819	19.45 ± 0.02
23	GRB 250605A	11.280	>23.6
24	GRB 250612B/EP250612a	9.460	21.80 ± 0.10
25	GRB 250617B	5.380	20.11 ± 0.08
26	GRB 250625A	1.150	-
27	GRB 250702F	18.080	20.11 ± 0.04
28	GRB 250704B/EP250704a	4.709	20.19 ± 0.11
29	GRB 250702B/EP250702a	34.200	>23.6
30	GRB 250725A	0.930	19.33 ± 0.02
31	GRB 250805A	1.240	21.16 ± 0.04
32	EP250806a	8.190	22.60 ± 0.20
33	GRB 250807A	0.621	18.98 ± 0.03
34	GRB 250807B	53.830	22.90 ± 0.30
35	GRB 250823A	1.934	20.92 ± 0.06
36	GRB 250919A/EP250919a	14.240	18.13 ± 0.02
37	GRB 250916A	159.840	23.00 ± 0.25
38	GRB 250924A	3.089	20.25 ± 0.05
39	GRB 251001B	3.819	21.31 ± 0.07
40	GRB 251005C	11.180	22.64 ± 0.25
41	GRB 251006B	13.560	22.12 ± 0.12
42	GRB 251011B	2.300	>23.3
43	GRB 251017A	3.960	20.30 ± 0.05
44	GRB 251021A/EP251021b	30.750	22.80 ± 0.20
45	GRB 251118C/EP251118a	15.840	20.64 ± 0.05
46	GRB 251126A	25.340	21.64 ± 0.05
47	GRB 251201B	1.400	18.08 ± 0.03
48	GRB 251202A/EP251202a	5.300	18.86 ± 0.03

Note. For GRB 250625A, “-” indicates that no measurement is available in VT_R since this target was contaminated by the blooming of bright stars nearby. But it was detected in VT_B with the brightness of 22.50 ± 0.15 mag at a mid-time of 1.15 hr post trigger, as reported in GCN 40830.

rate is around 77%. A slightly higher detection rate of 81% is also achieved for bursts triggered by external missions with ToO observations within 3 hr of mid-time, albeit with a limited sample size.

Thanks to the robust data link from space to ground centers, the good performance of the data processing and the rapid response by operation teams. The high detection rate of GRB optical counterparts, together with the efficient source identification, demonstrates VT's contributions to the GRB community, especially for studies of the GRB population and optically faint bursts. To date, a series of studies have been conducted based on VT X-band data processing results, including observational analyses of GRB 240825A (Wu et al. 2025), GRB 241105A (Dimple et al. 2025), etc. Further details on SVOM GRB observations are provided in Daigne et al. (2026).

In the future, further improvements will be implemented for the VT X-band data processing procedure, with a particular focus on targets located in complex backgrounds, such as those affected by contamination from nearby sources, local stray light, blooming, or pollution from detectors.

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 Chinese Academy of Sciences (grant No. XDB0550401).

ORCID iDs

Hua-Li Li  <https://orcid.org/0000-0002-7457-4192>
 Yu-Lei Qiu  <https://orcid.org/0009-0007-7207-4884>
 Li-Ping Xin  <https://orcid.org/0000-0002-9422-3437>
 Yang Xu  <https://orcid.org/0000-0002-8694-4672>

References

- Bai, M., Su, J., Li, B., et al. 2026, *RAA*, 26, 104005
 Burns, E., Svinkin, D., Fenimore, E., et al. 2023, *ApJL*, 946, L31
 Burrows, D. N., Kennea, J. A., Abbey, A. F., et al. 2007, *SPIE*, 6686, 668607
 Cai, H.-B., Qiu, Y.-L., Xin, L.-P., et al. 2026, *RAA*, 26, 104026
 Chen, K., Zhang, Y., Su, R. F., et al. 2026, *RAA*, 26, 104003
 Chen, Y., Wang, J., Yang, Y., et al. 2025, *RDTM*, 9, 198
 Cordier, B., Jeannin, L., Lafabrie, P., et al. 2026b, *RAA*, 26, 104006
 Cordier, B., Wei, J.-Y., Zhang, S.-N., et al. 2026a, *RAA*, 26, 104001
 Cordier, B., Wei, J.-Y., Tanvir, N. R., et al. 2025, *A&A*, 704, L7
 Cucchiara, A., Levan, A. J., Fox, D. B., et al. 2011, *ApJ*, 736, 7
 Dai, Z., Daigne, F., & Mészáros, P. 2017, *SSRv*, 212, 409
 Daigne, F., Turpin, D., Atteia, J.-L., et al. 2026, *RAA*, 26, 104035
 Dey, A., Schlegel, D. J., Lang, D., et al. 2019, *AJ*, 157, 168
 Dimple, Gompertz, B. P., Levan, A. J., et al. 2025, *MNRAS*, 544, 548
 Dong, X.-F., Huang, Y.-F., Zhang, Z.-B., et al. 2025, *ApJ*, 993, 20
 Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, *A&A*, 616, A1
 Galama, T. J., Vreeswijk, P. M., van Paradijs, J., et al. 1998, *Natur*, 395, 670
 Gao, H., Lei, W.-H., Xiao, S., et al. 2025, *ApJ*, 985, 33
 Gao, H., Lei, W.-H., Zou, Y.-C., Wu, X.-F., & Zhang, B. 2013, *NewAR*, 57, 141
 Gehrels, N., Chincarini, G., Giommi, P., et al. 2004, *ApJ*, 611, 1005
 Godet, O., Atteia, J.-L., Schanne, S., et al. 2026, *RAA*, 26, 104007
 Götz, D., Crepaldi, S., Doumayrou, E., et al. 2026, *RAA*, 26, 104013
 Greiner, J., Krühler, T., Klose, S., et al. 2010, *AIPC*, 1279, 144
 Han, X.-H., Xin, L.-P., Wang, J., et al. 2026, *RAA*, 26, 104034
 Hjorth, J., Sollerman, J., Møller, P., et al. 2003, *Natur*, 423, 847
 Holland, S. T., Sbarufatti, B., Shen, R., et al. 2010, *ApJ*, 717, 223
 Jaunsen, A. O., Rol, E., Watson, D. J., et al. 2008, *ApJ*, 681, 453
 Julakanti, Y., Eyles-Ferris, R. A. J., Schanne, S., et al. 2025, GCN, 41834, 1
 Kann, D. A., Klose, S., Zhang, B., et al. 2011, *ApJ*, 734, 96
 Lamb, D. Q., & Reichart, D. E. 2000, *ApJ*, 536, 1
 Lang, D., Hogg, D. W., Mierle, K., Blanton, M., & Roweis, S. 2010, *AJ*, 139, 1782
 Levan, A., Fruchter, A., Rhoads, J., et al. 2006, *ApJ*, 647, 471
 Levan, A. J., Malesani, D. B., Gompertz, B. P., et al. 2023, *NatAs*, 7, 976
 Levan, A. J., Schneider, B., Le Floch, E., et al. 2025, *A&A*, 704, L8
 Li, D., Zhang, Y., Su, R., et al. 2026, *RAA*, 26, 104002
 Li, H.-L., Xin, L.-P., Ma, Y.-N., et al. 2025b, GCN, 41836, 1
 Li, H.-L., Xin, L.-P., Qiu, Y.-L., et al. 2025a, GCN, 41654, 1
 Liang, E.-W., Li, L., Gao, H., et al. 2013, *ApJ*, 774, 13
 Liu, Y., Bai, M., Wei, M., Feng, K., & Li, B. 2026, *RAA*, 26, 104004
 Meegan, C., Lichti, G., Bhat, P. N., et al. 2009, *ApJ*, 702, 791
 Nousek, J. A., Kouveliotou, C., Grupe, D., et al. 2006, *ApJ*, 642, 389
 Oates, S. 2023, *Univ*, 9, 113
 Oke, J. B. 1974, *ApJS*, 27, 21
 Perley, D. A., Morgan, A. N., Updike, A., et al. 2011, *AJ*, 141, 36
 Qiu, Y.-L., Li, H.-L., Xin, L.-P., et al. 2024, GCN, 38516, 1
 Qiu, Y.-L., Xin, L.-P., Deng, J.-S., et al. 2026, *RAA*, 26, 104022
 Saccardi, A., Vergani, S. D., De Cia, A., et al. 2025, *A&A*, 671, A84
 Sanchez-Ramirez, R., Castro-Tirado, A. J., Caballero-Garcia, M. D., et al. 2025, GCN, 39343, 1
 Schanne, S., Chateau, F., Dagoneau, N., et al. 2026, *RAA*, 26, 104010
 Stanek, K. Z., Matheson, T., Garnavich, P. M., et al. 2003, *ApJL*, 591, L17
 Sun, J. C., Dong, Y. W., He, J., et al. 2026, *RAA*, 26, 104018
 Tanvir, N. R., Levan, A. J., González-Fernández, C., et al. 2017, *ApJL*, 848, L27
 Wang, F.-Y. 2013, *A&A*, 556, A90
 Wang, J., Qiu, Y.-L., & Wei, J.-Y. 2020, *RAA*, 20, 124
 Wei, J.-Y., Cordier, B., Antier, S., et al. 2016, arXiv:1610.06892
 Winkler, C., Courvoisier, T. J.-L., Di Cocco, G., et al. 2003, *A&A*, 411, L1
 Wu, C., Palmerio, J. T., Sadibekova, T., et al. 2026, *RAA*, 26, 104027
 Wu, C., Wang, Y., Li, H.-L., et al. 2025, *RAA*, 25, 105003
 Xie, W.-J., Zhao, D.-H., Wu, C., et al. 2024, GCN, 38478, 1
 Xie, W.-J., Cheng, Y. H., Wang, B.-T., et al. 2025b, GCN, 39333, 1
 Xie, W.-J., Lan, L., Guillot, S., et al. 2025a, GCN, 41614, 1
 Yao, Z.-H., Qiu, Y.-L., Deng, J.-S., et al. 2026, *RAA*, 26, 104024
 Yi, S.-X., Yu, H., Wang, F. Y., & Dai, Z.-G. 2017, *ApJ*, 844, 79
 Yuan, W.-M., Zhang, C., Chen, Y., & Ling, Z. 2022, in *Handbook of X-ray and Gamma-ray Astrophysics*, ed. C. Bambi & A. Sanganello (Springer), 86
 Zhang, B. 2007, *ChJAA*, 7, 1