A Real-time Monitor for TeV Gamma-Ray Flare with the LHAASO-WCDA Detector (Postprint)

Authors: G. M. Xiang, M. Zha, J. N. Zhou and Y. Xing

Date: 2025-01-07T00:00:00+00:00

Abstract

With its high duty cycle, wide field of view and high detection sensitivity, Water Chereknov Detector Array as one of sub-arrays of Large High Altitude Air Shower Observatory is a promising facility to monitor transient phenomena in the very high energy gamma-ray band. In this work, a real-time monitor for selected TeV extragalactic sources is introduced, this flare monitor is developed to detect very high energy flare events and for further studying the power-providing mechanism of blazar relativistic jets. The detailed information such as the searching method and sensitivity of this real-time flare monitor is also presented. In the end, successful multi-wavelength and multi-messenger observation of 1ES 1959+650 and IC 310 also confirms the capabilities and reliability of the monitoring system.

Full Text

Preamble

Research in Astronomy and Astrophysics, 24:125020 (10pp), 2024 December Printed in China. https://doi.org/10.1088/1674-4527/ad8b0d

A Real-time Monitor for TeV Gamma-Ray Flare with the LHAASO-WCDA Detector

G. M. Xiang[1],[2], M. Zha[3], J. N. Zhou[1], and Y. Xing[1]

[1] Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China; gmxiang@shao.ac.cn

[2] University of Chinese Academy of Sciences, Beijing 100049, China

[3] Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

Received 2024 April 11; revised 2024 September 26; accepted 2024 October 17; published 2024 December 13

Abstract

With its high duty cycle, wide field of view, and high detection sensitivity, the Water Cherenkov Detector Array (WCDA), as one of the sub-arrays of the Large High Altitude Air Shower Observatory (LHAASO), is a promising facility for monitoring transient phenomena in the very high energy gamma-ray band. In this work, we introduce a real-time monitor for selected TeV extragalactic sources. This flare monitor is developed to detect very high energy flare events and to further study the power-providing mechanisms of blazar relativistic jets. We present detailed information such as the search method and sensitivity of this real-time flare monitor. Finally, successful multi-wavelength and multi-messenger observations of 1ES 1959+650 and IC 310 confirm the capabilities and reliability of the monitoring system.

Key words: methods: data analysis – methods: observational – gamma-rays: galaxies

1. Introduction

Blazars are among the most powerful objects in the Universe and comprise the majority of gamma-ray sources in the extragalactic sky. Observations of blazars and their variability have been an active field of research. Based on long-term observations, blazars have shown variability over different timescales ranging from minutes to days, months, and even longer. Due to their favorable jet orientation, blazars exhibit some of the most energetic observable phenomena and extremely high gamma-ray luminosities. Many multi-wavelength campaigns have been deployed, providing important information on source acceleration models and the inner engine or black hole.

For example, the study of Very High Energy (VHE) flares from blazars can provide insights into the VHE emission mechanisms during flares and help distinguish between different emission scenarios, such as the Synchrotron Self-Compton (SSC) model [**?**] and the photon-hadronic model [**?**]. Furthermore, observations of VHE flare events can serve as tools to study other physics topics such as the extragalactic background light, intergalactic magnetic field [**?**], and Lorentz invariance violation [**?**]. While considerable research has been conducted on extragalactic VHE flares by various facilities, such as the gamma-ray sky survey by Fermi-LAT covering the 30 MeV–300 GeV energy range [**?**, **?**, **?**], the limitations of the detector's effective area in the VHE band have resulted in insufficient statistics to detect VHE transients.

Furthermore, ground-based Imaging Atmospheric Cherenkov Telescopes (IACTs) have been limited by their pointing nature and small field of view (FOV). Simultaneously, ground-based extensive air shower arrays have also carried out studies on VHE transients, such as an early warning monitor implemented on the ARGO-YBJ experiment [?]. Despite being a large FOV detector, its limited sensitivity resulted in only three flares of Mkn 421 being reported during its operation.

With unprecedented detection sensitivity (around 1.5% Crab Unit), large FOV (around 2 steradians), and high duty cycle (higher than 98%), LHAASO-WCDA has the capability to continuously and unbiasedly survey the northern hemisphere sky in the VHE band. These features make WCDA an ideal instrument for conducting real-time analysis of extragalactic transient events and provide new opportunities for discovering extragalactic blazar flares. Once a flare is identified by WCDA, an alert can be sent to other multi-wavelength instruments, such as Fermi-LAT, Swift, IACTs, and multi-messenger facilities such as IceCube, to trigger follow-up observations on a global scale.

Here we report the development and deployment of a real-time flare monitor designed to detect VHE flares using LHAASO-WCDA. After a brief introduction of LHAASO-WCDA in Section 2, we outline the mechanics of the flare monitor and discuss the settings for false alarm rates in Section 3; the candidate sources are also included in Section 3. The flare monitor sensitivity is presented in Section 4. Subsequently, we present results from test running data in Section 5. Finally, we provide a summary and outlook of this real-time monitoring system.

2. The LHAASO-WCDA Detector

The Large High Altitude Air Shower Observatory (LHAASO) is located at Haizi Mountain, Daocheng (4410 m a.s.l., 606 g cm^{-2}, 29°21 31 N, 100°08 15 E), Sichuan Province, China. The Water Cherenkov Detector Array (WCDA) consists of three separate pools with a total area of 78,000 m^2.

The area of Pool No.1 and No.2 is 150 × 150 m^2 each, containing 900 detection units of 5 × 5 m^2. The area of Pool No.3 is 300 × 110 m^2, containing 1320 detection units. Each detection unit is separated by black plastic curtains to block scattered light from other units. Each detection unit is equipped with a large photomultiplier tube (PMT) and a small PMT to enlarge the dynamic range. Pool No.1 is installed with 8-inch PMTs and 3-inch PMTs in each detection unit. To lower the threshold energy, the detection units in Pools No.2 and No.3 are installed with 20-inch PMTs and 3-inch PMTs.

By sampling the energy deposition and arrival time in each detection unit caused by air shower secondary particles, the direction and energy information related to primary particles can be reconstructed. To select gamma-like events, a composition-sensitive parameter, denoted as Pincness, with a cut value of less than 1.1 is required to select gamma-like air shower events. Additionally, only events with zenith angle less than 45° are utilized for monitoring analysis to ensure reconstruction quality. More details about the detector and reconstruction algorithm can be found in [?, ?].

3. Flare Monitor Scheme

The entire monitor scheme is composed of four main elements, which we describe in detail below: (1) target source selection, (2) background estimation method, (3) search for excess, and (4) flare monitor trigger condition.

3.1. Target Source Selection

Target sources were selected based on known or perceived probability of VHE gamma-ray emission. A list of potential VHE extragalactic candidates was compiled from an online catalog for TeV Astronomy (TeVCat; [?]) and the Third Catalog of Hard Fermi-LAT Sources (3FHL; [?]). TeVCat includes 251 detected VHE sources, both galactic and extragalactic; here we target only 66 extragalactic sources within the FOV of WCDA. The 3FHL catalog contains 1556 objects characterized in the 10 GeV–2 TeV energy range. Seventy-nine percent of the detected sources are associated with extragalactic counterparts and are expected from multi-wavelength observations to have the potential to generate VHE gamma-ray radiation. Eighty-two nearby extragalactic sources with redshifts $z < 0.3$ (not included in TeVCat) are included in the target list. Detailed information for all 148 sources can be found in Table 1 .

3.2. Background Estimation Method

To calculate the excess signal from a source, on-source events (N_{on}) and background maps (N_{off}) are generated using full-sky Hierarchical Equal Area isoLatitude Pixelization (HEALPix) with a resolution parameter n_{side} of 1024 [?]. The background maps are computed based on direct detector acceptance estimated with an integration time of 2 hours. To minimize the impact of certain strong and well-known gamma-ray sources, as well as specific regions, these areas are excluded from background computation. These regions cover the Crab Nebula, Geminga, Markarian 421, Markarian 501, and a region within \$±\$5° around the inner Galactic Plane. Both the event and background maps are smoothed with a disk function that accounts for the detector's point-spread function. Here we use the optimal radius of $1.58 \times \rho_{40}$, where ρ_{40} is the radius containing 40% of the total events.

To ensure continuous operation of the monitoring system, we utilize the acceptance generated during the same period on the previous day as the acceptance for the specific two-hour duration. A stability test, as described in [?], is conducted on WCDA test running data to demonstrate feasibility. As shown in Figure 1 [Figure 1: see original paper], the acceptance displays periodic variations, reaching a maximum difference of less than 3% at a 12-hour time separation, with the difference between two neighboring days for the same two-hour duration being completely negligible. Therefore, it is reasonable to use the acceptance from the previous two-hour period as the acceptance for the current two-hour period.

Due to low statistics in high N_{nhit} bins (specifically bin 4 and bin 5 in Table 2), a 0.5° acceptance smoothing radius has been used for these low-statistics analysis bins, implying that a large off-source region is employed to estimate the background.

3.3. Search for Excess

A likelihood ratio test is performed to detect flares from sources of interest. We define the expectation of the number of photons in the on-source region as $\langle N_{\text{on}} \rangle$ and the expectation in the off-source region as $\langle N_{\text{off}} \rangle$. We assume that the on-source count N_{on} follows a Poisson distribution with mean $\langle N_{\text{on}} \rangle$, and the off-source count N_{off} follows a Poisson distribution with mean $\langle N_{\text{off}} \rangle$. The likelihood functions for N_{hit} bin i can be expressed as follows:

The null hypothesis, $L_{b,i}$, states that all detected photons are due to background fluctuations. $L_{s+b,i}$ is the alternative hypothesis where a flare phenomenon exists; in other words, all detected photons come from background plus signal. Following the solution described in [**?**], the test statistic is defined using the likelihood ratio:

$$TS_i = 2 \ln \frac{L_{s+b,i}}{L_{b,i}}$$

where α_i is the ratio of on-source exposure to off-source exposure for analysis N_{hit} bin i. The total test statistic is the sum of test statistics from N_{hit} bin 0 to bin 6. According to Wilks' theorem [**?**], TS_{tot} approximately follows a χ^2 distribution with k degrees of freedom.

When searching for flares, two factors must be considered: spatial search and time duration search. Because we use a predefined sky map without optimization for any sources, the flare source should not be located exactly at the center of a sky pixel. To limit a reasonable angular distance between the sky pixel and the flare source and account for the pointing error of the WCDA detector, the maximum searching radius for the target source is set at 0.1°. Only the maximum TS value is kept to indicate the significance of the target source.

For the time duration search, any target source is monitored until it disappears from the FOV of the detector or reaches its culmination. The test statistics for 0.5, 1, 2, and 4-day transits, denoted as TS_{time}, are calculated. Ultimately, the maximum TS_{tot} from all spatial and four time durations is taken to represent the TS value of the target source for that day.

Flare searching specifically focuses on increases in flux as the primary concern. When $\alpha_i N_{\text{off}} > N_{\text{on}}$ for analysis bin i, Equation (2) will be replaced by 0 for that N_{hit} segment. Equation (3) takes the form:

$$TS_{\text{tot}} = \sum_{i=0}^{6} \max(0, TS_i)$$

In summary, the trigger condition is set as:

$$\max(TS_{\text{space,time}}) > TS_{\text{threshold}}$$

where $TS_{\text{threshold}}$ is the threshold that controls the false alarm rate.

3.4. Flare Monitor Trigger Condition

3.4.1. False Alarm Rate The monitoring system selects the maximum TS across spatial and time duration bins as the TS of the target source for a specific day. However, due to severe correlations between spatial and time duration searches, there is no simple distribution for calculating the chance probability of an excess. In this case, a Monte Carlo simulation of the search procedure is applied for a single source to determine the TS distribution, assuming no signal emission from the source. Based on this distribution, the False Alarm Rate (FAR) for a given $TS_{\text{threshold}}$ can be easily calculated. This process follows three detailed steps.

First, we determine the threshold for a source located at the same declination as the Crab Nebula (decl. $= 22°$). Second, we simulate sources at other declinations within the FOV of WCDA to check if the threshold is declination-dependent. Third, for extragalactic sources with stable strong emission (Mkn 421, Mkn 501), additional corrections to the thresholds have been made to achieve the same false alarm rate for each source.

A total of 10^6 simulated transit samples are produced to calculate the relationship between the false alarm rate and the $TS_{\text{threshold}}$, as shown in Figure 2 [Figure 2: see original paper]. Using interpolation, we find that the $TS_{\text{threshold}}$ values for false alarm rates of 1 flare event per target per year and 1 flare event per target per century are $TS_{\text{threshold}} = 24.35$ and $TS_{\text{threshold}} = 34.60$, respectively.

3.4.2. False Alarm Rate Declination Dependence Due to reduced on-source and off-source event counts at large zenith angles, the threshold could potentially be impacted. We investigated the relationship between $TS_{\text{threshold}}$ and declination and introduced a correction factor. We simulated results from 19 different declinations, ranging from -10° to +75°, to determine the threshold dependence on declination and its relationship with the false alarm rate.

The upper panel of Figure 3 [Figure 3: see original paper] shows the $TS_{\text{threshold}}$ required for false alarm rates of 1 event per year and 1 event per century. The lower panel reveals that the ratio between the threshold parameters required for these two false alarm rates remains constant as a function of declination. This independence of the ratio on declination enables us to apply a single declination-dependent correction to the threshold parameter that remains constant for all false alarm rates.

There is a slight decrease in $TS_{\text{threshold}}$ as the declination moves away from +30°, as shown in Figure 4 [Figure 4: see original paper]. Even though setting the same threshold for targets at different declinations would have a maximum impact of no more than 0.2 on the false alarm rate per year, we still apply corrections to the threshold at different declinations. We use a quadratic function to fit this relationship, with the best fit shown as the dashed line in Figure 4. The $TS_{\text{threshold}}$ for one event per target per year as a function of declination is expressed as:

$$TS_{\text{threshold}}(\text{decl.}) = 30.18 - 0.0008 \times (\text{decl.} - 30°)^2$$

According to Equation (7), the declination-dependent correction parameter is defined as:

$$C_{\text{decl.}} = \frac{TS_{\text{threshold}}(\text{decl.})}{30.18}$$

We apply this declination-dependent correction $C_{\text{decl.}}$ to the $TS_{\text{threshold}}$ of targets at different declinations, ensuring that the false alarm rates at different declinations are consistent with those at the Crab position.

3.4.3. False Alarm Rate with Strong Emission Strong targets with steady emission tend to generate higher TS values compared to targets without steady emission. Setting the same $TS_{\text{threshold}}$ as that for background regions would lead to an underestimation of the false alarm rate. Therefore, we need to account for this effect to ensure that the false alarm rate for strong emission sources matches that of background regions.

To address this, we utilize the simulation approach mentioned above. When considering the presence of steady emission sources, we account for fluctuations caused by steady emission added to the background. Unlike the previous case where the count in the background window followed a Poisson distribution with mean $\alpha \times N_{\text{off}}$, when considering steady emission sources, an additional term is included in the mean of the Poisson distribution for the background window count. The mean count for the background window is set as $\alpha N_{\text{off}} + R_{\text{tar}} \times \alpha N_{\text{off}}$, where R_{tar} represents the relative excess of the target source observed by WCDA with respect to the background window. $R_{\text{tar}} = (ON_{\text{all}} - \alpha \times OFF_{\text{all}})/(\alpha \times OFF_{\text{all}})$, where ON_{all} and OFF_{all} are the total on-source and off-source counts collected from the vicinity of the strong target over the entire data set. In this study, for Mkn 421, the values of R_{tar} are 0.11, 0.54, 1.79, 3.40, 5.89, and 1.31 for bins 0 to 5 respectively, while for Mkn 501, the values are 0.03, 0.16, 0.64, 1.49, 3.44, and 1.23.

In Figure 5 [Figure 5: see original paper], the upper panel illustrates the threshold for Mkn 421 with and without correction. The lower panel demonstrates that with the correction, we are able to effectively align the false alarm rate in the presence of steady sources with that of background regions, as shown in Figure 2.

The 148 selected target sources are classified into three categories based on observations: (I) two well-known sources detected by LHAASO-WCDA, Mkn 421 and Mkn 501; (II) extragalactic sources from TeVCat; and (III) nearby extragalactic sources from 3FHL. In the current monitoring scheme, the expected false alarm rate for all selected target sources has been set to 10 occurrences per year with equal weight for these three categories. The specific TS threshold values chosen are 23.28 for the first category, 30.94 for the second category, and 31.46 for the third category, as listed in the third column of Table 3 . Once a source is detected to exceed its threshold, an alarm email is sent to members of the working group. In addition to occasional alarm emails, daily summary reports about all selected target sources from the previous day are automatically sent to the relevant working group.

4. Sensitivity of the Flare Monitor

Next, we examine the sensitivity of the flare monitor to flares with different properties. The flux, duration, and source declination of the flare can all impact the detection probability. Although many complex models exist to describe flare light curves, for simplicity we only consider sensitivity for the case of constant flare flux. We calculate sensitivity by injecting flares with the same spectral index as the Crab Nebula as detected by LHAASO. For the off-source window, we sample from a Poisson distribution with mean m_i, and for the on-source window, we sample from a distribution with mean $\alpha \times m_i + f \times U_{\mathrm{Crab}}$, where f is the flare flux in Crab Units (U_{Crab}).

At the declination of the Crab Nebula, we performed simulations to study the relationship between sensitivity, duration, and flux while maintaining a false alarm rate of 10 events per year for the entire category. Figure 6 [Figure 6: see original paper] shows the detection probability for a fiducial flare with varying flux as a function of duration. As expected, increasing either the flux or the duration improves the detection probability.

Due to the reduced number of events at high zenith angles, the monitor sensitivity is strongly dependent on the declination of the target source. Figure 7 [Figure 7: see original paper] depicts the monitor sensitivity to flares at different declinations, based on a false alarm rate of 10 events per year for the target collection and with a flare duration of only 1 day. The data points in this figure account for the declination-dependent correction to the $TS_{\mathrm{threshold}}$. It is evident that sensitivity decreases significantly as the declination moves away from +30° (the latitude of LHAASO).

5. Test Run with LHAASO-WCDA Data

During the test run using the LHAASO-WCDA real-time alert system, a TeV gamma-ray flare from 1ES 1959+650 was detected on 2024 February 8. WCDA observed an increase in the gamma-ray flux from the blazar starting at MJD = 60347.02. By MJD = 60348.33, the accumulated pre-trial significance reached 8.7 standard deviations, with an integrated flux above 1 TeV exceeding 0.5 Crab Unit. An alert was promptly issued as ATel #16437 [?], triggering several multi-wavelength and multi-messenger follow-up observations by different detectors worldwide. The details are summarized below:

1. At X-ray energies, as reported in ATel #16449 [?], the Swift-XRT detector also discovered that 1ES 1959+650 was in a strong X-ray flare state, approximately 2.2 times higher than the overall average, with highly overlapping time coverage with the LHAASO-WCDA observation.
2. At GeV energies, as reported in ATel #16456 [?] and GCN#35746, preliminary analysis from Fermi-LAT observations between MJD 60338 and 60357 (2024 January 29–February 17) indicates that the blazar has been in a high state for a month, with a monthly average flux ($E > 100$ MeV) of flux = $(1.8 \pm 0.2) \times 10^{-7}$ ph cm^{-2} s^{-1} and index = 1.67 ± 0.05. This is approximately four times the average flux reported in the Fourth Fermi LAT Source Catalog.
3. From a neutrino multi-messenger perspective, IceCube also conducted a search within a 36-day time window (from 2024 January 15 00:00:00 UTC to 2024 February 20 00:00:00 UTC) and did not detect any signals, providing an upper limit on the time-integrated muon-neutrino flux of $E^2 dN/dE < 10$ GeV cm^{-2} at 90% CL [?].

On 2024 March 8, another alert (ATel#16513) about the radio galaxy IC 310 was issued [?]. This alert also triggered positive follow-up observations from the VERITAS experiment [?]. Detailed information about the alert and follow-up observations can be found in Table 4 .

In summary, this series of related multi-wavelength and multi-messenger observations demonstrates and establishes an excellent example of the capabilities of the LHAASO-WCDA real-time alert system.

6. Summary and Outlook

The LHAASO-WCDA real-time flare monitor has been fully operational since the end of 2023 and began sharing alerts with the MAGIC collaboration from January 2024. To date, several ATels have been announced, and a series of related multi-wavelength and multi-messenger observations have been conducted worldwide.

The LHAASO-WCDA real-time flare monitor aims to facilitate coordinated observations, offering opportunities to unravel the mysteries surrounding blazars, their VHE emission, and their jet mechanisms. More specifically, one of its purposes is to provide unbiased observations of TeV blazars, allowing for an increased sample of VHE flares. This contributes to understanding the nature and location of the dissipation region where flares are generated, as well as the particle populations and acceleration mechanisms involved in producing these flares.

The next steps for this monitoring system involve two main aspects. First, we are exploring additional monitoring topics, such as nova bursts, and conducting discussions on full-sky blind searches. Second, we are focusing on enhancing our processes to minimize processing time.

Acknowledgments

This work is supported in China by NSFC grant No. 12393853, the Department of Science and Technology of Sichuan Province, China with grant No. 24NSFSC0449, and NSFC grant No. U2031205. The authors particularly thank Professor H.B. Hu and Professor Z.G. Yao for helpful discussions and suggestions.

ORCID iDs

G. M. Xiang https://orcid.org/0000-0002-6911-5119

M. Zha https://orcid.org/0000-0003-0343-5571

J. N. Zhou

Y. Xing

References

Abdollahi, S., Ackermann, M., Ajello, M., et al. 2017, ApJ, 846, 34

Aharonian, F., An, Q., Axikegu, et al. 2021, ChPhC, 45, 085002

Ajello, M., Atwood, W. B., Axelsson, M., et al. 2021, ApJS, 256, 12

Ajello, M., Atwood, W. B., Baldini, L., et al. 2017, ApJS, 232, 18

Bartoli, B., Bernardini, P., Bi, X. J., et al. 2011, NIMPA, 659, 428

Biller, S. D., Breslin, A. C., Buckley, J., et al. 1999, PhRvL, 83, 2108

Buson, S. 2024, ATel, 16456, 1

Cao, Z., Aharonian, F., An, Q., et al. 2024, ApJS, 271, 25

Dwek, E., & Krennrich, F. 2013, APh, 43, 112

Fleysher, R., Fleysher, L., Nemethy, P., Mincer, A. I., & Haines, T. J. 2004, ApJ, 603, 355

Furniss, A. 2024, ATel, 16535, 1

Ghisellini, G., Celotti, A., Fossati, G., Maraschi, L., & Comastri, A. 1998, MNRAS, 301, 451

Górski, K. M., Hivon, E., Banday, A. J., et al. 2005, ApJ, 622, 759

Kapanadze, B. 2024, ATel, 16449, 1

Li, T. P., & Ma, Y. Q. 1983, ApJ, 272, 317

Neronov, A., & Semikoz, D. V. 2007, JETPL, 85, 473

Stecker, F. W., de Jager, O. C., & Salamon, M. H. 1992, ApJL, 390, L49

Thwaites, J., Blaufuss, E., Santander, M., & Vandenbroucke, J. 2024, ATel, 16462, 1

Wakely, S. P., & Horan, D. 2008, TeVCat: An online catalog for Very High Energy Gamma-Ray Astronomy, in Proc. 30th Int. Cosmic Ray Conf. 3 (Mexico City, Mexico: ICRC), 1341

Wilks, S. S. 1938, The Annals of Mathematical Statistics, 9, 60

Xiang, G., Zha, M., Yao, Z., Zhou, J., & Xing, Y. 2024a, ATel, 16513, 1

Xiang, G., Zha, M., Yao, Z., Zhou, J., & Xing, Y. 2024b, ATel, 16437, 1

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.