Rapid and Precise Localization of Celestial Gamma-Ray Sources: Experimental Study Postprint

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Abstract

In the high-energy electromagnetic band, astronomical detectors exhibit relatively low angular resolution. When confronted with large volumes of gamma-ray observational data, researchers must utilize data analysis software to rapidly identify positions of unknown celestial objects. This work presents a detailed study on the rapid and precise localization of gamma-ray bursts (Gamma-ray Burst, GRB) using high-energy gamma-ray data (greater than 100 megaelectronvolts, >100 MeV) from the Fermi Gamma-ray Space Telescope (Fermi), launched and operated since 2008, focusing primarily on the influence of different time and energy selections on the detection confidence level of celestial sources. The results demonstrate that selecting the time interval from the gamma-ray burst trigger time zero (T__0) to T__0+1000 s effectively localizes the high-energy counterpart positions of gamma-ray bursts. The optimal position derived from the high-energy gamma-ray TS localization map shows excellent consistency with follow-up observational positions in low-energy electromagnetic bands, indicating that the experimental algorithm can effectively calculate the true positions of such celestial gamma-ray transient sources.

Full Text

Experimental Research on Fast and Precise Localization of Astrophysical Gamma-Ray Sources

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Abstract

In the high-energy electromagnetic bands, astrophysical detectors suffer from poor angular resolution. When confronted with large volumes of gamma-ray observational data, researchers require data analysis software to rapidly identify the positions of unknown celestial sources. Using high-energy gamma-ray data (greater than 100 MeV) from the international Fermi Gamma-ray Space Telescope (), launched in 2008, we conducted a detailed study on the fast and precise localization of gamma-ray bursts (), focusing primarily on how different temporal and energy selections affect the detection significance of astrophysical sources. The results demonstrate that selecting a time range from the GRB trigger time zero point () to within 100 seconds can effectively localize the high-energy counterpart positions of gamma-ray bursts. The optimal positions derived from the high-energy gamma-ray TS maps show excellent agreement with follow-up observation positions in lower-energy electromagnetic bands, indicating that the experimental algorithm can effectively calculate the true positions of this class of astrophysical gamma-ray transient sources.

Keywords: gamma-ray sources; high-energy astrophysical satellite; detection significance

In recent years, surveys of the high-energy gamma-ray sky have become an important tool in astronomical research, as gamma rays can reveal various high-energy physical processes such as cosmic ray particle acceleration and radiation, and dark matter interactions [1]. Studying the gamma-ray spectral characteristics of astrophysical sources can verify whether certain high-energy physical processes dominate, such as the bump spectral feature peaking at 67.5 MeV formed by neutral pion decay [2]. On one hand, gamma-ray surveys can conduct targeted observations (Target of Observation) of sources already detected in other wavebands, such as the optical/infrared catalogs from the Hubble Space Telescope, the Sloan Digital Sky Survey (SDSS), and the Parkes Radio Telescope 64m radio survey [3], with the observational data further constraining the physical and chemical properties of target sources. On the other hand, high-energy gamma-ray detectors can be triggered by intense astrophysical gamma-ray transients. For example, gamma-ray bursts have emission timescales in the MeV band that are typically longer than those in the GeV band (usually not exceeding 100 seconds), and may still be observed thousands of seconds after the burst trigger [4-5]. Therefore, detectors can be applied to investigate the radiation mechanisms of such astrophysical gamma-ray transient sources. With the development of astronomical observations in China, particularly the launches of the Dark Matter Particle Explorer (DAMPE, “Wukong”) and the Hard X-ray Modulation Telescope (HXMT, “Insight”) [6-7], whose scientific goals focus on searching for multi-wavelength radiation from unknown sources and thereby explaining extremely high-energy physical processes that are difficult to realize in laboratories, rapid localization of unknown gamma-ray sources has become an effective means for real-time follow-up of these sources.

Since high-energy gamma-ray detectors have relatively poor angular resolution, mastering algorithms for precise localization of gamma-ray sources plays a crucial role in gamma-ray survey observations. This experimental research adopts the mature Fermi satellite’ s Large Area Telescope (LAT) gamma-ray survey observations as the experimental object, selects gamma-ray bursts as transient source samples, and employs (1) different time selections and (2) different central position selections to calculate TS maps of gamma-ray transient sources, ultimately obtaining optimized localizations. The resulting positions (including errors) are then compared with follow-up observations in other wavebands to adjust experimental parameters and achieve the research objectives.

1 Fermi Satellite Survey Observations and Experimental Sample Selection

The Fermi Gamma-ray Space Telescope (formerly) is an international collaborative project involving the United States, France, Italy, Japan, Sweden, and other nations. Its primary scientific objectives focus on active galactic nuclei, pulsars, gamma-ray bursts, cosmic rays, and other high-energy phenomena. The onboard Large Area Telescope (LAT) has a field of view covering 20% of the entire sky and began scientific observations on August 4, 2008, with data being released in real-time after one year. The gamma-ray observation energy ranges from 20 MeV to greater than 300 GeV. Individual incident astrophysical gamma-ray photons are recorded sequentially by the detector’ s multi-layered instrument, and the research team systematically analyzes these photon events and classifies them into categories such as the most commonly used “Source” and “Clean” photon types. According to official statistics, from August 4, 2008 to August 4, 2011, there were over 1.8×10^11 events recorded, with approximately 1.44×10^8 passing more stringent gamma-ray photon selection criteria and being released publicly. Figure 1 Figure 1: see original paper shows the gamma-ray distribution map for energies greater than 100 MeV from five years of observations. The Galactic plane region is the brightest area of gamma-ray detection, with several prominent point sources visible outside this region, such as the Large Magellanic Cloud () and the Crab Nebula ().

The experimental sample consists of 122 gamma-ray bursts observed by Fermi-LAT, covering the time period from August 4, 2008 to October 30, 2016. Figure 1(b) shows the temporal variation of photon count rates for GRB110731465 (the numerical designation follows the convention where the first six digits represent the date in yymmdd format and the last three digits distinguish different GRBs observed on the same day). As evident from the figure, within 100 seconds after the trigger time (Trigger Time,), the photon count rate exhibits a pulse-like distribution, while before T0 and after 1000 seconds, the count rate remains relatively stable. For each GRB in the experimental sample, we selected photon events with energies greater than 100 MeV detected within 1000 seconds after the trigger. Through preliminary screening, we found that 16 GRBs either had only low-energy gamma-ray photon detections below 100 MeV or had greater-than-100-MeV photon detections only at late times (after 1000 seconds). These GRBs were therefore excluded from the sample, leaving a total of 106 GRBs with high-energy gamma-ray detections.

2 Experimental Methodology Based on Fermi Science Tools

Our experiment is based on the maximum likelihood analysis using the official Fermi Science Tools. First, we calculate the test-statistic value (TS, where TS=25 corresponds to 5 confidence) for high-energy gamma-ray detections of GRBs, varying the start/end times and central positions [8]. The single-iteration data processing pipeline includes: (1) selection of photon event types, central position and radius (12°), observation time, and energy band (using the gtselect tool); (2) spacecraft position-related selections (using the gtmktime tool); (3) calculation of diffuse gamma-ray background (using the gtdiffuse tool); (4) photon exposure calculation (using the gtexposure tool); (5) maximum likelihood fitting (using the gtlike tool); and (6) confidence map calculation (using the gtfindsrc tool).

The algorithm design establishes threshold conditions for two parameters:

Time Interval Selection. For each individual GRB, all time start points (T0) are set to the GRB trigger time (T_trigger), while time end points (T1) are incremented sequentially (Δt), such as when Δt = 10s, T1 = 10s, 20s, 30s···The Δt values are 10s, 50s, and 100s respectively.

Central Position. This step involves two positions: (a) the initial position (P0), which uses the preliminary GBM localization result as P0; and (b) the position of the maximum TS value from the TS map obtained in the single-iteration processing (P1), which is then used to perform maximum likelihood fitting again to obtain the final TS maximum for that iteration.

Based on the results from the above algorithm, we plot the distribution of characteristic quantities as a function of time selection. These quantities are: (a) the localization error radius (R95); (b) the distance between the maximum TS position and positions from other observations (r); (c) the ratio of each maximum TS value to the TS at T0 (denoted as R1); and (d) the ratio of the estimated number of photons from the GRB (N_GRB) to the total observed photons (N_total) within the corresponding time interval (denoted as R2). In these plots, the algorithm automatically identifies the maximum TS value across all selections, denoted as TS_max, with the corresponding end time designated as T1_best.

Second, we select the time range from T0 to T1_best and execute the data processing pipeline once more using the position P2 (the position at T1_best) to obtain the final TS map, providing the maximum TS value (TS_max2) and its corresponding position (P3).

Finally, we compare the positions obtained from follow-up observations in other wavebands with the position P3 from the TS map and its confidence error contours to test the accuracy of the gamma-ray source localization.

3 Experimental Results and Discussion

Figure 2 [Figure 2: see original paper] displays the distribution of characteristic quantities (R95, r, R1, R2) obtained from our algorithm as a function of the selected end time (T1) for two GRBs. The blue vertical dotted line indicates the time position (T1_best) where TS is maximum (i.e., TS_max).

As can be seen from the figure, TS_max is not always located at the time of maximum T1, but rather mostly at intermediate time positions. This may be due to three reasons: (1) After a certain time, the number of observed photons no longer increases significantly; (2) After some time, the spacecraft position is affected by other factors, such as entering the South Atlantic Anomaly (SAA) or having the observation boresight too close to the Earth’s limb, resulting in excessively high Galactic background and preventing LAT from properly counting photons from that direction; and (3) Since the selected photon range is within a circle of 12° radius, photons collected after some time that are far from the initial position (P0) cause the number of photons from the GRB (N_GRB) to increase only slightly while the total photon number (N_total) increases more rapidly, making the R2 ratio smaller and consequently reducing the TS value. On the other hand, when both the localization error radius (R95) and the position distance (r) are greater than 1°, R95 should be larger than r. When both are less than 1°, since the angular resolution at 100 MeV (68% containment angle) is approximately 1°, we do not require R95 to necessarily be greater than r. Under this procedure, we obtain reasonable TS_max values and the maximum position at this time selection.

Figure 3 [Figure 3: see original paper] shows the TS maps obtained under the T1_best selection, presenting the initial position (P0), final localization position (P3), TS value, and 95% confidence error contours for the two bursts. Figure 3 demonstrates that: (a) the TS values at both burst positions exceed 25, corresponding to greater than 5 detection confidence threshold; and (b) the follow-up observation position in the optical band (UVOT) for GRB110731465 lies within the 95% confidence contour of our experimental localization P3, while the X-ray band follow-up observation position for GRB120709883 deviates slightly from within P3’ s 95% contour. However, since both r and R95 are less than 1°, and considering the angular resolution of high-energy gamma rays at 100 MeV (greater than 1°), this constitutes an effective localization.

The emission timescale of GRBs in the keV energy band, such as those observed by Fermi’ s Gamma-ray Burst Monitor (GBM) in the 8 keV–40 MeV range, typically does not exceed 100 seconds. We compared the localization precision of high-energy gamma-ray positions within the T90 duration versus under the T1_best selection. For example, for GRB110731465 with a T90 range of 0–57.6 seconds, Figure 2 shows that the TS value within T90 is 8.6, much smaller than the TS_max of 280.4 for the 0–T1_best time range. Therefore, our algorithm can accurately identify the optimal time window from multiple time intervals and automatically calibrate the gamma-ray central position to determine the maximum TS position.

We statistically analyzed the distribution of detection significance types under the T1_best selection. Generally, when TS_max $>$ 100, it indicates strong detection confidence (Strong); when 55 $<$ TS_max $<$ 100, medium confidence (Middle); when 25 $<$ TS_max $<$ 55, low confidence (Low); and when TS_max $<$ 25, no significant detection (None). The results show that % of the sample shows significant gamma-ray detection, and % shows strong gamma-ray detection.

Table 1 Distribution of TS_max of 106 GRBs with the selected end time (T1_best)

4 Experimental Summary

This paper presents an algorithm for localizing high-energy gamma-ray transient sources, primarily by examining how detection significance (TS) varies with time and investigating the effects of different end times on detection significance. The results indicate that the optimal end time typically lies between 100 seconds and 1000 seconds, which may be due to spacecraft operational status, changes in the boresight position, or the intrinsic distribution of gamma-ray photons. The experimental scheme yields significant gamma-ray detection for % of the GRB sample and strong gamma-ray detection for % of the sample. In summary, the experimental protocol can rapidly determine the positions of gamma-ray sources from observational data, and these positions can be disseminated through networks such as GCN to other space- or ground-based telescopes and detectors for effective follow-up observations, enabling multi-wavelength studies of unknown astrophysical gamma-ray sources.

This experimental algorithm can serve as an open laboratory discipline experiment with moderate computer performance requirements, making it suitable for teaching and scientific research in institutions with graduate programs in astronomy or high-energy physics. In the servers of various astronomical institutions, teachers and students can apply this algorithm as a code package for precise localization of other celestial objects or systems [9-10].

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