Research in Astronomy and Astrophysics, 24:104001 (10pp), 2024 October https://doi.org/10.1088/1674-4527/ad683a
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The Design of GECAM Scientific Ground Segment

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Received 2022 April 22; revised 2022 September 28; accepted 2022 October 7; published 2024 September 4

Abstract

The Gravitational wave burst high-energy Electromagnetic Counterpart All-sky Monitor (GECAM) is a dedicated mission for monitoring high-energy transients. Here we report the design of the GECAM Scientific Ground Segment (GSGS) in terms of the scientific requirements, including the architecture, the external interfaces, the main function, and workflow. Judging from the analysis and verification results during the commissioning phase, the GSGS functions well and is able to monitor the status of the payloads, adjust the parameters, develop the scientific observation plans, generate the scientific data products, analyze the data, etc. Thus, the on-orbit operation and scientific researches of GECAM are guaranteed.

Key words: gravitational waves – gamma-rays: general – telescopes

1. Introduction

The concept of the Gravitational wave burst high-energy Electromagnetic Counterpart All-sky Monitor (GECAM) mission was first proposed in 2016 March, shortly after the Laser Interferometer Gravitational-Wave Observatory (LIGO) announced the discovery of gravitational waves (GWs, Abbott et al. 2016). In 2017, a binary neutron star coalescence candidate (designated GW170817) was observed through GWs with multi-messenger observations (LIGO Scientific Collaboration et al. 2017). In 2018 December, the GECAM mission was officially established as a project of the Strategic Priority Research Program of Chinese Academy of Sciences. The main scientific purpose is to monitor the Gamma-Ray Bursts (GRBs) coincident with GW events, fast radio burst events, magnetars or other bursts with all-sky and all-time coverage (Lu et al. 2020; Huang et al. 2020; Lin et al. 2020; Su et al. 2020; Wang et al. 2020; Yu et al. 2020). The GECAM mission consists of two micro-satellites (GECAM-A and GECAM-B), each comprised of 25 Gamma-ray Detectors (GRDs) and 8 Charged Particle Detectors (CPDs), operating on the same orbit with opposite phases (Han et al. 2020; Li et al. 2020). As illustrated in Figure 1, all the sky can be monitored with GECAM-A and GECAM-B. The BeiDou short message service provided by the BeiDou Navigation System was adopted in the GECAM mission. Once an event is triggered onboard, the key information of this event, such as the trigger time, the source location, the trigger detectors, the detection significance, the light curves and the energy spectrum, will be downlinked to the ground within several minutes via BeiDou short message.

Each GECAM satellite features 25 GRDs (round) and 8 CPDs (square) arranged on the hemispheric cupola of the satellite dome (Li et al. 2020, 2022), as diagrammed in Figure 1. The GRD module consists of a LaBr3:Ce scintillator and an SiPM array for detecting the gamma-ray photons in the energy range from 5 keV to 5 MeV (An et al. 2022; Liu et al. 2022; Zhang et al. 2022b, 2022c). The CPD module consists of a plastic scintillator and a SiPM array that detects charged particles of energies from 300 keV to 5 MeV (Zhang et al. 2022a; Xu et al. 2022). The trigger and localization of the burst can be performed onboard. Once triggered, the locations of events such as GRBs can be calculated onboard by analyzing the data of the multiple GRDs on the satellite (Liao et al. 2020). Meanwhile, the charged particle burst events can be distinguished by jointly analyzing the GRD and CPD data.

The GECAM mission consists of six main segments: the satellite segment, the rocket segment, the launch segment, the telemetry, tracking and control segment (TT&C), the Space

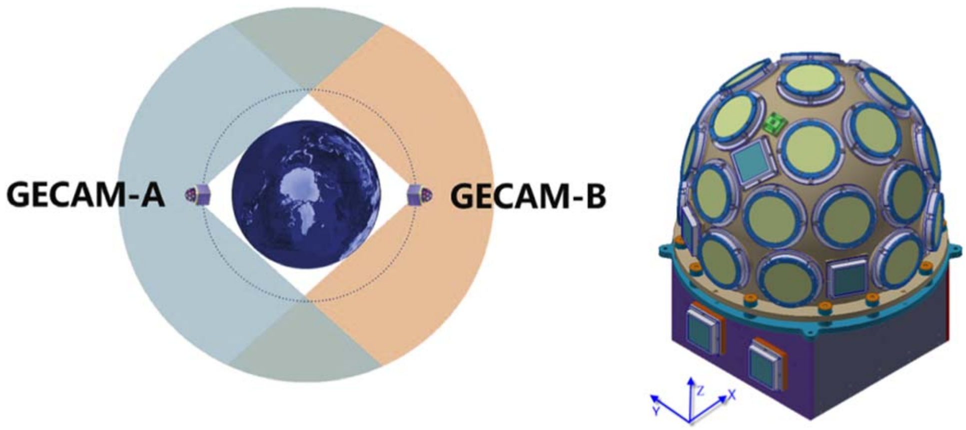

Figure 1. Diagram of the GECAM mission and the payload. Due to obscuration by the Earth, only 70% of the sky can be monitored by one satellite. With two satellites running in opposite phases on the same orbit, all the sky can be monitored.

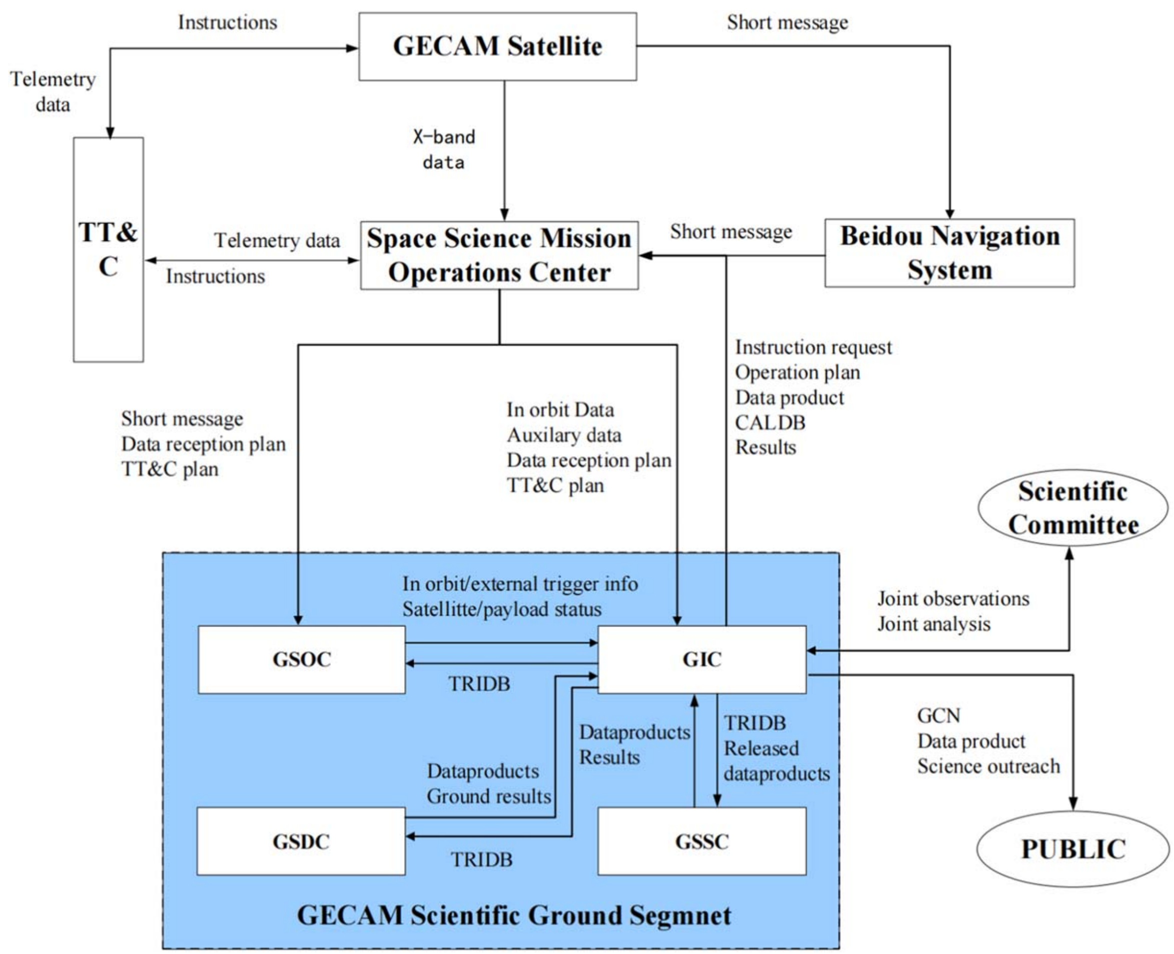

Figure 2. Overall flow chart of the GECAM mission.

science Mission Operations Center (SMOC), and the GECAM Scientific Ground Segment (GSGS). The overall flow chart of the GECAM mission is depicted in Figure 2. There are three links between the space segment and the ground segment.

1. *S*-band: The telemetry data are downloaded by the TT&C with the China Satellite Monitoring and Control Network that comprises several TT&C stations. The instruction requests and operation plans of the payload proposed by GSGS are also uplinked via *S*-band.
2. *X*-band: The SMOC downloads the observation data via three ground stations (in Beijing, Kashi and Sanya, respectively) and sends to GSGS after pre-processed (Ma et al. 2022). Thereafter, these data are processed into the standard scientific data products and released to the public by GSGS.
3. Short message link: Once triggered onboard, the messages are downloaded to the ground with the BeiDou Navigation System, processed offline and released to the public by GSGS via the Gamma-ray Coordinates Network (GCN) and other services immediately.

The scientific ground segment is an important part of the overall mission, which provides a platform to guarantee the efficient operation of satellites, an essential link between the science and the data, a window to the scientific community and science users as other missions like Insight-HXMT, ASO-S and XRISM (Jia et al. 2018; Huang et al. 2019; Loewenstein et al. 2020). For the GECAM mission in particular, in order to fulfill its core scientific objectives and guide follow-up observations for trigger events that occur randomly in space and time, GSGS must achieve the goal of "Rapid response, Rapid processing, Accurate positioning, and Rapid release of the trigger information." In other words, GSGS needs to search, locate, classify, and validate all types of trigger events as soon as possible. In this paper, the overview of GSGS tasks and functionality is described in Section 2. The scientific production definition and processing, the data release and user support, the on-orbit performance, and the summary are presented in Sections 3, 4, 5, and 6 respectively.

2. GSGS Tasks and Functionality

2.1. Overview

The main tasks of GSGS can be summarized as follows:

1. Make the schedule for scientific operation;
2. Monitor the payload status and performance to ensure the safe and effective operation;
3. Perform the on-orbit calibration and produce the response effects of the detectors;
4. Produce, archive, and release the data product;
5. Provide a quick look of the observations;
6. Search, localize, and classify the triggers on the ground.
7. Science user support.

Based on the tasks mentioned above, GSGS is further divided into four parts, namely the GSGS Interaction Center (GIC), the GECAM Science Operation Center (GSOC), the GECAM Science Data Center (GSDC), and the GECAM Science Support Center (GSSC) as shown in Figure 2. The main functions are as follows:

GIC: responsible for the overall system, which includes: organizing the general system workflow and establishing the interface with external systems; building the workplace, computing resources, and network environment required for the operation of the system; building the trigger/burst database (TRIDB) and information interaction platform, which collects, collates and distributes all the related trigger information in the system; coordinating the joint observations and joint analysis with other projects; and carrying out science outreach work.

GSOC: responsible for the science operation of the mission, which includes: carrying out on-orbit monitoring of instruments to determine and adjust operating parameters or update software; making the on-orbit operation plans, and building the Burst Alert System (BAS) for rapid response to a burst.

GSDC: responsible for processing and management of the scientific data, which includes: building the product database, producing and archiving the scientific data product; searching the trigger offline, processing all the triggers as soon as possible including re-positioning, re-classifying and giving a quick-look result.

GSSC: responsible for the science support, which includes: carrying out scientific simulations in order to support the on-orbit operations and calibrations; building a calibration database (CALDB) and follow-up the on-orbit update; developing data analysis software and providing scientific user support; developing a burst alert (BA) system to process the scientific result with manual on-call handling; and the establishing GECAM homepage to release the data products, software and notice, etc.

GIC, the GSGS center, retrieves almost all the data from SMOC, distributes data, and shares information between different centers via TRIDB, archives the data product, CALDB, scientific results, and proposes the instruction request and operation plan to the SMOC. In addition, all the scientific data products will be released to the public.

2.2. Observation Monitoring

Due to the influence of the space environment and the operating temperature, the counting rate level and payload performance on-orbit are different from those on the ground. In order to ensure the stable operation of the instrument, the payload is monitored comprehensively at different levels with different data:

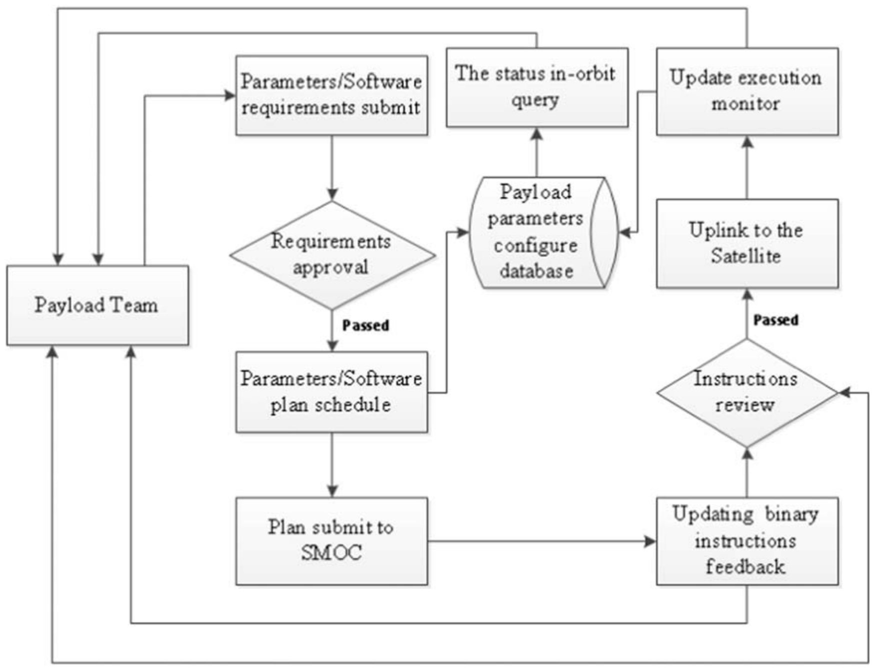

Figure 3. The processing flow of the payload operation plan.

(1) The total satellite level monitoring: using the data transmitted via the *S*-band to monitor the total working condition of the satellite and payload.

(2) Payload operating status monitoring: using the engineering data transmitted via the *X*-band, such as current, voltage, temperature, and other parameters, to determine the payload working status and quickly respond to abnormalities.

(3) Payload performance monitoring: using the scientific data transmitted via the *X*-band to produce the energy spectrum and light curve of each detector, to conduct comprehensive analysis and evaluation of the payload performance, and to check abnormalities by combining engineering data if necessary. (Zhang et al. 2022d).

(4) Data analysis monitoring: performing detailed scientific data analysis to check whether the detector performance variation trend is abnormal or not, and to determine the update of the calibration database, such as energy response and detection efficiency.

2.3. Observation Planning

There are two types of observation plans, namely payload operation plan and scientific observation plan.

The payload operation plan includes the scheduling of operating instructions for switching on/off of payload, switching main/backup modes, adjusting operation parameters, and updating software. The processing flow is illustrated in Figure 3. When an update requirement for payload parameter, payload software, or payload control command is submitted by the payload team, the following feasibility evaluation is carried out. Once approved, the GSOC will schedule the payload operation plan, then the SMOC will translate it into a binary command. After being confirmed with the payload team, the binary command is transmitted to TT&C, uplinked to the satellite, and executed. By monitoring the command counts with the telemetry data, we can check whether the command is received and executed correctly.

The scientific observation plan is made to maintain maximum observation efficiency. As affirmed in Figure 4, the effective area is axisymmetrically distributed, while the largest area is in the direction of 30° from the payload optical axis. Hence, the target should be adjusted to 30°, or as close to 30° as possible. In addition, since the target will be obscured by the Earth periodically when the satellite is in the obscured area or SAA area (where the background is relatively high), the payload can be scheduled to turn off bias or shutdown to save energy.

3. Data Processing

3.1. The Data Products of GECAM and Pipeline Processing

The GECAM data are divided into several classes based on the product level, such as raw data, and L0, L1, L2, and L3 data. The raw data and L0 data are produced by SMOC, and the L1, L2 and L3 data are produced by GSGS with pipeline as drawn in Figure 5.

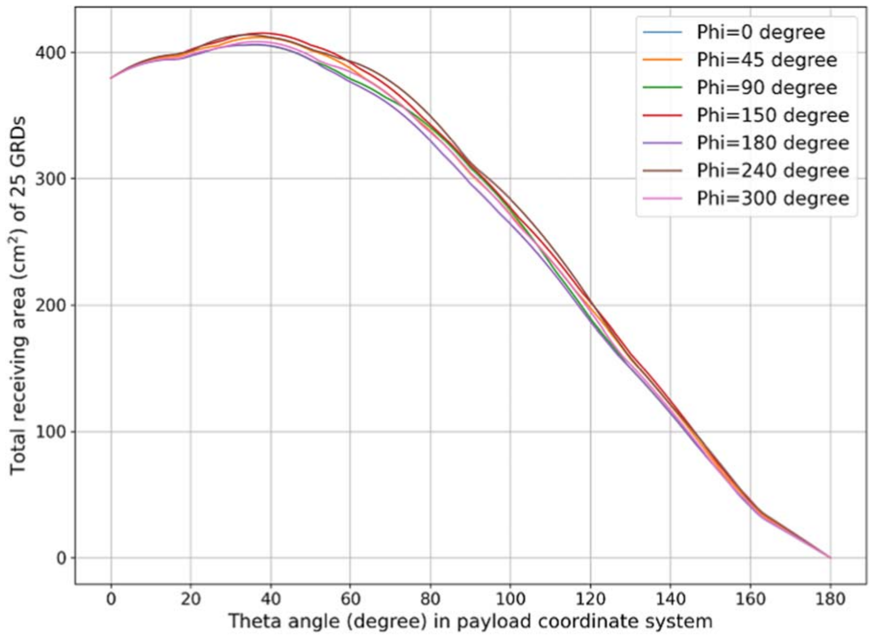

Figure 4. The effective area distribution in the field of view of the payload.

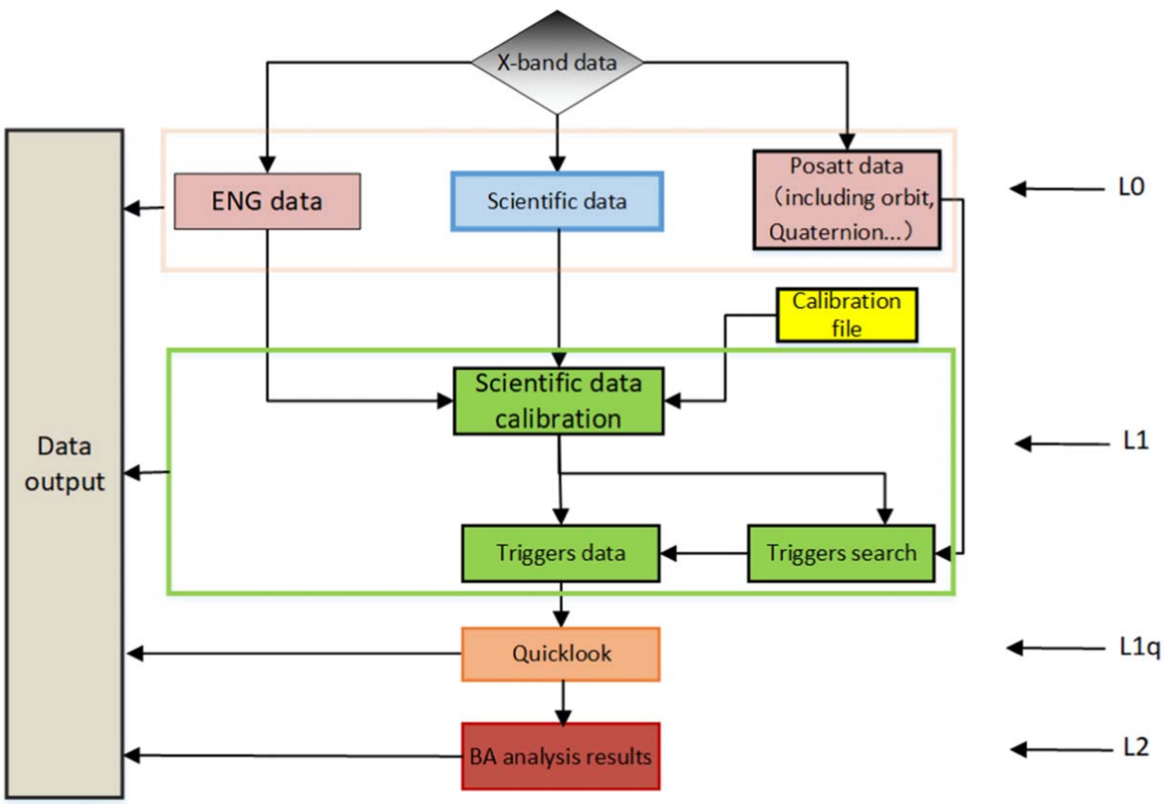

Figure 5. The GECAM data processing pipeline.

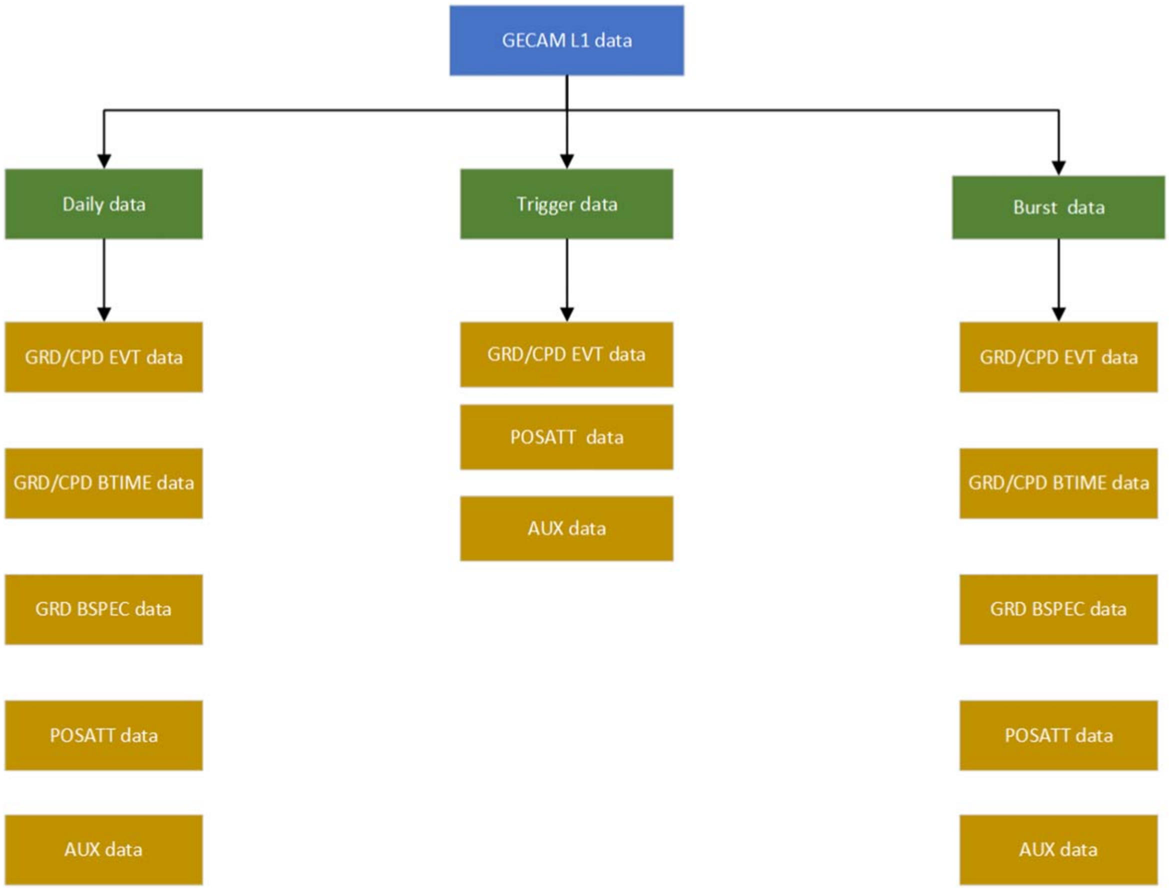

Figure 6. The structure of the GECAM L1 data products.

1. raw data: source data downlinked from the satellite.
2. L0 data: un-calibrated data parsed from the raw data.
3. L1 data: calibrated data produced automatically by pipeline from the L0 data, including data decomposition, E−C transition, etc. The L1 data are organized into three categories: daily data, trigger data, and burst data as illustrated in Figure 6.
4. L1q data: quick-look results of trigger/burst data, including:
   (a) the light curves generated by the combinations of different detectors, time bins, and energy bands;
   (b) the energy spectrum of the trigger/burst;
   (c) the fitted background spectrum;
   (d) the location;
   (e) the duration, such as T90 and T50.
5. L2 data: similar to L1q, while produced by manually setting parameters in background removal and spectrum fitting processes.
6. L3 data: the catalogs, such as the GRB catalog, GW GRB catalog, neutrino GRB catalog, FRB catalog, and kilonova catalog.

3.2. Calibration Database

The GECAM calibration database (CALDB) is constructed following the standard of NASA's High Energy Astrophysics Science Archive Reasearch Center (HEASARC). It includes response matrices by Monte Carlo simulations, the definition of PI, the on-orbit energy-channel convention, the on-orbit energy resolution, and the on-orbit look-up-table for the binned data. The CALDB files are stored as FITS format files for flexibility and compatibility across different platforms, and the metadata are stored in CALDB index files which can be used by the standard CALDB software.

The energy-channel relationship and the resolution of CALDB files are generated every month based on the average detector status. The on-orbit look-up-table and PI definition of CALDB files update occasionally based on the scientific requirements. The energy-channel relationship and the resolution of all detectors have been simulated and calibrated on-ground under room temperature (Guo et al. 2020). However, the gain of the SiPM arrays in the detectors varies with temperature. Thus they will be re-calibrated on-orbit where the temperature varies between −20°C and 20°C. The calibration

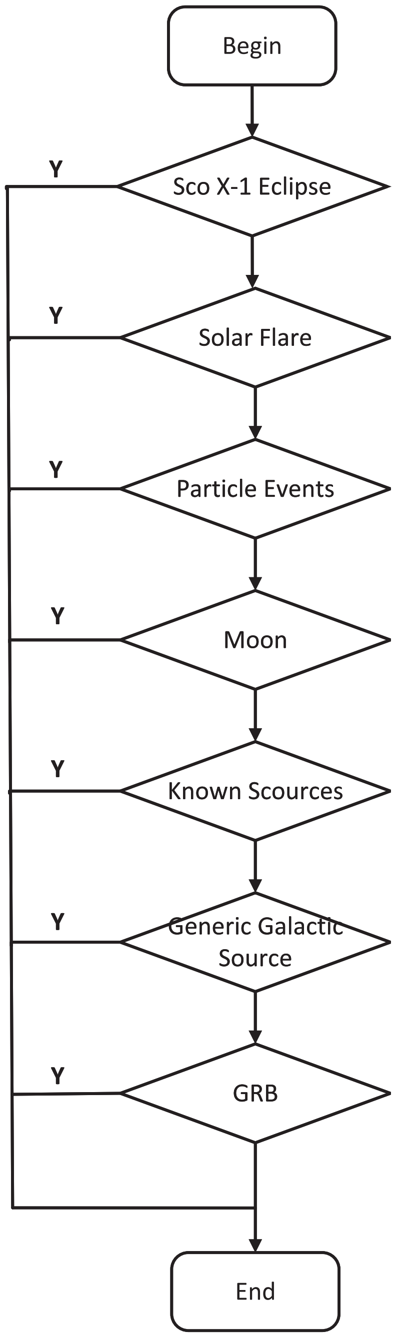

Figure 7. Schematic diagram of ground classification.

pipeline monitors the status of all the detectors every one hour, and the detector gain is calculated by comparing the on-orbit signal amplitudes of lines in the background spectrum (37.4 keV, 85.8 keV, 511 keV, and 1470 keV) to the on-ground results (Guo et al. 2020). The detector resolution is calculated from the offset of the four spectral lines and the deviation of the signal baseline.

3.3. Trigger Search and Classifaction

As mentioned above, the trigger and localization of the burst is performed onboard GECAM. Meanwhile, triggers will be searched from the scientific data on the ground, which is an important supplement to the onboard trigger. Applying more computing resources and complex algorithms on the ground increases the possibility of discovering new trigger/burst events. There are two types of search options: (1) the blind search: deep search at different timescales, different starting phases, and different energy bands with a more detailed space grid and new search algorithm. (2) target search: once we acquire the burst information from other satellites or instruments, the target search will be carried out with the known information, such as trigger time, location, classification, etc. When a new trigger/burst event is found, the trigger/burst data within the specified time duration will be cut from the daily data file according to the mission requirements, and new trigger/burst data products will then be generated. If a trigger is also detected by other satellites, a novel cross-correlation method will be applied to enhance the precision of localization (Xiao et al. 2021). If no trigger is found, an upper limit on the fluency will be given.

The algorithm of the trigger/burst search is as follows:

1. the templates are established considering the burst times, locations, and different energy spectra of the burst sources;
2. a likelihood function is constructed using the observation data and the instrument response with multiple energy band (25 detectors $\times$ 8 energy channels) observations taken into consideration;
3. the likelihood ratio is obtained between the observation measured under the assumption of the real signal and the observation assuming only the background exists;
4. Once the likelihood ratio exceeds the threshold, it is recognized as a trigger/burst signal.

The classification of a trigger is estimated onboard GECAM. To further improve the classification accuracy, a ground-based selection procedure is developed with input parameters such as trigger time, satellite position, further optimized ground localization, hardness ratio, Mcllwain-L, burst duration, etc. As is diagrammed in Figure 7, the characteristics of the trigger event are analyzed one by one, such as particle events, solar flares, magnetars, eclipses, known sources, etc. If the selection criteria for these events could not be met, the event is then considered to be a GRB.

In addition to the automatic pipeline mentioned above, we have also established a manual processing method, i.e., BA on duty. The main responsibility of the BA is to distinguish different events from different triggers. Software is developed for GECAM BA, which monitors the internal triggers

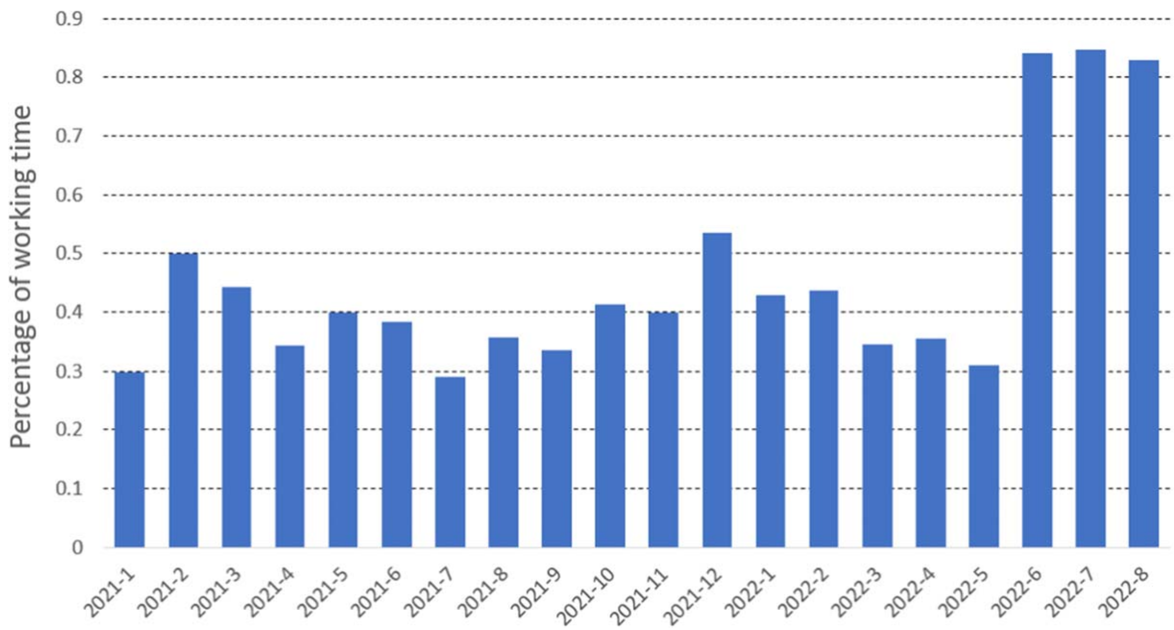

Figure 8. The percentage of working time of GECAM-B.

generated by GECAM and external triggers fetched from outside such as Gamma-ray Coordinates Network/Transient Astronomy Network (GCN/TAN) notice. The gold criterion is to find correlated triggers which have similar trigger time and localization, since the probability of two different instruments generating the same error trigger is negligible. Among the non-correlated triggers, the internal triggers generated by GECAM are reviewed by BA in detail. BA goes through the quick-look results, such as the light curve and the trigger localization, to identify the type of trigger.

3.4. BeiDou Short Message Processing

The GECAM In-Flight Realtime Trigger and Localization Software continuously monitors the detector background count rates for the occurrence of a significant increase in different energy ranges and timescales to detect GRBs and other transients (Zhao et al. 2024). When a trigger occurs, the trigger alert data, i.e., trigger time, burst spectrum, onboard localization, and classification, are downlinked to the ground in real-time via BeiDou short messages within 1 minute (Li et al. 2021). The other alert data include the light curve of each GRD which extends from ∼50 s before the trigger to ∼200 s after the trigger, while the light curve is provided on timescales ranging from 50 ms to 50 s, with shorter timescales concentrated around the trigger time. The light curve data will be downlinked to the ground in about 10 minutes. A pipeline of the localization and classification is done automatically on the ground with better accuracy by using a finer angular grid and accounts for differences in burst spectra. A detailed description of the auto-ground localization algorithm is described in Y. Huang et al. (2024). Users worldwide are informed within seconds of the flight and ground localization.

4. Science User Support

According to the data policy of the GECAM mission, all the scientific data from GECAM will be released to the public immediately, except for the event files, which will be released in less than one year. A dedicated GECAM website (gecam.ihep.ac.cn) allows users to browse, retrieve, download scientific data products and analyze the products with GECAM software (Song et al. 2020). Besides, the website also provides useful information and user support, such as the latest mission information and observation results, the latest data products, and update of the software tools. The users can also get support and help from the FAQ section.

In addition, considering that the GECAM mission will play a key role in transient monitoring and research, we provide the following additional features: (1) Trigger/burst event homepage. It will show the main and key information for each trigger/burst with figures and tables, including the trigger time, positioning information, short message processing results—light curve and energy spectrum, satellite position, and also the solar GOES optical variation and geomagnetic activity information (2) DATAVIEW tools. It will give a quick look of the light curves with different time durations or time resolutions.

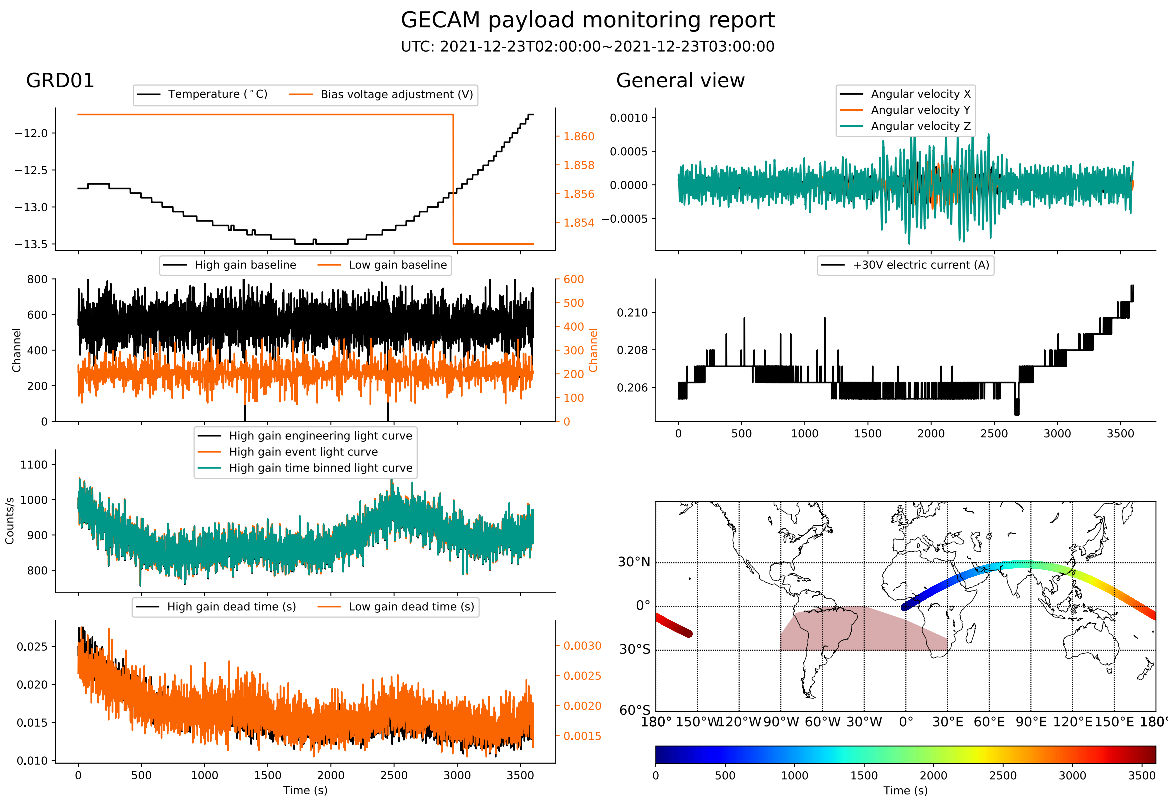

Figure 9. The payload performance monitoring of GECAM.

5. On-orbit Performance

GECAM was successfully launched aboard a Long March 11 on 2020 December 10 (UTC-8), and finished the commissioning phase in 2022 February. Now it has started the routine phase. After launch, some power problems on the GECAM satellites occurred. Thereafter, only GECAM-B began scientific observations partially, and no more in the anti-geocentric pointing. Fortunately, the power failure of GECAM-B was recovered so that it works continuously except in the South Atlantic Anomaly (SAA) area with anti-geocentric pointing as designed. The working time percentage increased from approximately 40% to more than 80% since 2022 June, as demonstrated in Figure 8.

So far, the satellite has been tested on-orbit for more than one year. Up to 2022 August 31, 1485 onboard triggers were transmitted to the ground by BeiDou short message, in which more than 100 interesting bursts were obtained and most of them have been published on the GCN. The payload status and performance have been monitored and all the instruments work well. Figure 9 shows some payload monitoring results of GECAM, including the temperature, the channel of the baseline, the light curve, dead time, and so on.

6. Summary

The GECAM satellites were launched successfully and the commissioning phase has been completed. The main tasks of the GSGS, including the science operation, the data processing, and the data distribution, are progressing well, judging from the on-orbit analysis and verification results. The high-quality data products, the important trigger information, together with the analytical tool will released to the public soon, which we hope will play an important role in the research on the high-energy transients.

Acknowledgments

This work is supported by the National Key R&D Program of China (2022YFF0711404, 2021YFA0718500), International Partnership Program of Chinese Academy of Sciences (grant No.113111KYSB20190020), the National Natural Science Foundation of China (NSFC, Grant No. U1938106) and the open subject of the National HEP Data Center (E029S2S1). We thank support from the Strategic Priority Research Program on Space Science, the Chinese Academy of Sciences (grant Nos. XDA15360102, XDA15360300, XDA15052700 and E02212A02S).

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