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Design and Implementation of Autonomous Detection Management for Dark Matter Particle Explorer Payload: Postprint

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Abstract

The payload of the dark matter particle detection satellite possesses multiple operating modes, necessitating continuous switching between these modes during in-orbit detection to achieve optimal detector performance. Each mode transition requires the configuration of numerous operational state parameters across the payload' s 28 electronic front-end circuits, neutron acquisition and processing circuits, trigger system circuits, high-voltage power supply chassis, and payload data management unit. To effectively conduct dark matter particle detection, enhance the flexibility of payload detection mode transitions, and reduce the complexity of parameter configuration during mode switching, this paper investigates the in-orbit autonomous detection management of the dark matter particle detection satellite payload. The operational modes of the detector payload are analyzed, and the design and software implementation of an event-driven autonomous detection scheme are presented, which integrates ground-based planning experts with on-board autonomous detection execution mechanisms. Additionally, reliability measures within the autonomous detection framework are analyzed, enabling all-weather, continuous, and agile detection capabilities for the detector while reducing dependence on ground remote command injection.

Full Text

Design and Implementation of Autonomous Detection Management for the DAMPE Satellite Payload

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Abstract: The Dark Matter Particle Explorer (DAMPE) satellite payload features multiple operating modes that must be continuously switched during on-orbit operations to maintain optimal detector performance. Each mode transition requires configuring numerous operational parameters across 28 front-end electronics (FEE) circuits, neutron acquisition and processing circuits, trigger system circuits, high-voltage power supply units, and the payload data management system. To effectively conduct dark matter particle detection, enhance the flexibility of payload mode transitions, and reduce the complexity of parameter configuration during mode switching, this paper investigates the on-orbit autonomous detection management of the DAMPE satellite payload. The analysis of detector payload operating modes is presented, along with the design and software implementation of an event-driven autonomous detection scheme that combines ground-based planning experts with on-board autonomous execution units. Reliability measures for autonomous detection are also analyzed, enabling round-the-clock, full-coverage agile detection capabilities while reducing dependence on ground command injection.

Keywords: DAMPE, Payload, Autonomous detection management

The Dark Matter Particle Explorer (DAMPE) satellite is one of the first batch of scientific satellite projects under China’ s strategic space science pilot program, independently developed and launched by China. Its mission is to search for evidence of dark matter particles by observing high-energy particles (including positrons) and gamma-ray energy spectra from space, while also conducting research on cosmic ray origins and space astronomy.

The DAMPE satellite payload consists of six components: a silicon array detector, a plastic scintillator array detector, a BGO calorimeter, a neutron detector, high-voltage power supply units, and the payload data management system. The silicon array detector uses eight FEE circuits for scientific data acquisition, processing, and configuration; the plastic scintillator array detector uses four FEE circuits; the BGO calorimeter uses 16 FEE circuits; and the neutron detector uses a dedicated neutron acquisition and processing board. The high-voltage power supply units provide the required high voltage for the FEE circuits of the plastic scintillator and BGO detectors (the silicon detector can generate its required high voltage internally). These four detector types work collaboratively to accomplish scientific detection tasks, with the acquired scientific data ultimately packaged by the payload data management system and transmitted to the satellite platform for downlink to ground stations. The payload data management system is responsible for overall power management, detection task management, scientific data management, and system monitoring for the entire payload system.

During on-orbit operations, the payload must be switched between different operating modes based on varying detection requirements. Mode transitions are accomplished by executing a series of command sequences that configure parameters for each detector’ s front-end electronics circuits. This configuration process is complex and entails significant time overhead. Moreover, the satellite often needs to conduct observations outside ground station coverage areas, where command injection is either impractical or impossible. To ensure that the payload can complete detection tasks in non-coverage areas or with limited telemetry/control time, reduce ground command injection workload, and obtain optimal detection results, the payload must possess on-orbit autonomous detection management capabilities—a trend toward intelligent and agile spacecraft development [1~3].

This paper investigates the autonomous detection management of the DAMPE satellite payload, presenting both the management scheme and its software implementation. Additionally, reliability measures for autonomous detection management are analyzed.

1.1 Payload Operating Modes

The payload operates in five primary detection modes during on-orbit observations: Baseline Calibration Mode (Silicon Raw Data), Baseline Calibration Mode (Silicon Baseline Update), Electronics Linear Calibration Mode, MIPS Signal Calibration Mode, and Observation Mode.

Baseline Calibration Mode (Silicon Raw Data): The silicon array detector is configured to raw data transmission mode, directly downlinking raw baseline detection data for ground-based calculation of baseline and noise values. The trigger system generates trigger signals at a frequency greater than 200 Hz to complete payload baseline calibration, requiring 70 seconds.

Baseline Calibration Mode (Silicon Baseline Update): The silicon array detector operates in baseline update mode, autonomously calculating baseline values on-orbit. The trigger system generates trigger signals at 50 Hz to complete baseline calibration, requiring 30 seconds.

Electronics Linear Calibration Mode: This mode includes 20 digital-to-analog converter (DAC) settings. In addition to managing common operational parameters for each detector, each DAC value requires specific parameter configuration before detection. The trigger system generates trigger signals at 20 Hz, with each DAC value requiring 70 seconds of detection time.

MIPS Signal Calibration Mode: Also known as detector precision calibration, this mode utilizes hit information from the BGO calorimeter to generate trigger signals.

Observation Mode: The standard acquisition mode for scientific detection, enabling analysis of detected scientific data to provide evidence for dark matter particle existence.

Additionally, when the satellite passes through the South Atlantic Anomaly (SAA), high voltage may be reduced to protect the detectors, with restoration required after exiting the anomaly. During high-voltage reduction periods, detectors cease observation. These two states are defined as High-Voltage Reduction Protection Mode and High-Voltage Restoration Mode, which together with the five detection modes constitute the generalized payload operating modes.

During on-orbit operations, detectors must continuously switch between modes to maintain optimal performance. Each mode transition requires executing command sequences to configure multiple operational states across 28 FEE circuits, the neutron acquisition and processing circuit, trigger system circuits, high-voltage power supply units, and the payload data management system. Statistical information on the number of commands and configuration parameters for each mode is shown in .

1.2 Event-Driven Mode Transition

Payload autonomous detection mode transitions are implemented using an event-driven approach based on operating mode events. The seven modes in the generalized payload operating mode set constitute event content, with each detection requirement forming an event table. The event table is sized according to maximum weekly detection requirements. The on-board autonomous execution unit queries the event table during idle periods. When the on-board system time matches a time specified in the event table, the corresponding mode management process is executed autonomously according to the event identifier, and the event is cleared from the table. As shown in the event table format, each event occupies 8 bytes.

The autonomous detection management system comprises planning experts, ground systems, ground intelligent execution units, space-ground links, spacecraft hardware, and on-board payload autonomous detection execution units. [Figure 1: see original paper] illustrates the control structure of payload autonomous detection management.

The entire autonomous detection system is an event-driven architecture that organically integrates planning experts and on-board autonomous execution units. Planning experts (including scientific application specialists, telemetry/control specialists, and operations control specialists) are responsible for overall scientific mission planning and scheduling—an essential component for autonomous payload detection. Based on detection tasks, planning experts determine constraints for each detector and formulate high-level weekly detection plans by incorporating ground-processed detection results. These high-level plans are further decomposed by ground intelligent execution units to generate detailed uplink data blocks (event tables) and control commands. These data blocks and commands are transmitted via space-ground links to the on-board payload autonomous detection execution unit, which completes autonomous detection management tasks, performs result identification and fault handling to minimize mission losses. The on-board unit returns identified detection results and system status parameters to ground systems, providing a basis for planning experts to formulate subsequent detection plans.

1.3 Software Implementation

The software implementation of autonomous detection management is performed by the payload data management software, as this subsystem is responsible for overall payload power management, detection task management, scientific data management, and system monitoring.

Based on the control structure shown in [Figure 1: see original paper], the software architecture is divided into four components: uplink data block reception and parsing, event search and decision-making, autonomous operating mode switching, and event table management. The task flow diagram for autonomous detection management is shown in [Figure 2: see original paper].

Uplink Data Block Reception and Parsing: Uplink data blocks include event table data and parameter configuration blocks generated according to detection plans. The data block format follows the CCSDS packet telecommand standard, defined as follows: packet identifier (2 bytes), packet sequence control (2 bytes), packet length (2 bytes), and application data (variable length). The packet identifier indicates the uplink data block type. Packet sequence control includes grouping flags and packet sequence count. Packet length is variable, representing the byte count from the first to last data byte in the application data field. The application data field contains ground-injected information in even-byte format, with the final two bytes serving as a checksum for all other data in the field.

Upon receiving uplink data blocks, the payload data management software performs step-by-step parsing and verification. Blocks with illegal formats or checksum errors are discarded, while valid blocks are cached. Non-event-table injection blocks are stored in corresponding memory buffer areas for use during mode transitions. Event table injection blocks are appended to the system event table according to the 8-byte event format. The implementation must also handle repeated uploads of the same injection block, which can be managed by ensuring packet sequence counts differ between consecutive blocks.

Event Search and Decision-Making: During idle periods, the software searches the operating mode event table buffer, scanning the entire event table in each search cycle. When an event identifier matches one of the seven specified event identifiers, the event is considered valid and proceeds to decision processing. The decision logic is as follows: Let TS be the current system time and TE be the time indicated by the event table time code. (1) If TS < TE-5s, the event execution time has not arrived; the event is skipped and the search continues. (2) If TE-5s TS TE+5s, the event execution time has arrived; the event execution flag is set, the search process is terminated, and the event content is cleared. (3) If TE+5s TS, the system time has exceeded the event execution time; the event is deemed a timeout, skipped without execution, and cleared while recording a timeout event identifier.

Autonomous Operating Mode Switching: Based on event search and decision results, the software autonomously completes the command sequence for switching each detector’ s operating mode. To ensure detection data integrity, the payload trigger is disabled before executing the configuration command sequence to stop data generation. According to interface protocols between the payload data management system and each detector, the appropriate operating mode parameters are configured sequentially. After configuration completion, the trigger is re-enabled to finish the mode switch. For the two baseline calibration modes, a single configuration initiates the detection process. For electronics linear calibration mode, each calibration requires approximately 70 seconds, after which the system automatically switches to the next calibration. For MIPS signal calibration and observation modes, the spare parameters in the event table format determine whether FEE bulk configuration parameters are required. If needed, bulk parameter configuration precedes individual detector settings.

Event Table Management: Event table management includes enabling/disabling, clearing, sorting, and backup functions. Event tables can be enabled or disabled via ground indirect commands; when disabled, the software stops searching the event table and payload operation must be controlled through ground command injection. When ground experts modify detection plans, they can clear all on-board events by sending an event table clear command. To facilitate searching, events are sorted by time code in ascending order, with smaller time codes at the head of the table and larger ones at the tail. New events are inserted at positions corresponding to their time codes, and executed events are removed with remaining events shifting forward. To prevent event table loss due to payload data management computer power cycling or reset, the event table is periodically backed up (every 30 minutes) to the spacecraft management computer, from which it can be retrieved after reinitialization.

2 Reliability Design for Autonomous Detection Management

Given the unique characteristics of the DAMPE satellite, ensuring round-the-clock, full-coverage detection capability requires comprehensive reliability design in the autonomous detection management system [4-5].

2.1 South Atlantic Anomaly Handling

When the satellite passes through the South Atlantic Anomaly, high-voltage reduction settings protect the payload detectors. Since the satellite cannot autonomously determine SAA entry and exit times, planning experts and ground intelligent execution units must calculate these times in advance using orbital predictions. These are then uplinked to the on-board autonomous detection execution unit as high-voltage reduction protection mode events and high-voltage restoration mode events.

2.2 High-Voltage Power Supply Periodic Maintenance

The high-voltage power supply units provide operating voltage for photomultiplier tubes in the plastic scintillator and BGO detector FEE circuits. Due to resource constraints, these units cannot continuously store configuration information during on-orbit operations. Upon reset, a high-voltage power supply unit defaults to output level 0, causing the photomultiplier tubes it serves to cease normal operation. To minimize prolonged observation interruptions in non-coverage areas, periodic autonomous maintenance of the "operating high-voltage value" is implemented, enabling rapid recovery to normal operation after faults.

Whenever the payload data management system receives a set of high-voltage power supply configuration commands, it forwards them to the appropriate unit and simultaneously backs up the latest command parameters in memory. With periodic maintenance enabled, the current high-voltage parameters are retransmitted to the power supply unit every 60 minutes. Each maintenance command is transmitted twice to ensure reliable delivery. This maintenance is suspended during SAA passage to avoid conflicts with high-voltage protection operations, and the function can be enabled or disabled via ground command injection.

2.3 FEE Current Anomaly Monitoring

To ensure FEE operational safety, the software implements autonomous monitoring of FEE operating status. Real-time current telemetry parameters for each FEE are collected every second. If an FEE current anomaly (exceeding a specified threshold) occurs continuously for three seconds, that FEE is powered off and the monitoring result is returned via engineering telemetry. For BGO and plastic scintillator FEEs, the high-voltage power supply unit must be powered off first, followed by the FEE power supply after a 300ms interval. For silicon detector FEEs (which generate high voltage internally), only the FEE power supply needs to be switched off. Each power-off command is executed twice to ensure reliability. The FEE current anomaly monitoring function can be enabled or disabled via ground command injection. As a critical parameter, the FEE current threshold can be modified via ground injection and is stored in three copies in memory using a two-out-of-three voting redundancy design to effectively resist single-event upsets that could cause false monitoring actions.

2.4 Internal Memory EDAC Error Correction [5]

The event table and operating mode management parameters are stored in the on-board computer's internal memory. Exposure to high-energy space radiation causes single-event upsets, where a memory bit may flip from "0" to "1" or vice versa. Such data corruption directly impacts normal system operation. To address this, Error Detection and Correction (EDAC) technology is employed for memory areas, capable of detecting and correcting single-bit errors. When a data error is detected at a memory address, the corrected data is rewritten to that location.

3 Conclusion

Addressing the unique requirements of the DAMPE satellite, this paper presents the design and software implementation of payload autonomous detection management technology. The event-driven autonomous payload operating mode switching technology enables round-the-clock, full-coverage agile detection capabilities while reducing ground command injection workload. The reliability measures implemented in the software effectively ensure payload safety and the reliability of autonomous detection management.

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