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A System for Generating the Trigger Signals of the Spaceborne GAMMA-400 Telescope

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Abstract—The GAMMA-400 space project is one of the new generation of space observatories designed to search for signs of dark matter in the cosmic gamma emission, and to measure the characteristics of diffuse gamma-ray emission and gamma-rays from the Sun during periods of solar activity; gamma-ray bursts; extended and point gamma-ray sources; and electron, positron, and cosmic-ray nuclei fluxes with energies in the TeV ranges. The GAMMA-400 γ-ray telescope constitutes the core of the scientific instrumentation. The nature of the intended experiments imposes stringent requirements on the gamma telescope's system of trigger signal formation, now being developed using the state-of-the-art logic devices and fast data links. The design concept of the system is discussed, along with the chosen engineering solutions and some experimental results obtained during the operation of the system prototype using a positron beam with energies of 100–300 MeV from the PAKHRA S-25R synchrotron at the Lebedev Physical Institute.

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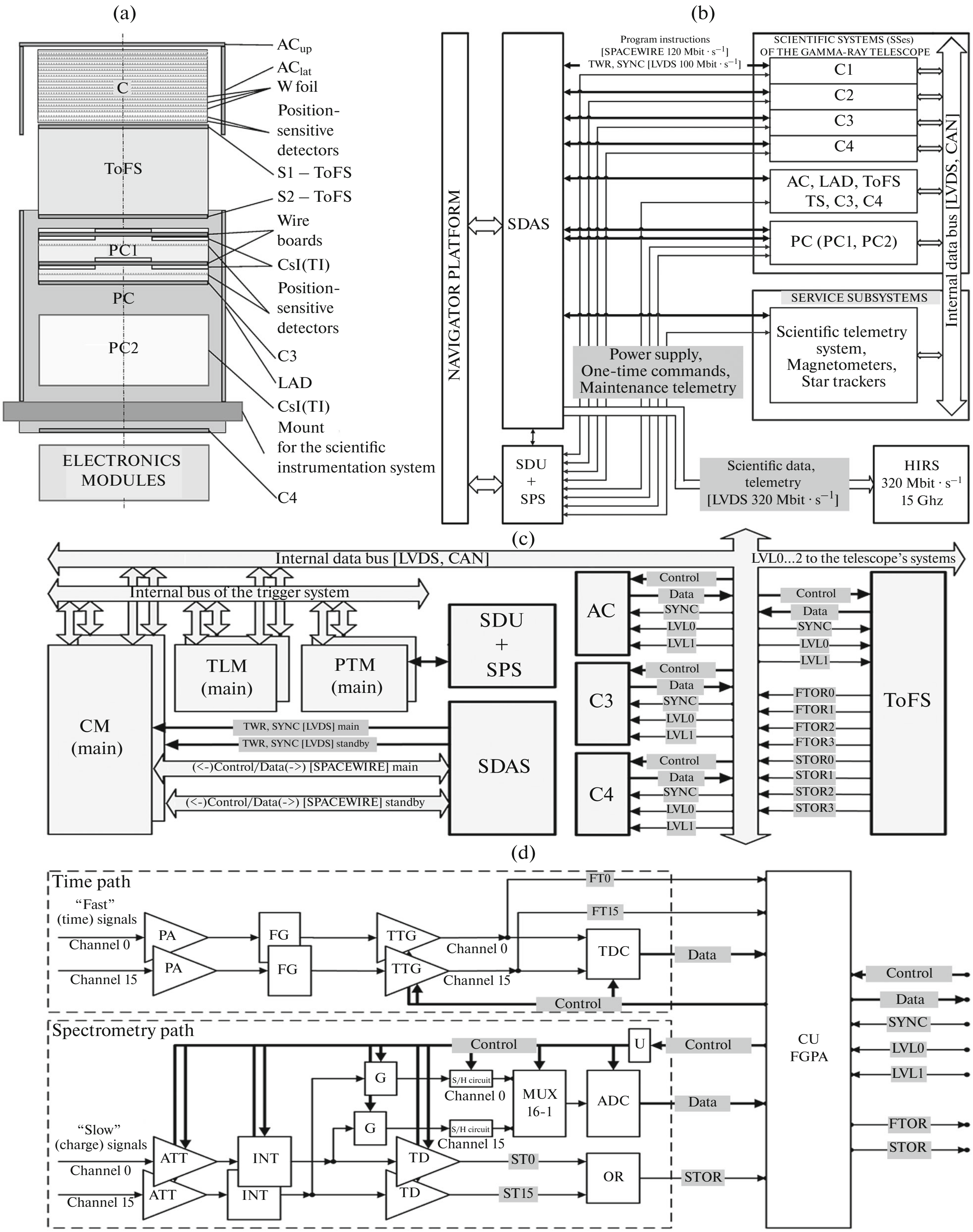
INTRODUCTION

The spaceborne GAMMA-400 gamma-ray telescope [1, 2] is a precision detecting system composed of several thousand unified detecting and electronics modules. It is planned to launch the telescope on the NAVIGATOR satellite platform [3] being developed at NPO Lavochkin to a high-apogee orbit with a mean distance from the Earth of ~120 000 km. The basic technical parameters of the space observatory are a weight of ~4000 kg, electric power of ~2000 W available for the scientific instrumentation, and an ~100 GB/day flow of scientific data to the ground-based part of the complex. Physical and functional block diagrams of the gamma-ray telescope are shown in Figs. 1a and 1b, respectively.

GAMMA-RAY TELESCOPE SYSTEM OF TRIGGER SIGNAL GENERATION

Trigger signal generation system TS of the of the GAMMA-400 γ-ray telescope generates triggers that correspond to the recording of different types of events (see Table 1), based on output signals of the frontal electronics modules of the telescope's detecting systems. To enhance its reliability, the system was developed using a dual redundancy scheme; the data exchange links are also doubled, with every link having its own receive–transmit units. A schematic functional diagram of the trigger generation system is shown in Fig. 1c. The trigger generation logic of the gamma-ray telescope is based on a three-level scheme, i.e., two fast hardware levels LVL0 and LVL1 and a slower software-generated LVL2 level. The frontal electronics modules that provide the initial information for generating the triggers are combined devices; each module composed of two paths (time and spectrometer) allows the connecting of up to 16 detecting modules (see Fig. 1d). The time path–generating amplifier of the units (PA, FG, and TTG) is built of discrete radio components; four-channel ASICACAMTDC-GPX2 converters with a time resolution of ~20 ps are used for time analysis (TDC). The generated TTG time signals arrive at the TDC inputs, and at the module's common control unit CU based on an FPGA integrated circuit (a Microsemi Pro ASIC3 in the current version of the system prototype) that enures interaction with the trigger logic module of the system. The spectrometer path is based on a 16-channel ASICIDEASIDE3380 converter. The generated charge signals are stored in the sample-and-hold (S/H) circuit and, upon arrival


(a)
C
ToFS
PC1
PC
PC2
ELECTRONICS MODULES
AC$_{up}$
AC$_{lat}$
W foil
Position-sensitive detectors
S1 – ToFS
S2 – ToFS
Wire boards
CsI(TI)
Position-sensitive detectors
C3
LAD
CsI(TI)
Mount for the scientific instrumentation system
C4
(b)
NAVIGATOR PLATFORM
SDAS
SDU + SPS
Program instructions [SPACEWIRE 120 Mbit · s^{-1}]
TWR, SYNC [LVDS 100 Mbit · s^{-1}]
SCIENTIFIC SYSTEMS (SSes) OF THE GAMMA-RAY TELESCOPE
C1
C2
C3
C4
AC, LAD, ToFS TS, C3, C4
PC (PC1, PC2)
SERVICE SUBSYSTEMS
Scientific telemetry system, Magnetometers, Star trackers
Internal data bus [LVDS, CAN]
Power supply, One-time commands, Maintenance telemetry
Scientific data, telemetry [LVDS 320 Mbit · s^{-1}]
HIRS 320 Mbit · s^{-1} 15 Ghz
(c)
Internal data bus [LVDS, CAN]
LVL0...2 to the telescope's systems
Internal bus of the trigger system
CM (main)
TLM (main)
PTM (main)
SDU + SPS
SDAS
TWR, SYNC [LVDS] main
TWR, SYNC [LVDS] standby
(<-)Control/Data(->) [SPACEWIRE] main
(<-)Control/Data(->) [SPACEWIRE] standby
AC
C3
C4
Control
Data
SYNC
LVL0
LVL1
ToFS
FTOR0
FTOR1
FTOR2
FTOR3
STOR0
STOR1
STOR2
STOR3
(d)
Time path
"Fast" (time) signals
Channel 0
Channel 15
PA
FG
TTG
TDC
FT0
FT15
Data
Control
Spectrometry path
"Slow" (charge) signals
ATT
INT
G
S/H circuit
MUX 16-1
ADC
U
TD
ST0
ST15
OR
STOR
CU FGPA
Control
Data
SYNC
LVL0
LVL1
FTOR
STOR

of the relevant trigger, are successively transmitted via analog multiplexer MUX to the ADC to obtain the digitized value of the charge isolated in the corresponding detecting module. The TTG thresholds are software-set at a level of ~40% of the signal from the minimum ionizing particles (MIP) that correspond to particles with charges $Z \geq 1$ generating signals FT_i used in generating levels LVL0 and LVL1 of the trigger logic, where $i = 0, ..., 9$ is the scintillation band identifier for each of the four planes of time-of-flight system ToFS. The thresholds of threshold discriminators TD are set at ~200% of the MIP, which corresponds to particles with $Z \geq 2$, generating signals ST_i used in generating trigger LVL1. The FT_i signals are stored in the status register of the ToFS discriminators, the content of which is transmitted along with the time information from the TDC via trigger signal LVL0 to trigger logic module TLM via a fast data link to decide on the generation of the first-level LVL1 trigger.

The LVL0 trigger is generated by the trigger logic module based on the signals of the ToFS ~100 ns after the charged particle has crossed the telescope aperture, provided that a signal with an above-threshold amplitude arrives from at least one of the sides of each ToFS planes in the assigned time interval (100–1000 ns). Signals FT_i and ST_i from each side of each ToFS plane are summed logically, generating signals $FTOR_j$ and $STOR_j$ where $j = 0..1$ is the identifier of the ToFS plane side. The signals from one side of each plane are then blended logically with the signals from the opposite side of each plane according to OR or AND, depending on the program settings. This generates signals $TOFL_k$ and $TOFH_k$, where $k = 0..3$ is the ToFS plane identifier; the coincidence of the signals with the set trigger mask generates common signals TOFL and TOFH. The TOFL signal, which corresponds to the passage of particles with $Z \geq 1$, is delivered to the systems of the gamma-ray telescope as the LVL0 trigger. The TOFH signal, which corresponds to particles with $Z \geq 2$, is used to generate the LVL1 trigger. The generation of the LVL1 trigger starts after analyzing the content of the status registers of the ToFS discriminator to estimate the position of the particle track, and to check the conditions of the particle hitting the main aperture of the device. Based on an analysis of the time points of a particle crossing the corresponding ToFS planes, particles traveling from the upper hemisphere are then selected. The state of anticoincidence system AC is simultaneously analyzed, allowing for suppression of the reverse current effect, based on a time analysis of the trigger times of the AC and ToFS [5, 6]. The response of detector S3 is also integrated into the trigger to improve the separation of hadronic and electromagnetic cascades, based on an analysis of the energy density distribution in the S3 bands. The signal of leakage detector S4 indicates that the energy of the recorded particle has not been completely released in calorimeter PC2, and additional analysis of the spatial profile of the cascade at the LVL2 level is required to estimate the possibility of it being restored. The LVL1 trigger initiates the gathering of information from the systems of the gamma-ray telescope and its storage in the buffer memory. The LVL2 trigger suppresses fast false triggers based on a preliminary analysis of the track information in tracking converter C and the spatial energy density distribution in calorimeter PC. The final decision is then made on transmitting the information about an event to the ground-based part of the scientific complex via scientific data acquisition system SDAS [4].

Table 1. Conditions for generating the first-level LVL1 trigger for the main types of events recorded by the telescope (simplified presentation)

LVL1 trigger	Recorded event
TOFL & (not AC) & S3	γ
TOFL & AC & S3	$e^{\pm}$
TOFL & AC & (not S3)	p, d
TOFH & AC	He, heavy nuclei

Fig. 1. (a) Physical schematic of the GAMMA-400 gamma-ray telescope: (C) position-sensitive tracking converter; (PC1 and PC2) spectrometric units of position-sensitive calorimeter PC based on a CsI(Tl) scintillator; (S3) pre-shower scintillation detector (PC1 + S3) of the calorimeter; (S4) scintillation leakage detector; (ToFS) time-of-flight system consisting of four perpendicularly-oriented planes composed of 10 BC-408 scintillator bands, each with sizes of 1000 × 100 × 10 mm^3 and combined pairwise into detectors C1 and C2 positioned at a distance of 50 cm from each other; (AC_{up}) upper anti-coincidence detector; (AC_{lat}) lateral anti-coincidence detectors; (LAD) lateral anticoincidence detectors of the calorimeter (detectors S3, S4, ToFS, AC, and LCD are constructed of modules with unified structure and circuits, and differ in the size and the number of scintillation bands). (b) Functional schematics of the GAMMA-400 gamma-ray telescope: (SDAS) scientific data acquisition system; (SDU) switching device unit; (SPS) secondary power supplies of the gamma-ray telescope's systems; (C1–C4) self-contained sections of tracking converter C; (TS) trigger generation system; (HIRS) highly informative radio system. (c) Functional schematic of the trigger generation system: (CM) control module for the preprocessing of scientific data and exchanging information with the SDAS, (TLM) trigger logic module for generating triggers based on output signals of the frontal electronics modules; (PTM) power-supply and telemetry module that ensures interaction between switching device unit SDU and secondary power supplies SPS of the gamma-ray telescope. (d) Functional schematic of the unified frontal electronics module: (PA) pre-amplifier, (FG) fast generator with zero-pole compensation for isolating the fast signal edge and restoring the basic link; (TTG) tracking threshold generator; (TDC) time-to-digital converter, (CU) common control unit of the module; (ATT) input attenuator; (CI) current integrator; (G) signal generator; (TD) threshold discriminator; (S/H) sample-and-hold circuit; (MUX) analog multiplexer; (ADC) 12-bit analog-to-digital converter; (U) control unit of the spectrometry path.

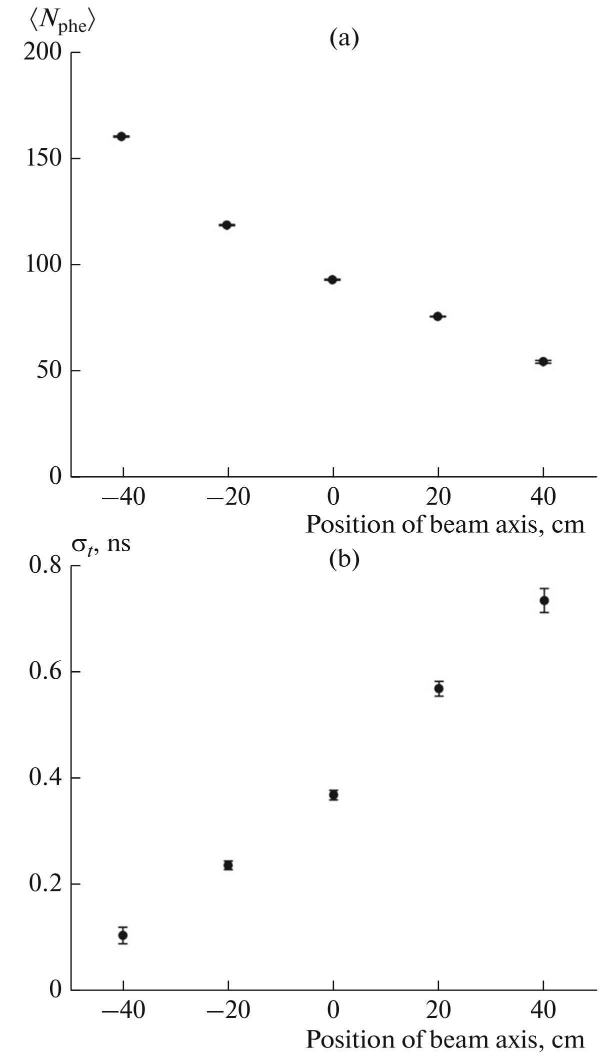


Fig. 2. Results from measurements made using the prototype of the trigger generation system of the GAMMA-400 gamma-ray telescope: (a) Average number of photoelectrons ⟨N_{phe}⟩ recorded at the face of the prototype's detector; (b) characteristic time resolution σ_t of the prototype's detector as a function of the position of the axis of the positron beam with an energy of 300 MeV, relative to the center of the prototype's scintillation band. Statistics: $\sim 10^4$ incident positrons at every point.

RESULTS FROM TESTING THE SYSTEM PROTOTYPE USING A POSITRON BEAM

Our measurements were made on the PAKHRA synchrotron's beam of secondary positrons with energies of 100–300 MeV. The prototype is a band of a BC-408 scintillator with sizes of 1280 × 100 × 10 mm, wrapped in a diffuse light reflector and visible from the opposite short faces by two photodetector modules composed of four SiPM SensL MicroFC-60035-SMT sensors and a frontal electronics module. The prototype was installed on a remotely operated platform that allowed the detector to move in a range ±40 cm with respect to the beam axis. Results from measurements obtained using the system prototype are shown in Fig. 2. To isolate particles incident on the telescope from the upper hemisphere at a level of 99% on a time-of-flight base of 50 cm, the ToFS detectors must have a characteristic time resolution no worse than ~500 ps. As can be seen from the figure, this requirement is met for the scintillator band with a length of ≤100 cm (the band length of the ToFS of the telescope). To enhance the time resolution and efficiency of isolation to ~300 ps and 99.99%, respectively, the photodetector module was upgraded by installing in each detector eight SiPM SensL MicroFJ-60035-TSV that had better noise characteristics and efficiency of photon recording. The upgraded version of the positron-beam prototype was to have been tested by the end of 2018.

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