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The structure, logic of operation and distinctive features of the system of triggers and counting signals formation for gamma-telescope GAMMA-400

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Abstract. Scientific project GAMMA-400 (Gamma Astronomical Multifunctional Modular Apparatus) relates to the new generation of space observatories intended to perform an indirect search for signatures of dark matter in the cosmic-ray fluxes, measurements of 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, electron/positron and cosmic-ray nuclei fluxes up to TeV energy region by means of the GAMMA-400 gamma-ray telescope represents the core of the scientific complex. The system of triggers and counting signals formation of the GAMMA-400 gamma-ray telescope constitutes the pipelined processor structure which collects data from the gamma-ray telescope subsystems and produces summary information used in forming the trigger decision for each event. The system design is based on the use of state-of-the-art reconfigurable logic devices and fast data links. The basic structure, logic of operation and distinctive features of the system are presented.

1. Introduction

The GAMMA-400 space project [1-3] is intended for precision investigation of the cosmic gamma-ray emission in the wide energy range from several MeV up to TeV region, e^-/e^+ fluxes with energies up to several TeV and cosmic-ray nuclei fluxes with energies up to ~10^{15} eV. For gamma rays with the energy >100 GeV expected energy and angular resolution are ~1% and ~0.01° respectively and electron/protons rejection factor is ~$5{\cdot}10^5$. The GAMMA-400 space observatory will be launched at the middle of the next decade on the Navigator service platform [4] designed by Lavochkin Association on the elliptical orbit with following initial parameters: an apogee ~300000, a perigee ~500 km, a rotation period ~7 days, and inclination of 51.4º. The GAMMA-400 observatory is expected to operate more than 5 years, reaching an unprecedented sensitivity in the indirect search of dark matter signatures and in the study of the unresolved and unidentified so far gamma-ray sources. For the above reasons one of the main concerns in assembling of GAMMA-400 is the high reliability of the particle detectors and of the associated electronic subsystems. The planned scientific complex main technical parameters are: weight ~2500 kg, power consumption ~2000 W, total scientific, and service downlink transmission up to 100 GByte/day.

2. The structure of the GAMMA-400 gamma-ray telescope

The GAMMA-400 gamma-ray telescope includes following main detector subsystems [5, 6]:

- Converter-tracker C consists of 22 layers of double (x, y) silicon strip coordinate detectors. The first twenty layers are interleaved with tungsten conversion foils meanwhile the last two layers have no tungsten. The total converter-tracker thickness is about 1 radiation length. The converter-tracker information is used for high precision determination of the gamma-quanta conversion point coordinates and reconstruction of charged particles trajectory;
- Anticoincidence system (AC: ACtop is top detector and AClat are four lateral detectors AClat1–AClat4) surrounding convertor-tracker for discrimination between incoming charged particles and gamma-quanta with an efficiency of $\geq$99.99%;
- A hodoscope of four layers of plastic scintillation counters (time-of-flight system, TOF is two detector planes S1 and S2) which provides the fast trigger to gamma-ray telescope readout electronics and measures the particle charge, crossing time and position, and separates upward from downward going particles within at most 10^{-8} level;
- An 80 cm x 80 cm, ~21 radiation length thick coordinate-sensitive calorimeter CC to measure the incoming particles energy with resolution of 1-2% for gamma-rays with $E_\gamma \geq 100$ GeV and separate $e^\pm$ and photons from hadrons at the $\sim 5 \cdot 10^{-5}$ level. The CC includes preshower CC1 (consists of two CsI(Tl) planes with total thickness of ~ $2X_0$, 2 layers of double (x, y) silicon strip coordinate detectors and fast plastic scintillation detector S3), CC2 is CsI(Tl) based total-absorption calorimeter, and anticoincidence and leakage plastic detectors LD and S4.

On the figures 1 and 2 the physical scheme and functional diagram of the under consideration variant of gamma-ray telescope construction are presented.

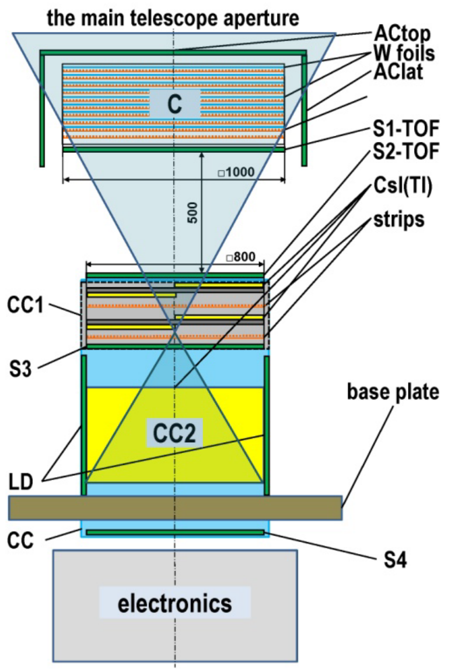

Figure 1. The physical scheme of the GAMMA-400 gamma-ray telescope.

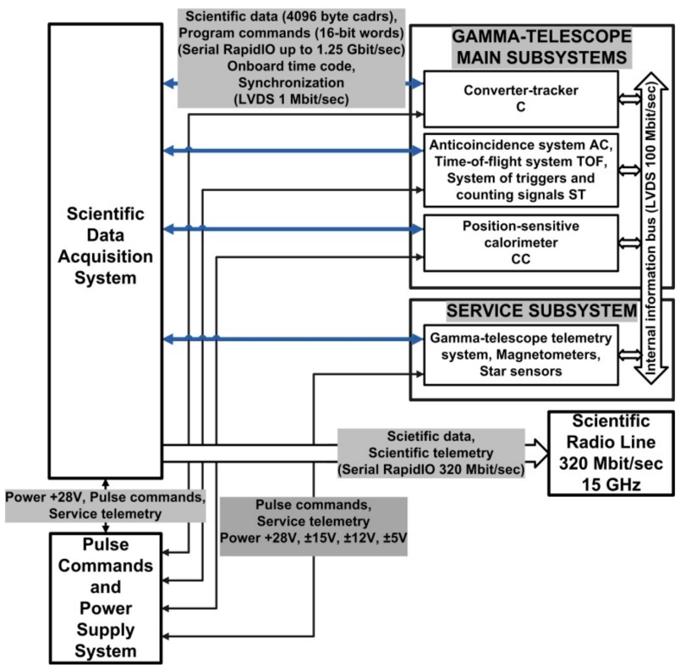

Figure 2. The functional diagram of gamma-ray telescope.

For control of gamma-ray telescope operation, one can use up to 100 radio commands in the form of either voltage pulse with duration ~0.1÷0.3 s with amplitude equal to satellite power or "dry contacts" – pulse on/off or switch on/off from onboard control system obtained through pulse commands and power supply system PCPSS, providing secondary power supply for gamma-telescope subsystems, radio commands sharing, its transmitting into gamma-telescope subsystems and transition of the telemetry parameters to the onboard telemetry system, and up to 65535 programming commands (16-bits control words) translating from onboard control system by scientific data acquisition system SDAS, providing acquisition and pre-processing data from telescope, storage it in non-volatile mass memory, transfer into high-speed scientific radio line for its transmission to the ground segment of the project, control information reception from spacecraft onboard control system through MIL-STD-1553B serial bus, its decoding and transfer into telescope subsystems [7].

Four fast plastic sub-detectors of the gamma-ray telescope AC, TOF, S3 and S4 are included in fast trigger logic in the main telescope aperture. The construction and electronics of these detectors are very similar with exception of absence of time measurement parts in S3 and S4 and difference in counters amount, length and orientation, so only TOF description, as the most complicated subsystem will be presented. The time of flight system includes two detector planes S1 and S2 located at the distance of 50 cm between convertor-tracker C and calorimeter CC. Each TOF detector plane is composed of two oriented perpendicularly layers of 1 cm thick and 10 cm width BC-408 counters. The upper TOF plane S1 (layers 0 and 1) consists of 10 + 10 scintillator counters of 100 cm length and lower TOF plane S2 (layers 2 and 3) consists of 8 + 8 counters of 80 cm length. Each side of TOF counter is viewed by photo detector block consists of six 6 mm × 6 mm, mounted on PCB silicon photomultipliers (SiPM) manufactured by SensL, having separated "fast" and "slow" signal outputs [8]. The "fast" and "slow" SiPM outputs of the same counter side are summed up to have a good redundancy and light collection efficiency, and these summed signals are fed to time and charge measurement parts of unified 16-channel front-end electronics unit (figure 3) correspondingly.

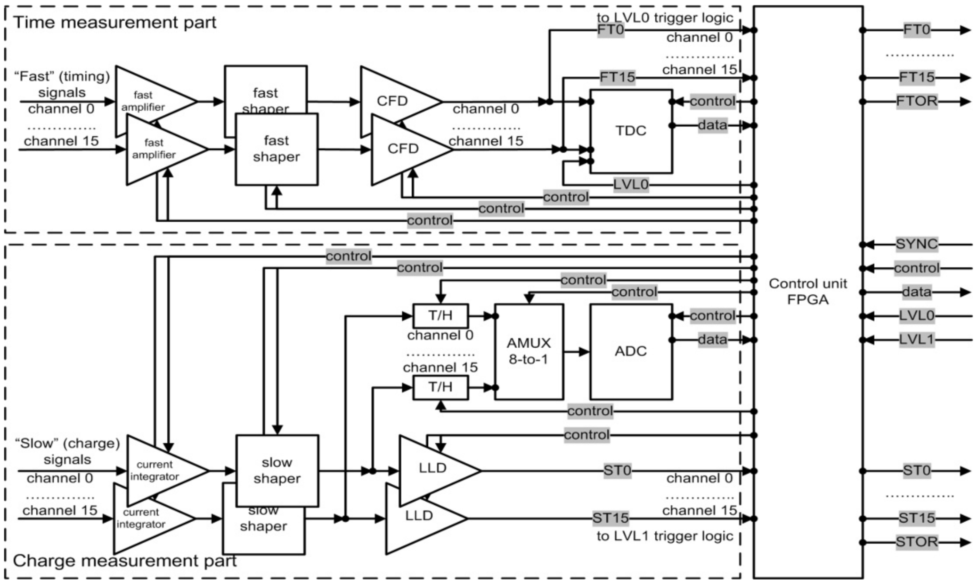

Figure 3. Functional diagram of TOF front-end electronics unit. FTOR and STOR – ORed FT_j and ST_j signals. SYNC – common synchronization strobe. LVL0 and LVL1 - level 0 and level 1 trigger signals.

Each time measurement channel includes amplifier, fast shaper with pole-zero cancellation circuit to select the leading-edge part of the signal and to quickly restore a stable baseline, and constant fraction discriminator CFD. The CFD outputs are fed to time-to-digital converter with ~25 ps resolution and fast trigger formation logic. Each charge measurement channel has current integrator, slow shaper, leading edge discriminator LED and track-and-hold unit TH. The "slow" shaped signals are memorized into TH and transmitted sequentially via analogue multiplexer AMUX to 12-bit analogue-to-digital converter ADC for total light released in the counters measurement. The fast amplifier and current integrator gain, shapers parameters, hold delay, CFD and LED thresholds and output pulse duration are programmable. The CFD thresholds are set at ~40% of the minimum ionizing particle (MIP) signal, relates to $Z \geq 1$ particles, forming FT_j signals (j=0..9/0..7 is counter identifier for upper/lower TOF plane correspondingly) used in LVL0 and LVL1 triggers logic. The

LED thresholds are set at ~200% MIP, relates to Z≥2 particles, forming ST_j signals used in LVL1 trigger logic. The FT_j and ST_j signals are stored in a pattern registers, and set of scalers in front-end electronics unit count how many FT_j and ST_j signals are presented in a time interval of up to 2 s. The LVL0 trigger signal initiates the transfer of pattern registers information into trigger logic module through high speed LVDS data link for LVL1 trigger formation.

3. The structure of system of triggers and counting signal formation

The system of triggers and counting signals formation represents the electronic structure consists of the set of programmable front-end detector units, trigger logic module for triggers signals formation from detecting subsystems and control and interface module, provides communication with SDAS and the final level of events data reduction and processing. In order to increase the reliability, the system is designed using a scheme with two hot- and cold-reserved subsystems. Data exchange signals are double redundant and each redundant line assigns with its own allocated data transceiver. Simplified functional diagram of triggers and counting signals formation system is presented on figure 4.

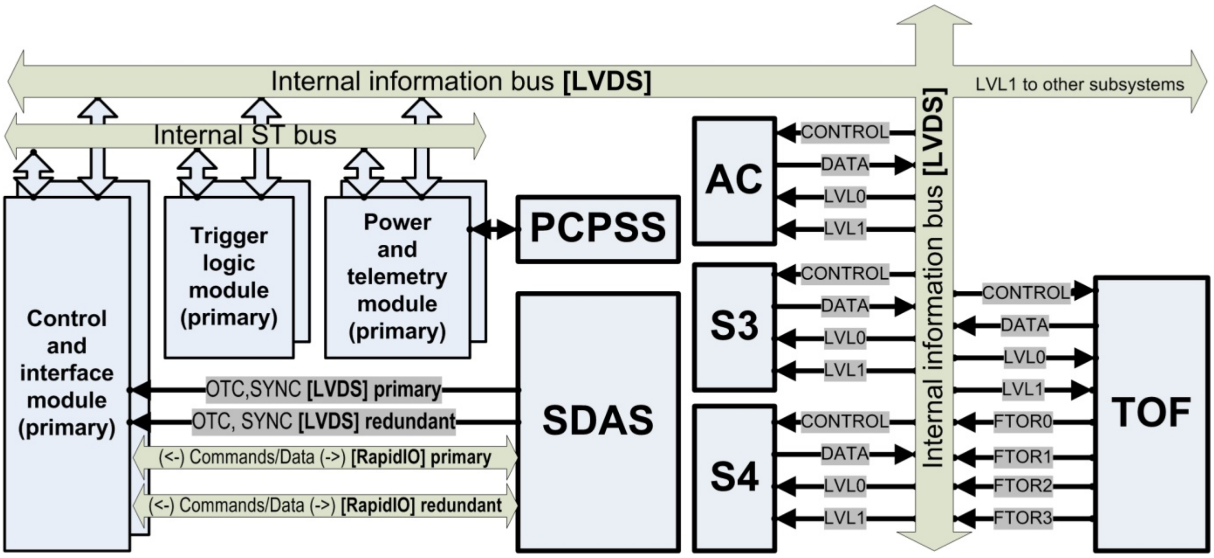

Figure 4. Functional diagram of triggers and counting signals formation system.

The GAMMA-400 gamma-ray telescope trigger system is based on three levels of triggers: two fast, hardware levels LVL0 and LVL1, and slow software level LVL2:

- The level 0 trigger LVL0 is generated by TOF system when a charged particle passing through the gamma-telescope acceptance, when at least one counter side in each TOF plane produces a signal above a threshold, and provides, in about 50 ns, the reference time label for the time measurements. For this purpose, all "fast" and "slow" outputs of each TOF counter side are combined in OR to form TOFL and TOFH signals, according to the threshold that has been passed. Indeed in the TOF readout electronics both a low ~40% MIP and a high ~200% MIP threshold are implemented for signals from each counter side. Then the signal originated from one plane side is matched in OR or AND (depending on a programmable setting) with one coming from the other side. The coincidence of TOF planes with a trigger mask enables TOFL and TOFH signals. The TOFL signal corresponds to the transit of a particle with Z≥1, passing the low threshold, whereas TOFH is related to higher Z ions with Z≥2, passing the high threshold. The TOFL signal is send to TOF, AC, S3 and S4 sub-detectors as LVL0 trigger;
- The level 1 trigger LVL1 formation begins with the TOF particle hit counters pattern analysis and crossing time one for acceptance checking and upward/downward particles selection. Then the AC hit counters pattern is considered, taking into account backsplash events suppression by time analysis method [9, 10]. The S3 preshower response is also included in

trigger for hadron and electromagnetic showers separation, and the S3 signal is enabled if the conditions on a defined combination of the S3 hit counters pattern with enough energy deposition are fulfilled. The leakage detector S4 signal indicates that sufficient part of incident particle energy is not absorbed in CC2 total absorption calorimeter and this event has a bad energy measurement precision. The LVL1 trigger initiates the process of data acquisition from gamma-telescope subsystems and storing it into intermediate buffer memory. Two scalers in trigger logic module count how many LVL0 and LVL1 signals are presented in a time interval of up to 2 s. In table 1 some examples of simplified LVL1 trigger conditions are presented;

- The level 2 trigger LVL2 suppress spurious fast triggers, finds preliminary tracks on the convertor-tracker and analyzes energy deposition in position-sensitive calorimeter by using stored on level 1 stage data, and makes a final decision about transmitting or not registered information to the ground segment of scientific complex.

Table 1. Simplified set of LVL1 trigger conditions used to select different types of events.

LVL1 Trigger	Selected events
$TOFL \wedge \overline{AC} \wedge S3$	γ
$TOFL \wedge AC \wedge S3$	e±
$TOFL \wedge AC \wedge \overline{S3}$	p, d
$TOFH \wedge AC$	He, heavy ions

Then the collected event information is compressed, structured, combined with the service data and sent to scientific data acquisition system SDAS for temporary storing in non-volatile mass memory or for direct transferring into high-speed scientific radio line.

4. Conclusions

The system of triggers and counting signals formation of the GAMMA-400 gamma-ray telescope constitutes the pipelined processor structure which collects data from the gamma-ray telescope detector subsystems and produces summary information used in forming the trigger decision for each event. The use of the flexible distributed system provides possibility for adaptive and operational management of the parameters of gamma-telescope registration modes, allows for the optimization of a search for a specific physics channel according to the survey strategy. In order to increase the reliability, the system is double redundant and selected electronics components are space qualified and radiation tolerant. Additional reliability level is achieved by minimization of high integrity chips amount.

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