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To cite this article: I V Arkhangelskaja *et al* 2019 *J. Phys.: Conf. Ser.* **1181** 012083

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Additional aperture detectors of gamma-telescope GAMMA-400 calibrations on synchrotron “PAKHRA”: possibility of temporal profiles fractal analysis

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Abstract. GAMMA-400 (Gamma Astronomical Multifunctional Modular Apparatus) will be the new generation satellite gamma-observatory. The gamma-ray telescope GAMMA-400 consists of anticoincidence system (top and lateral sections - ACtop and AClat), the converter-tracker (C), time-of-flight system (two sections S1 and S2), position-sensitive calorimeter CC1, electromagnetic calorimeter CC2, scintillation detectors of the calorimeter (S3 and S4) and lateral detectors of the calorimeter LD. Three apertures provide events registration both from upper and lateral directions. The main aperture provides the best angular (all double (X, Y) tracking coordinate detectors layers information analysis) and energy resolution (energy deposition in the all detectors studying). The main aperture created firstly due to converter-tracker (C): gammas converted in tungsten conversion foils are registered. Triggers in the main aperture will be formed using information about particle direction provided by time of flight system and presence of charged particles or backslash signal formed according to analysis of energy deposition in combination of both layers anticoincidence systems ACtop and AClat individual detectors. Other two apertures used for observation of transient events do not require best angular resolution as gamma-ray bursts and solar flares both from upper and lateral directions. Additional aperture allows particles registering from upper direction, which don't interact with converter-tracker and don't formed TOF signal. Particles detection in additional aperture starts with signal of CC1 fast discriminators in anticoincidence with TOF. Energy band for gammas registration in this aperture is similar to the main one. In the lateral aperture low energy (0.2-100 MeV) photons classified by using simple anticoincidence signals from the individual detectors of LD and CC2. Higher energies γ -quanta ($E > 100$ MeV) recognized using energy deposition analysis in the individual detectors of S3, S4, LD and CC2. Prototype of additional aperture functioning of GAMMA-400 contains two detectors. One of them AC/LD prototype based on BC-408 scintillator with dimensions of $128 \times 10 \times 1$ cm³. Other is CC1 prototype composed of CsI(Tl) crystal with dimensions of $33 \times 5 \times 2$ cm³. The positron beam with energies 100-300 MeV was used for calibration of prototypes of GAMMA-400 detectors on synchrotron “PAKHRA”. We calculate fractal dimension of temporal profiles measured during calibrations of AC/LD and CC1 prototypes. Preliminary results are 1.50 ± 0.05 and 1.48 ± 0.08 correspondingly. This is similar to Poisson statistics or Erlang one with coefficient up to 10.



1. GAMMA-400 apertures short description.

The gamma-ray telescope GAMMA-400 (Gamma Astronomical Multifunctional Modular Apparatus) consists of three types of detectors: double (X, Y) tracking coordinate detectors, used in the converter-tracker (C) and position-sensitive calorimeter CC1, plastic and non-organic scintillators [1, 2]. Following detectors based on BC-408 plastics: time-of-flight system TOF (two sections S1 and S2), top (ACtop) and lateral (AClat) sections of anticoincidence system, scintillation detectors of the calorimeter (S3 and S4) and lateral detectors of the calorimeter (LD) (its installation required for particles registration from lateral directions). All detector systems ACtop, AClat, S1-S4 and LD consist of two sensitive layers of 1 cm thickness each [3]. Two calorimeters made of CsI(Tl): position-sensitive (CC1) and electromagnetic (CC2) ones. CC1 contain of 2 strips layers and 2 scintillation layers. The thickness of CC1 and CC2 is $\sim 2 X_0$ ($\sim 0.1 \lambda_0$) and $\sim 20 X_0$ ($\sim 0.9 \lambda_0$) respectively (where λ_0 is nuclear interaction length). The total calorimeter thickness is $\sim 22 X_0$ or $\sim 1.0 \lambda_0$ for vertical incident particles registration and $\sim 54 X_0$ or $\sim 2.5 \lambda_0$ for laterally incident ones [3]. The silicon photomultipliers (SiPM) are used in all scintillation detectors instead of vacuum PMT for minimization of power consumption. The physical scheme of the under consideration variant of gamma-ray telescope GAMMA-400 construction and its three apertures are shown at figure 1.

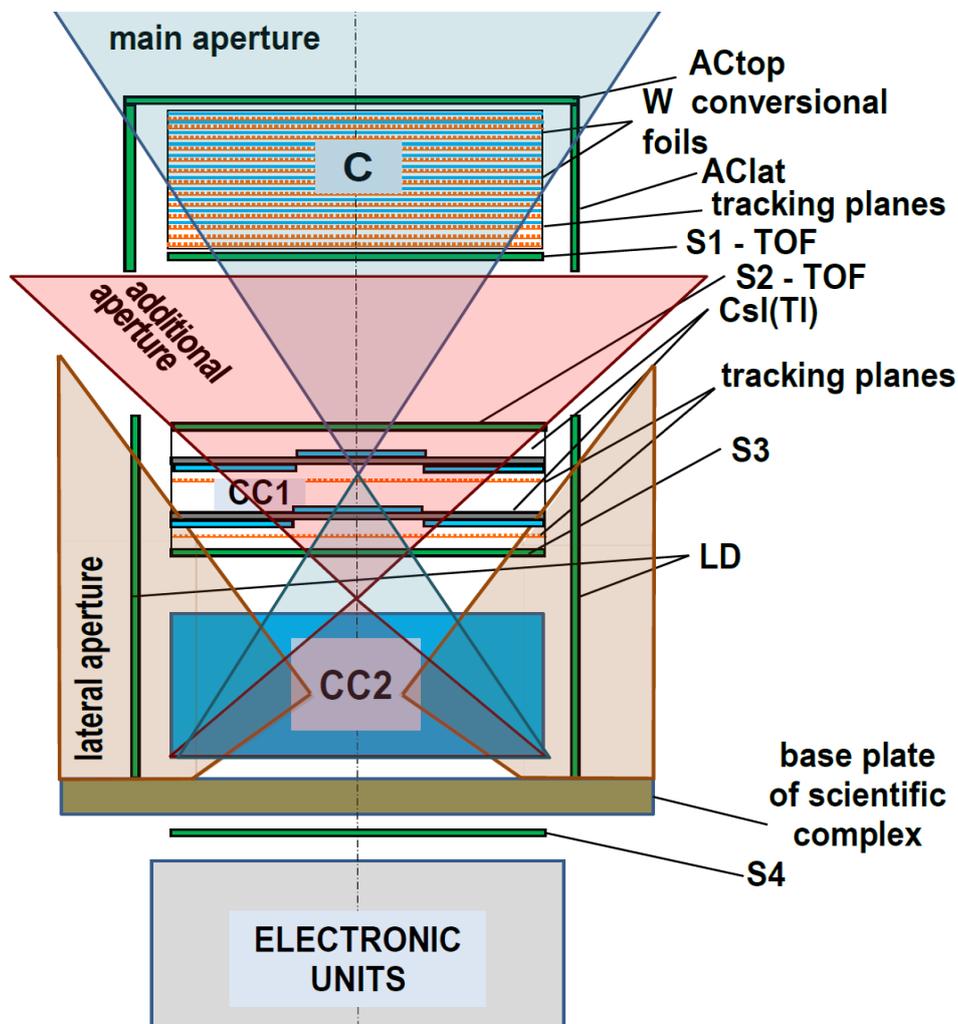


Figure 1. The physical scheme of the under consideration variant of GAMMA-400 gamma-ray telescope construction and its three apertures.

The gamma-ray telescope is optimized for registration of γ -quanta and charged particles with energy above 100 GeV with the best parameters in the main aperture from upper direction. The main aperture is created firstly due to converter-tracker (C): gammas converted in tungsten conversion foils are registered. Triggers in the main aperture will be formed using information about particle direction provided by TOF system and about presence of charged particles or backsplash obtained from ACtop and AClat anticoincidence detectors in energy band of 20 MeV-1.0 TeV for gammas and $E > 100$ MeV for electrons [4]. Gamma-telescope operated in event by event registration mode in this aperture. Other two apertures are used for observation of transient events as gamma-ray bursts and solar flares both from upper and lateral directions do not require best angular resolution. Additional aperture allows to registered particles from upper directions which don't interact with converter-tracker and don't formed TOF signal. Particles detection in additional aperture starts with signal of CC1 fast discriminators in anticoincidence with TOF [4]. Energy band for gammas registration in this aperture is similar to the main one. In the lateral aperture low energy (0.2-100 MeV) photons classified by using simple anticoincidence signals from the individual detectors of LD and CC2. Higher energies γ -quanta ($E > 100$ MeV) are recognized using energy deposition analysis in the individual detectors of S3, S4, LD and CC2. The angular resolution is provided by double (X, Y) tracking coordinate detectors layers in the CC1. Electromagnetic shower starting point position is defined due to methods analogues to using in accelerator technique (so-called «center-of-gravity technique») allow accuracy ~ 1 mm for electrons (positrons) with $E \sim 8$ GeV – for example, in experiments BTeV [5] and PANDA [6].

2. Prototype of additional aperture of GAMMA-400 calibration on synchrotron “PAKHRA”

High-energy γ -quanta are registered in GAMMA-400 mostly by formation of electron-positron pairs in converter-tracker C. The positron beam with energies 100-300 MeV [7] was used for calibrations of prototypes of GAMMA-400 detectors on synchrotron “PAKHRA”. Scheme of beam forming and apparatus installation on synchrotron C-25P “PAKHRA” is presented at figure 2.

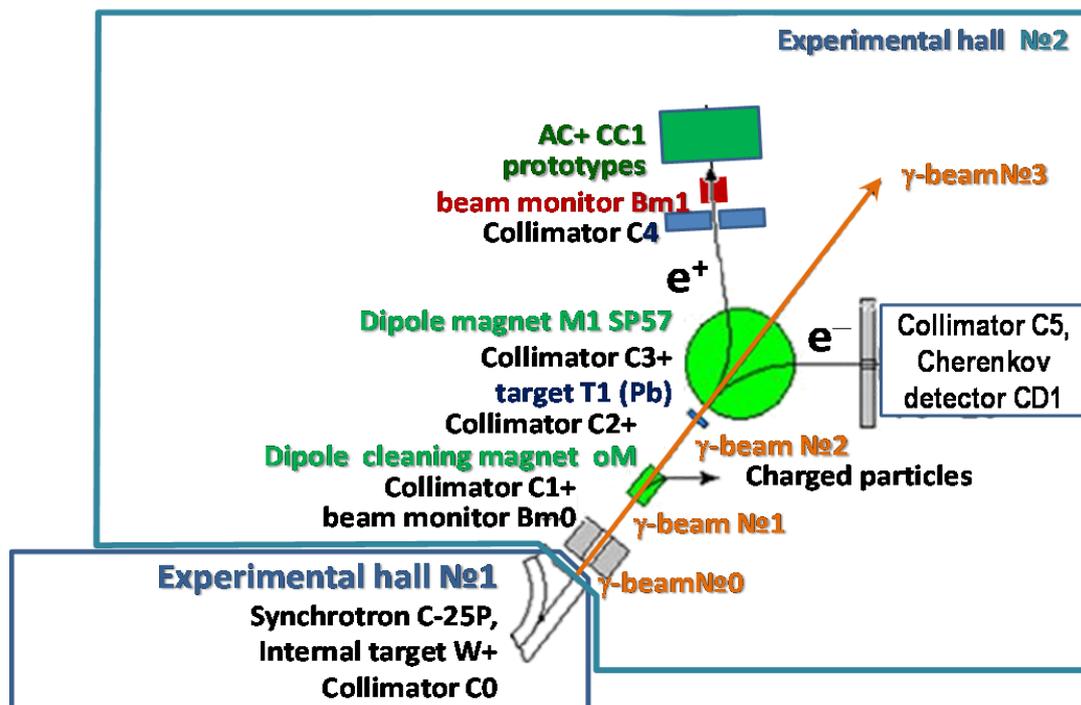


Figure 2. The scheme of beam forming and apparatus installation on synchrotron C-25P “PAKHRA”.

GAMMA-400 prototype of additional aperture functioning consist of two detectors. One of them is BC-408 based with dimensions of $128 \times 10 \times 1 \text{ cm}^3$ (one detecting strip from AC prototype) and other composed of CsI(Tl) crystal with dimensions of $33 \times 5 \times 2 \text{ cm}^3$ (one block of CC1 prototype).

3. Fractal dimension of temporal profiles measured during calibrations of AC and CC1 prototypes

For investigation of time series corresponding to solar flares, gamma-ray bursts and other transient events fractal analysis is often applied. It has some features that allow it to be used to study sets with characteristics varying over a wide range: scaling (two events with similar temporal profiles but with different durations have a fractal dimensions) and the possibility to process simultaneously the fractal dimension distributions obtained by using data from different detectors if the background fractal dimensions for these detectors are the same. Moreover, the fractal dimensions must be different for the temporal profiles of events caused by different physical processes [8, 9]. Thus background fractal dimension is useful characteristic of detector.

Fluctuations of count rate registered in scintillation detector during satellite experiments caused due to three reasons. First is fluctuations background caused by gammas and charged particles cosmic and magnetosphere origin. Statistical fluctuations of such background are described by Poisson or Gauss statistics outside the radiation belts and other disturbed regions of magnetosphere. Second reason is fluctuations of produced scintillation photons and photoelectron number in photomultiplier. Corresponding statistical fluctuations are poissonian or gaussian in the first approximation in the linear region of SiPM. Other reason is transient processes in electronic system.

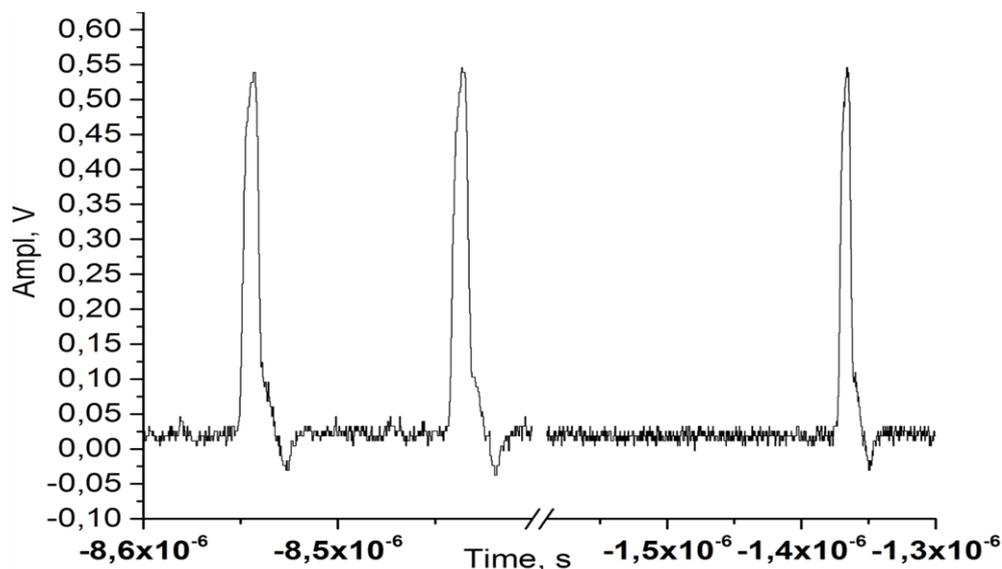


Figure 3. The example of trend of CC1 prototype, $E_{\text{positrons}}=300 \text{ MeV}$, run#5, December 6, 2017.

There are some methods for time profile fractal dimension definition. In the main, these methods based on dissection of a time profile on bins and analysis of count rate statistical fluctuations in each bin [8, 9]. If amount of experimental points in bin k is not enough for statistical analysis (usually if $k \leq 20$) then cell algorithm of fractal dimension definition is used [8, 9]: the part of plane in which analyzable curve is locate covers by cells with side δ . Let $N(\delta)$ -amount of cells, which has one generic point with this curve even if. Then we define certain gauge for this curve:

$$L = N(\delta) \times \delta^D \quad (1)$$

For usual (non fractal) curve $L=0$ for $\delta \rightarrow 0$ but for fractal curve gauge (1) is nonzero for some $D \neq 1$. For practical application it is more suitable to plot dependence of $N(\delta)$ for set of different δ . If it looks

$$N(\delta) = a \times \delta^D \quad (2)$$

for $a > 0$, then fractal dimension is equal D .

We have measured continuous temporal profiles of signals from CC1 and AC prototypes and then simulate time target events operation modes of apparatus using time intervals between signals as marker of event registration (single count). Then we modeled background temporal profiles using summation of “registered counts” in time intervals defined as integer numbers of signal duration $\Delta t_{sig_{AC}} \sim 20$ ns and $\Delta t_{sig_{CC1}} \sim 5$ μ s and use cell algorithm for simulated temporal profile fractal dimension calculation - see, for example, [8]. In our work minimal sides of the cell are 20 ms and 5 μ s for CC1 and AC prototypes correspondingly. Then we used values of 30, 40, 50 and 60 ms for CC1 prototype and 10, 20, 30, 40 and 50 μ s for AC one.

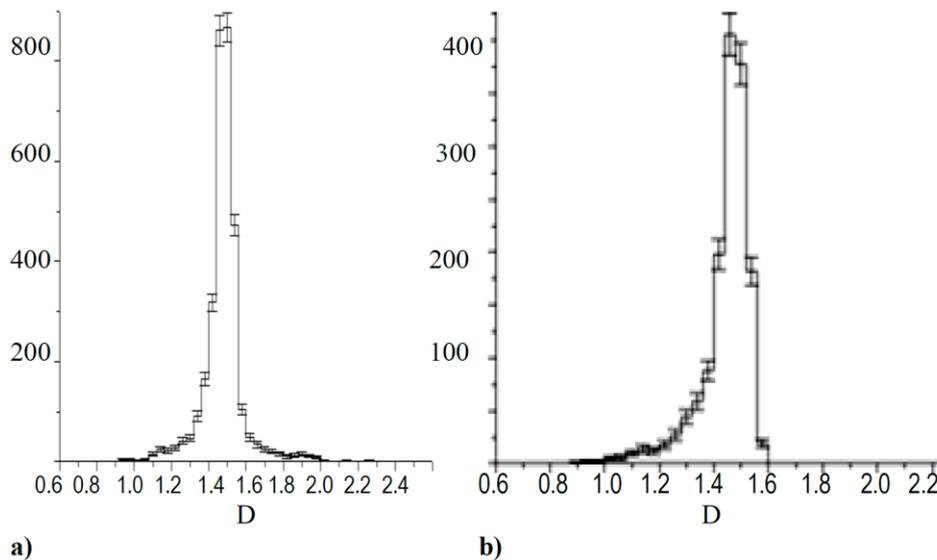


Figure 4. Fractal dimensions distributions of temporal profiles: a) obtained from trends of CC1 prototype, in particular, one shown at figure 3; b) LAD detectors of BATSE experiment.

The whole curve of time profile was divided to k strips. In every strip we have calculated maximum and minimum values of the count rate σ : σ_{max} and σ_{min} . Sum of the cells with the width δ_j in strip k that have at least one common point with our curve were calculated by:

$$N_k = \frac{\sigma_{max} - \sigma_{min}}{\delta_j} + 2; \quad (3)$$

$$N_j = \sum_k N_k$$

If we build a line through all points of the graphic of $\lg N_j(\lg \delta_j)$ and its angle α don't equal to 135° ($D \neq 1$) then we determine the fractal dimension of our time profile: $D = -\text{tg } \alpha$. In common, the received value D is not a real fractal dimension and our time profile is just – prefractal [9] - because really fractal is a limit of some endless process but we have a minimal value – time resolution of the detector. The example of trend of CC1 prototype is presented at figure 3, its fractal dimensions distribution – at figure 4a. Analysis of this distribution gives fractal dimension $D=1.48 \pm 0.08$.

For comparison let's consider fractal dimension of real temporal profiles obtained in orbital experiment, for example BATSE [11, 12] (Burst and Transient Source Experiment) onboard the Compton Gamma Ray Observatory (CGRO). CGRO [13] was launched on April 5, 1991 and finished its functioning on June 4, 2000. BATSE registered γ -emission temporal profiles in four energy bands: 25-50 keV, 50-100 keV, 100-300 keV and > 300 keV. For obtaining the event temporal profiles with high resolution Large Area Detectors (LAD - NaI(Tl) scintillation detector 50.8 cm in diameter and 1.27 cm thick) were used [11, 12]. No any onboard and ground data filtering were used in this experiment. Fractal dimensions of BATSE background and events temporal profiles were investigated in [14]. Following this work, in our examination we used data with the time resolution of 64 ms, sides of the cell were 200 ms, 300, 400, 500 and 600 ms. Its fractal dimensions distribution is presented at figure 4b. Analysis of this distribution gives fractal dimension $D=1.47\pm 0.06$. Both results are similar to Poisson statistics or Erlang one with coefficient up to 10.

4. Conclusion

The additional aperture of GAMMA-400 gamma-ray telescope allows registering particles from upper directions which don't interact with converter-tracker and don't formed TOF signal. Prototype of additional aperture functioning of GAMMA-400 contains two detectors. One of them is single strip of AC prototype based on BC-408 scintillator with dimensions of $128\times 10\times 1$ cm³. Other is CC1 prototype composed of CsI(Tl) crystal with dimensions of $33\times 5\times 2$ cm³. We calculate fractal dimension of AC/LD and CC1 prototypes temporal profiles measured during calibrations and obtain preliminary results of 1.50 ± 0.05 and 1.48 ± 0.08 correspondingly. Analysis of LAD detectors of BATSE experiment fractal distribution gives fractal dimension $D=1.47\pm 0.06$. Both results are similar to Poisson statistics or Erlang one with coefficient up to 10.

Acknowledgments

Authors thank for the support from National Research Nuclear University MEPhI in the framework of the Russian Academic Excellence Project (contract No. 02.a03.21.0005, 27.08.2013)

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