# An experimental sample of the field gamma-spectrometer based on solid state Si-photomultiplier

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## ABSTRACT

Design of optical-electronic devices and systems involves the selection of such technical patterns that under given initial requirements and conditions are optimal according to certain criteria. The original characteristic of the OES for any purpose, defining its most important feature  ability is a threshold detection. Based on this property, will be achieved the required functional quality of the device or system. Therefore, the original criteria and optimization methods have to subordinate to the idea of a better detectability. Generally reduces to the problem of optimal selection of the expected (predetermined) signals in the predetermined observation conditions. Thus the main purpose of optimization of the system when calculating its detectability is the choice of circuits and components that provide the most effective selection of a target.

**Keywords:** measuring systems, SiPM, scintillator, gamma ray

## 1. INTRODUCTION

The basis of the national economy and industry are the country's natural resources. Status and development of mineral complex, its technical and technological support to largely determine the economic, energy and military security of any country and its geopolitical influence in the world. In modern conditions, there are special requirements to the technical and technological support of exploration work due to the exhaustion of the fund of subsurface, relatively easily discovered fields, as well as the fact that the search operation has to be carried out in severe geomorphological environments (large depth range, arctic latitudes and mountainous areas with no infrastructure, the shelf of the northern seas and etc). This work is a part of project for mass production of a new generation of field gamma spectrometry equipment based on si-photomultiplier (SiPM), which has enhanced characteristics of sensitivity, accuracy and autonomy combined with low weight and size parameters.[1–4]

## 2. RESULTS

In practice, radiometry mate PMT to a scintillator is adjusted to ensure maximum transmission of the radiation flux from the scintillator to the sensitive area of a PMT. In contrast to the radiometer, gamma spectrometer, the detection efficiency is ensured not so much a significant predominance of the useful signal above the noise level, how the resolving power of a detector's energy spectrum. One of the main factors influencing the flow rate of scintillation at the site of the detector, and the resolution of gamma-spectrometer (both in amplitude and in time) is a method of joining contact surfaces of the crystal and the photomultiplier sensor and, as a consequence, the design build "crystal  sensor PM". One of the important operating characteristics of the designed test bench

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of gamma field spectrometry (TB GFS) based on matrix solid-state photomultiplier is the linearity of its transfer characteristic within the dynamic range of measured energies. In accordance with the technical specifications, the specified parameter must be less than 1%. High linearity of the transfer characteristics of the device allows to increase the accuracy of the quantitative spectrum analysis, in particular, the accuracy of determining the nucleotide composition of the sources of ionizing radiation. The transfer function of the measuring device remains linear as long as the signal at the output of the SiPM is proportional to the intensity of radiation from a gamma-ray burst on the sensitive area of the receiver. In an ideal situation each photon created in the scintillation crystal to trigger only a single micro-silicon photomultiplier, so the energy particles are absorbed by scintillation crystal is proportional to the number of "detections" of microwells SiPM. If two or more photons were absorbed by the same microcache in the same period of time, the output signal will be the same as if microcache absorbed only one photon. Therefore, the output signal of the SiPM goes to saturation at a certain flux of photons. The exit speed of the transfer characteristics in the saturation regime can be estimated by the ratio:

$$N_{fired} = M(1 - \exp^{\frac{PDE - N_{ph}}{M}}) \quad (1)$$

where $N_{fired}$ is the number of triggered microwells; $M$ is the total number of microwells on a sensitive area of a PMT is determined by the choice of the model receiver; $PDE$ detection efficiency of photons takes into account the geometrical fill factor sipm; $N_{ph}$ number of photons incident on the active area of the SiPM. The exit speed of the transfer characteristics in the saturation mode, in turn, affects the accuracy of determining the centroid of the peak measured by the instrument spectral component of the gamma radiation.

One of the possible methods of finding the optimal way of joining crystal-PMT is a computer simulation of the flash in the crystal, initiated by a gamma-quantum, approach lighting and fiber optics lighting devices, as well as traditional for the specified software (for example, one of the most popular programs for automation of optical systems design Zemax). In Zemax (the inconsistent mode of calculation of the beam) uses a statistical approach to generating beam and its further tracing. For the simulation of devices based on scintillation sensors traditionally used tracing Monte-Carlo. For calculations of the optical system and method of docking the crystal-PMT at the modeling stage it is necessary to choose an adequate model of the crystal (its optical properties) and the model for calculating the luminous flux. Since the developed device designed for the detection of radiation of low power, that is actually a separate gamma-ray flashes, when the selection of models for calculation will be guided by the following provisions:

- Illumination may occur at any point in the crystal volume, and the likelihood of the outbreak, the same for all points.
- Gamma-ray burst cause the illumination of a single point, and the radiation from this point is distributed in all directions.

## 3. THE MAIN APPROACHES TO THE DEVELOPMENT OF TB GFS

Based on the original requirements specification, the developer conducts the necessary research, development and technological works, paying particular attention to ensure the following requirements in accordance with GOST R 15.201-2000:

- the safety, health and environmental (including their persistence in the process of exploitation products);
- resources;
- established for the conditions of use of the product of values of indicators
- determining the technical level;
- resistance to external influences;
- interchangeability and compatibility of components and products in General.



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The primary stage of development of TB GFS is the analysis of the requirements specified in the technical assignment. On the basis of this analysis identifies possible technical solutions. Formed an approximate appearance of the proposed development, specified the composition, architecture, internal and external communications. Identifies options to protect, compensate and suppression, if required. The list of problems and contradictions that must be resolved in the development process.

The development of TB GFS was carried out according to the requirements specified in the technical specification. Based on the totality of the General requirements, it is possible to generate more detailed requirements for the elements of the device. Formation of private requirements allows each group of specialists to solve specific assigned to them, tasks in the sphere of their professional activity. It is separately possible to allocate design requirements to software and hardware and to software. Requirements for hardware and software required make it possible to determine the main functional solutions that can be applied in this development. In accordance with the General requirements, are determined by:

- the architecture of the device;
- circuitry (manufacturer, cost, temperature range, WWF);
- used the sensitive element;
- the required computing power;
- the main components and modules;
- used antenna modules;
- the interaction between the blocks;
- internal communications between nodes
- external interfaces;
- power requirements (nominal ripple, consumption, etc.);
- means for indication and alarm;
- controls;
- ability to use the purchase of ready solutions;
- the protection from external factors.

Based on the requirements of the technical specifications for the implementation of TB ASG developers has taken the following decisions. TB GFS consists of two structurally complete unit: the Sensor Unit and a processing Unit.[5–7] The device consists of two independent units: the Sensor unit (SU) and processing Unit (PU). The sensor is the sensing element and there is primary processing of the measured data, after which they are converted into digital form and transmitted to the processing Unit by radio. Information exchange between the processing unit and the Sensor is carried out according to the Bluetooth standard. The processing unit performs algorithmic processing of the data, calculates the measurement result displays information for the operator, produces, coordinates, and carries out recording of the received information in memory. Also, the processing unit transmits the measured data to further consumers on any digital interface.

As the element base, to accelerate the development apply to both domestic and foreign low-cost electronic items that are freely available. Not used elements in respect of which manufacturers recommend not to use them in new development. Not used in the design and elements, the development of which has not yet passed the stage of certification. All items apply to electrical load and temperature conditions specified in the technical documentation on them. At a later stage, in the framework of import substitution and reduce dependence on foreign suppliers, it is recommended to replace the foreign elements of their domestic counterparts. As a



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sensitive element used a bunch of the scintillator-PMT. As used scintillator NaI crystal of rectangular shape, with dimensions of 141428 mm. the Scintillator of this material has several advantages in comparison with others, in particular, it is not susceptible to magnetic interference. As a photoelectron multiplier used solid-state photomultiplier brand PB-ArrayC-60035-4P company SensL. Its accessibility and the ratio price/quality makes it attractive for use as the main type of solid-state photomultiplier for TB GFS. Module PMT contains 4 active area 6x6 mm, and the total size of the contact area is 14x14 mm, which corresponds to the size of the side of the scintillation crystal. Process research is required to determine the best way of joining scintillator-PMT. Analysis of algorithms, the required software and hardware implementation, with the solution of tasks in real-time, as well as the requirements for data storage and display, gives you to choose as of hardware and software, in accordance with the TOR, the following modules and elements that provide the following options:

- Microcontroller or ARM7 CortexM3 architecture with a frequency of 72 MHz; - (AT MEGA1281-16AU (ATMEL) Sensor) - (LPC2478FBD208 processing Unit)
- internal memory: rewritable 512 KB.
- RAM: 96 KB;
- the Amount of external memory: rewritable 2 GB (memory card format microSD, a chip family K9HCG08U1M, AT24C16AN), RAM - 2 MB.
- Modules inter-module communication (data exchange between the Sensor unit and processing Unit ) is performed via radio modules, Bluetooth Low Energy, series BTM111-CM;
- Availability of digital interfaces Ethernet, USB, RS232, CAN, GSM, is implemented using specialized circuits such as SN65240, HX1188NL and embedded microcontroller LPC2478FBD208;
- the Presence of a module GLONASS/GPS positioning accuracy up to 5 m;
- Ni-MH or Li batteries with 3.6 V nominal capacity 1000 Ah or above.

An analysis of the above decisions shows that they are sufficient for software and hardware implementation of algorithms for detection, recognition and mapping. The sensing element is a scintillation crystal NaI. Receiver of photons excited in the crystal particles, and a Converter of the number of photons in the electrical signal is a solid state photomultiplier. The signal from the PMT, each module is fed to a corresponding preamplifier, which produces a signal gain to an acceptable level, for the peak detector. After detection, fast ADC produces a digitized received signal is measured. The signal in digital form is fed to the control unit, where it is the primary processing and conversion into a form required to effect a transfer of the Bluetooth module. Subsystem measurement prepares the measurement data for algorithmic processing and transmission to the processing unit. The subsystem determining the level of radiation recalculates the measured signal level in the corresponding physical quantities. However, the definition level for each channel, the corresponding plot of the energy spectrum. The subsystem of determining the spectrum of radiation forms a spectrum of the measured signal according to the received data. Received in the subsystem spectrum will continue to be subjected to processing algorithms to determine the spectra which elements are present in the measured signal. The data obtained are converted to the required form and given to the Bluetooth module for further transmission via radio link to the processing unit. FThe basic module of the processing Unit is a control unit and storage, which is the connecting link between the other parts. Their interaction and provides the correct work. It receives commands from the management bodies, in accordance with which selects the mode of operation, the displayed information signaling methods, used functions, etc. depending on the operation modes, the control unit and storage is formed is displayed on the info screen. The information may contain data about the measurement location, device status, status of batteries, service and other information. Unit positioning, controlled by a control unit and storage, determines the coordinates and passes them for further use. The coordinates can be used for reference information of the operator with its location, and the generation of a mapping of the terrain. With the help of Bluetooth module exchanges information with the Sensor unit. The received data are decompressed and used for algorithmic signal processing. The main processing of the received data by the processing unit and data storage. In its composition



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this unit has subsystems for performing the basic algorithms, as well as to store the necessary databases and the obtained results. Unit external interfaces designed to output the data to external consumers via the selected interface. To transfer results, depending on requirements, can be carried out on one or more interfaces at the same time. This block contains the main modules, each of which implements a specified function. The measurement results are downloaded to the desired modules, where it is processed, and recording the result. Data for algorithms to work (constants, spectra, etc.) are taken from the base of the storage module. Location data can be recorded and used from the appropriate database. Also in the module storage is the ability to work with data for any other information, whether it be messages, notes, annotations, etc. The determination of the coordinates is performed by modules receiving signals from the satellite system GLONASS and GPS for mobile devices with low power consumption and possibility of programming your system shutdown. The transmission of signals between the blocks according to the Bluetooth Protocol must be realized by using antennas ANT-2.4-JJB-ST Modules inter-module communication (data Exchange between the sensor and the Block) are radio modules Bluetooth Low Energy. The exchange Protocol should be sufficient to transfer the amount of data required to solve the tasks. The radius of a stable connection should not be less than 5 meters. Vnutriglaznae must be done wired or detachable way. Allow modules on the same printed circuit Board. Communication should have the ability to quickly restore the damaged, unambiguous identification and marking. Interfaces for communication with external devices should have connectors that are specified in the electrical specifications. Allowed to save weight and size, make adapter cables for connection of PGS to external customers. The data exchange Protocol shall be in accordance with generally accepted standards. Batteries TB electric shock should the electrical capacity be sufficient to run the CBC within the time specified in the TOR. The power sources must function in specified in TS temperature regimes. The value of batteries is 3.63,6 V. Voltage converters and secondary sources of feeds should ensure the stability of its output voltages is not less than 1% with a possible change in the input voltage of batteries in the range of from 2.7 to 4 V. To inform the operator about the state of the device, and to display received measurement results, need to be used with LCD indicator low consumption, adapted for wearable devices. The resolution of the indicator shall be not less than 320640 pixels. Minimum screen brightness should not be less than 100 KD. Screen size should be at least 3.5 inches. When using the screen at low temperatures, shall be provided with a heater element. As management bodies intend to use the membrane keyboard. Keyboard must be attached to the front panel of the processing Unit. It should be the following operator:

- switching on and off of the device;
- Switching;
- Run the algorithms and additional tasks;
- the Management indication;
- Basic settings and adjustments of the device.

To save time and reduce development cost as possible, it is possible to purchase individual modules, solving any required for the functioning of the EO tasks with acceptable quality. To ensure the normal functioning of the EO in conditions different from normal, there need to be elements of the decisions. Must be ensure the functioning conditions when exposed to a magnetic interference, high and low temperatures, humidity.

## 4. PO

The development of information technology in the field of Geology and geodesy allows to automatically detect and analytical control of sources of ionizing radiation in real time. In this regard, key elements of a gamma-ray spectrometers are not only detectors of radiation, storage systems and data processing, but also the algorithms of statistical analysis of measurement data. The purpose of the theoretical study of algorithms for processing spectrometric data at different stages of the geophysical survey of the area is the formation of the analytical base for developing efficient system software TB FGS that meet the performance requirements and technical characteristics of scientific and technical results. Theoretical aspects to develop the following algorithms for processing spectrometric information in the field of measurement:



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- the Algorithm of automatic recognition of the spectra (hereinafter, the algorithm of ARS).
- Algorithm for automatic anomaly detection (hereinafter  the algorithm AOA).
- Algorithm for radiation mapping of the area (hereinafter, the algorithm RKM).

The need to determine the isotopic composition of gamma radiation often occurs when conducting gamma shooting. As a rule, this problem can be solved by carrying out spectroscopic studies of samples in stationary conditions. After measurements specialized gamma spectrometer processing the obtained spectra by using programs that run on personal computers. However, in the process route of the geological survey the capability of measuring the spectrum in this way is limited. Therefore, the task of carrying out the Express analysis of the composition of gamma radiation easy inexpensive field gamma spectrometer. It is necessary to ensure minimum participation of the operator to operate the system in automatic mode, taking into account the field measurements.[8–10] In this regard, the development of the algorithm ARS of gamma radiation, able to function in conditions of limited computational resources becomes relevant. In most cases, the main objective of ARS is the separation of the spectral components corresponding to individual radionuclides, the total spectral characteristics. This task is considerably complicated in connection with an energy drift of the spectrometer, as well as noise due to randomness of the processes during the measurements. The following are methods used to implement automatic recognition of the spectra of gamma radiation.

Theoretical study of the algorithms for processing the measured data in the process of field gamma survey were carried out in the framework of modern probabilistic and statistical approach to solving complex problems of geophysical surveys in the area. Prepared base for scientific research and applied works on the development and implementation of system software EA PGS in accordance with the requirements of the technical specifications. The main conclusions on the basis of the study:

- most of the existing programs of processing spectrometric data used recognition algorithms spectra of oriented interactive actions of the operator. Therefore this implementation of the algorithms cannot be applied for operation in the pedestrian GFS, requiring full automation of measurement procedures.
- For GFS based on crystal scintillator automatic detection of the spectral components is considerably complicated in connection with the energy the drift, characteristic of this type of device, as well as noise due to randomness of the processes during the measurements.
- using the known algorithms of processing of spectra of gamma-radiation in its original form in the composition of GFS can not fully meet the requirements for devices based on scintillation detector.
- For statistical evaluation of the results of measurements of pedestrian anomaly detection of sources of gamma radiation in the field proposed data filtering method of the moving average with symmetric window is subject to restrictions of length and the number of subintervals of the observation.
- the Main advantage of moving average method is to reduce the amount of computation (especially during peak load) and the timing requirements of the computing means of the device.
- in the absence of a priori information about the shape, size, anomalies of gamma-ray radiation, as well as their correlation characteristics (the law of field distribution and dispersion) are invited to perform data processing within put interval measurements using the criterion of Neyman-Pearson. This criterion is the most powerful, since it allows to obtain the highest theoretically possible probability of detection for a given probability of false alarm.
- Known algorithms for gamma-spectrometric mapping of the terrain vary considerably in efficiency and rigor to computational abilities of the hardware. The most promising are the algorithms based on nonparametric search of peaks, related to their self-sufficiency.
- to develop a mapping algorithm to work in the field of pedestrian spectrometer on the basis of the scintillation detector, it is necessary to ensure the adaptation of the techniques used with the aim of improving sustainability and lowering the computational cost.



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## 5. CONCLUSION

Joining process the PMT-scintillator developed on the basis of the comparative analysis of the results of computer modeling of radiation sources and optical systems with the software Zemax. Processing of the calculation results allows to draw the following conclusions:

- the authors Obtained the dependence of the energy of radiation of gamma-ray flares from the parameters of optical systems for various configurations of a connecting structure for a crystal with different packing options in direct optical contact with the sensitive area of PMT and crystal Packed with various options mirror traps.
- Calculated energy losses of the radiation on the input surface of the receiver with different variants of docking crystal-PMT is shown that the smallest losses occur for the crystal, Packed in white diffusing tape from the mirror trap in the form of a hollow waveguide of circular cross-section.
- it is Shown that the most preferable from the standpoint of compliance with requirements to ensure uniform illumination of the detector surface is used as a mirror trap optical waveguide of square cross section, whose dimensions are consistent with both the crystal and the sensitive area of a PMT; wherein the residual nonuniformity (20%) is associated with absorption of radiation when passing flash in the crystal and in the fiber.

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## REFERENCES

[1] Hedler, H. and Henseler, D., "Silicon photomultiplier and radiation detector," (Aug. 22 2011). US Patent App. 13/822,835.

[2] Becker, E. M. and Farsoni, A. T., "Wireless, low-cost, fpga-based miniature gamma ray spectrometer," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **761**, 99–104 (2014).

[3] Fujita, T., Kataoka, J., Nishiyama, T., Ohsuka, S., Nakamura, S., and Yamamoto, S., "Two-dimensional diced scintillator array for innovative, fine-resolution gamma camera," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **765**, 262–268 (2014).

[4] Wang, L. L., Klein, D., and Beddar, A. S., "Monte carlo study of the energy and angular dependence of the response of plastic scintillation detectors in photon beams," *Medical physics* **37**(10), 5279–5286 (2010).

[5] Kataoka, J., Kishimoto, A., Fujita, T., Nishiyama, T., Kurei, Y., Tsujikawa, T., Oshima, T., Taya, T., Iwamoto, Y., Ogata, H., et al., "Recent progress of mppc-based scintillation detectors in high precision x-ray and gamma-ray imaging," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **784**, 248–254 (2015).

[6] Hall, D. J., Holland, A., and Soman, M., "The influence of electron multiplication and internal x-ray fluorescence on the performance of a scintillator-based gamma camera," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **678**, 64–77 (2012).

[7] Yokota, Y., Kurosawa, S., Ohasi, Y., Kamada, K., and Yoshikawa, A., "Growth of shape-controlled ce: Y 3 al 5 o 12 scintillator crystal and their scintillation properties," *Journal of Crystal Growth* **452**, 69–72 (2016).

[8] Bagán, H., Tarancón, A., Ye, L., and García, J. F., "Crosslinked plastic scintillators: A new detection system for radioactivity measurement in organic and aggressive media," *Analytica chimica acta* **852**, 13–19 (2014).



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[9] Konyakhin, I. A., Malyshev, A. V., et al., "Autocollimaton sensor for measuring the deformation of objects and modules containing environmentally hazardous substances," in [*SPIE Photonics Europe*], 98991Y–98991Y, International Society for Optics and Photonics (2016).

[10] Shavrygina, M. A., Konyakhin, I. A., Timofeev, A. N., and Verezhinskaia, E. A., "Optical-electronic system controlling the position of a railway track with the help of reference marks," in [*SPIE Photonics Europe*], 988916–988916, International Society for Optics and Photonics (2016).



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