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Software for Studying Cosmic Ray Variations with the Neutron Facilities of the Experimental Complex NEVOD

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Abstract

One of the possible approaches to studying the state of the heliosphere and physical processes and phenomena on the Earth is the detection of variations in the background neutron flux. These variations may arise from changes in the cosmic ray flux intensity, specifically its hadronic component, whose interaction with the nuclei of matter near the detector produces neutrons that moderate to thermal energies through multiple successive elastic collisions. Such studies are conducted at the PRISMA-36, URAN, and "Neutron" facilities, which are part of the Experimental Complex (EC) NEVOD (National Research Nuclear University MEPhI, Moscow).

Data visualization software is an integral part of such physical experiment. It enables the graphical representation of time series of specific facility parameters used for physical analysis, as well as for monitoring of individual detector states, which is critically important for ensuring the quality and reliability of experimental information. The article describes the architecture and GUI design of software for the graphical representation of experimental data from the neutron detectors of the EC NEVOD for monitoring the operability of the PRISMA-36, URAN, and "Neutron" facilities, as well as for analyzing cosmic ray variations. The main parameters of detector signals used to solve the above-mentioned tasks are presented. Features of the software developed in the Python programming language are discussed.

Keywords: cosmic rays, neutron detectors, neutron background variations, data visualization.

1. Introduction

Detection of the background thermal neutron flux allows for the investigation of long-period [1, 2] and short-period [3] variations of cosmic rays (CR), CR anisotropy [4, 5] and solar CR [6, 7], the influence of various meteorological parameters on the neutron flux [8, 9] (including atmospheric pressure and air humidity [10], soil moisture and terrain [11, 12]), as well as various geophysical processes (tidal waves in the Earth's crust, free oscillations of the Earth, etc.).

At the Experimental Complex NEVOD (National Research Nuclear University MEPhI, Moscow) [13], the studies of cosmic ray variations are conducted by detecting thermal neutrons using three scientific facilities: PRISMA-36 [14], URAN [15], and "Neutron" [16].

The schematic diagrams of the detectors used in these facilities are shown in Fig. 1.

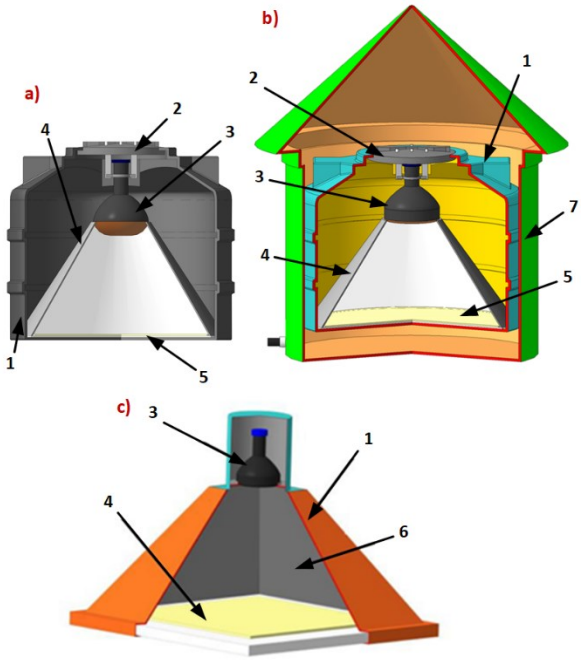


Fig. 1. Detectors of the PRISMA-36 (a), URAN (b), and "Neutron" (c) facilities: 1 – light-isolated housing; 2 – cover with suspension; 3 – PMT; 4 – scintillator; 5 – light-reflecting cone; 6 – light-reflecting coating; 7 – outer housing.

The PRISMA-36 facility is located on the 4th floor of the EC NEVOD and consists of three independent clusters of 12 detectors each. The distance between detectors is 3.6 m × 5.3 m, and the total area of the facility is about 500 m^2. A 200-liter black polyethylene cylindrical tank with a height of 570 mm and a diameter of 740 mm is used as the light-isolated housing for the PRISMA-36 detector. A specialized inorganic scintillator (SL6-5 phosphor) based on ZnS(Ag) with the addition of ^{6}LiF (enrichment degree with the ^{6}Li isotope is 90%) with an area of 0.36 m^2 is installed at the base of the detector housing. A PMT EMI 9350KA is used to record light flashes from the scintillator.

The URAN facility is located on the roofs of two EC NEVOD buildings and consists of 72 detectors divided into 6 clusters of 12 detectors each. The distance between detectors is about 5 m, and the total area of the facility is 10^3 m^2. The URAN detectors are nearly identical in design to those used in the PRISMA-36 facility. The LRB-2 phosphor [17] with the addition of B_2O_3 is used to register thermal neutrons, and the FEU-200 photomultiplier tube serves as the photodetector. Since the detectors operate in outdoor conditions, they have an additional outer metal housing for protection against environmental influences and mechanical damage.

The "Neutron" facility includes one cluster of 5 detectors located in the EC NEVOD building at various heights (from -3 m to 10.5 m) from the ground surface and under different thicknesses of absorber (from 35 to 350 g/cm^2). The detectors have pyramidal light-isolated housings with dimensions of 1000×1000×700 mm^3. The inner surface of housings is painted with a diffuse reflective coating. A FEU-200 PMT is used as the photodetector. The scintillator is similar in composition to that used in the PRISMA-36 detectors and has an area of 0.75 m^2.

Signal is read out from the detectors via an integrating circuit with an integration constant of 2.7 μs for PRISMA-36, 20 μs for URAN, and 5 μs for "Neutron".

All three facilities have identical data acquisition systems in terms of organization and operating principle. They include:

- the clusters local posts of data acquisition and processing for digitizing analog signals from detectors, selecting signals based on trigger conditions (the signal from any detector exceeds the amplitude threshold of 10 ADC l.s.b. which corresponds to 16 mV), and assigning timestamps to registered signals with an accuracy of 10 ns;

- the central posts of control, synchronization, data collection, and processing for receiving, storing, and primary processing of cluster data, arriving as digitized signal waveforms with a sampling frequency of 100 MHz and a duration of 20 μs (2048 points with a step of 10 ns).

2. Characteristics of the detector signals

Signals from the detectors can be of two types: from neutrons (neutron signals) and from charged particles or PMT noise (background signals). Neutron and background signals differ in pulse shape. Examples of these signals are shown in Fig. 2. Parameters enabling the separation of these two signal types were defined in [14]: signal duration and rise time (leading edge duration).

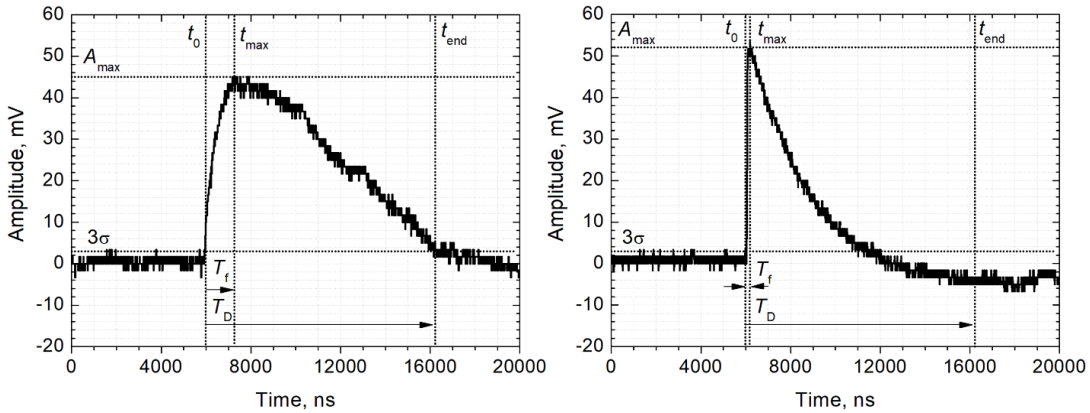


Fig. 2. Examples of neutron (left) and background (right) signals from detector. Signal parameters: A_{max} is the signal amplitude, t_0 and t_{end} are the signal start and end times, $T_D = t_{end} - t_0$ is the signal duration, T_f is the signal rise time.

The main characteristics of signals from the detectors of the PRISMA-36, URAN, and "Neutron" facilities are determined in real time processing of their waveforms directly during the data taking process. These include (Table 1): amplitude, pulse duration, signal leading edge duration, mean value and r.m.s. deviation of the ADC baseline, results of signal type identification (neutron or background) taking into account the specified selection criteria.

Table 1 – Main characteristics of the detector signals

Parameter	Description
time_ns	Event registration time according to the internal clock of the cluster electronics unit in nanoseconds
amplitude	Signal amplitude in ADC l.s.b. (A_{max})
pds_mean	Mean value of ADC baseline in ADC l.s.b.
pds_rms	r.m.s. deviation of ADC baseline in ADC l.s.b.
zero_crossing	Signal duration in nanoseconds (T_D)
zc_result	Signal identification result based on pulse duration parameter: 0 – background, 1 – neutron
rise_time	Signal leading edge duration in nanoseconds (T_f)
rt_result	Signal identification result based on pulse leading edge duration parameter: 0 – background, 1 – neutron

Based on these parameters and taking into account the threshold conditions (amplitude threshold), the selection criteria (for *rise_time* and *zero_crossing*) and the atmospheric pressure corrections, the neutron and background counting rates, used for detector operability monitoring, are calculated for each detector of the facilities:

1. Taking into account the threshold conditions and selection criteria, the average neutron counting rate $N(t)$ is calculated for each detector of the facility.
2. The obtained counting rate values are corrected for atmospheric pressure:

$$N_{corr}(t) = N(t) \cdot e^{\beta \cdot (P(t) - P_0)}, \quad (1)$$

where β is the barometric coefficient, P_0 is the mean atmospheric pressure, $P(t)$ is the current atmospheric pressure in mbar. The coefficient β is set constant for each detector, and the mean pressure P_0 is also set manually.

3. Taking into account the average counting rate $< N_{corr}(t) >$ over a specified time interval, the variation value is calculated:

$$Var = \frac{N_{corr}(t) - < N_{corr}(t) >}{< N_{corr}(t) >} \cdot 100\%. \quad (2)$$

A specialized software (SW) has been developed for data acquisition from the PRISMA-36, URAN, and "Neutron" facilities, for visualization of time series of thermal neutron flux variations, as well as for monitoring and analysis of individual detectors' operating parameters.

It should be noted that direct analogues are absent in the open literature, since software for monitoring specific detector arrays in cosmic-ray physics is traditionally developed for unique hardware configurations and is not presented in stand-alone publications. In accelerator physics, as in cosmic-ray physics, the works that are encountered either address general visualization libraries or astrophysical catalogs, or else solve problems posed for specific instrumentation [18–20], but do not address the problem of cluster monitoring of ground-based facilities with discrete parameters. Therefore, this software may be characterized as unique within its class of tasks.

3. Software for studying cosmic ray variations

The software for studying cosmic ray variations implements the following set of functions:

- control of the electronics units (EU) of the clusters of the PRISMA-36, URAN, and "Neutron" facilities;
- reading out of data from the facilities' EUs, and recording of information into relational databases (DB) and on the hard disk drives of the facilities' control computers;
- visualization, processing, and express analysis of experimental information from the facilities.

The software was developed in the Python 3.11 programming language [21] using additional libraries: PyQt5 [22], PyQtGraph [23] for creating graphical interfaces, psycopg2 [24] for working with the PostgreSQL relational database management system (DBMS) [25], MessagePack [26] for writing and reading experimental data, NumPy [27], SciPy [28], pandas [29] for experimental data processing.

3.1. Software architecture

The architecture of the software for studying cosmic ray variations at the PRISMA-36, URAN, and "Neutron" facilities includes three components:

- the "Server" for interacting with the electronics units of the facilities' clusters;
- the "Online Client" for visualizing recorded experimental information and monitoring the facility status in real time;
- the "Offline Client" for detailed analysis of experimental data and facilities' statuses over a specified time interval.

The software architecture is shown in Fig. 3.

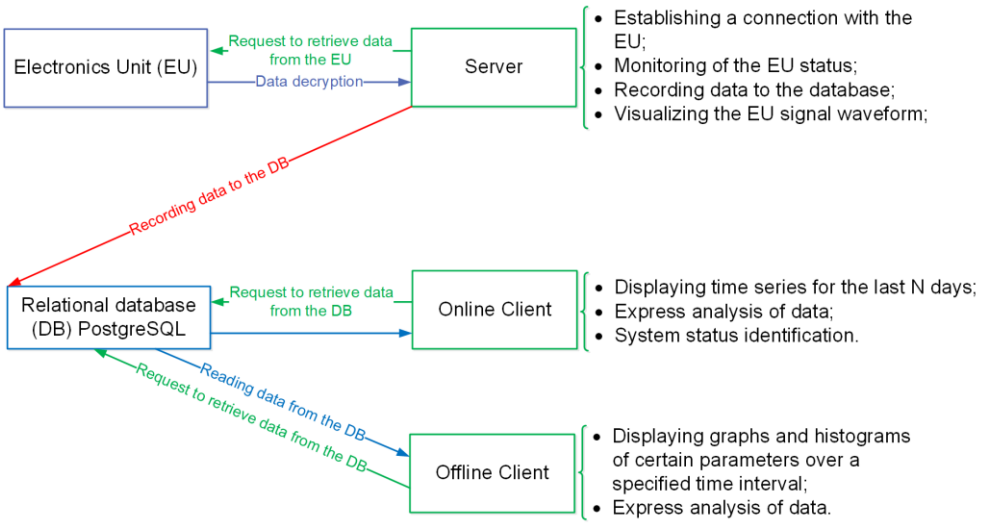


Fig. 3. Diagram of the architecture of the software for studying cosmic ray variations at the PRISMA-36, URAN, and "Neutron" facilities.

The "Server" program runs on the facility's control computer. It controls and configures the EUs, performs primary processing of the information received from them, and records the processing results into the DB. After establishing a connection with the EUs and starting the measurement process, the program waits for data packets from the electronics units, caches the received information, processes it, and writes the processing results to the PostgreSQL relational DB. To monitor system operation, the "Server" program interface displays waveforms of registered signals as graphs in real time, and also presents various service and statistical information about the obtained experimental data and the measurement process in text form.

The client part of the software can be run on any personal computer that is part of the EC NEVOD local area network. It sends queries to read data from the relational DB and performs their visualization in online or offline modes.

The "Online Client" of the software implements the following functionality:

- online display of graphs of averaged variation values and neutron counting rates for all operating detectors of the facility;
- online indication of the statuses of individual detectors of the facility's clusters based on detector's neutron and background counting rates over the last minute;
- online indication of operational statuses of the individual clusters and facility as a whole;
- configuration of event selection parameters;
- configuration of alarm thresholds for individual detectors;
- express analysis of data;
- export of data processing results.

The "Offline Client" is intended for displaying graphs and histograms of various signal and facility parameters for a specified time interval, express analysis of data, exporting data processing results. It can also be used to periodically load the latest data from the DB in the automatic mode.

For the PRISMA-36, URAN, and "Neutron" facilities, the graphical user interfaces of the software are identical except for the number of detector and/or cluster widgets displayed in the windows. The software interface is described below using the PRISMA-36 facility as an example.

The software architecture supports horizontal scalability, allowing new detectors and clusters to be added via a configuration file.

3.2. Software interface: Server

The graphical user interface of the "Server" program for the PRISMA-36 facility (Fig. 4) is built at startup dynamically according to the configuration file. The configuration file contains information about the **number of clusters in the facility**, their network and operational settings, DB connection settings, etc.

The interface includes 4 main elements:

- a control panel with *Connect*, *Disconnect*, *Start*, *Stop* buttons for establishing/terminating network connection to the EUs of the facility's data acquisition system, and for starting/stopping the measurement process;
- a panel for displaying information about the number of events registered by each cluster of the facility (the number of fields depends on the number of clusters in the facility);
- a panel for displaying service information about program operation including mandatory tabs *Log* (history and results of various operations) and *Status* (fill level of internal message queues), as well as several *Status Cl #N* tabs (statistical information on the number of events and quality of data packets for each cluster), the number of which depends on the number of clusters in the facility;
- a graph display panel including several tabs (the number depends on the number of clusters in the facility) for event-by-event rendering of signal waveforms from cluster detectors, which provides the possibility to set axis limits or auto-scaling, to enable/disable rendering of individual graphs, and to enable interactive tools for express analysis of graphs: horizontal (red line) and vertical (orange line) cursors, and a crosshair cursor (green lines).

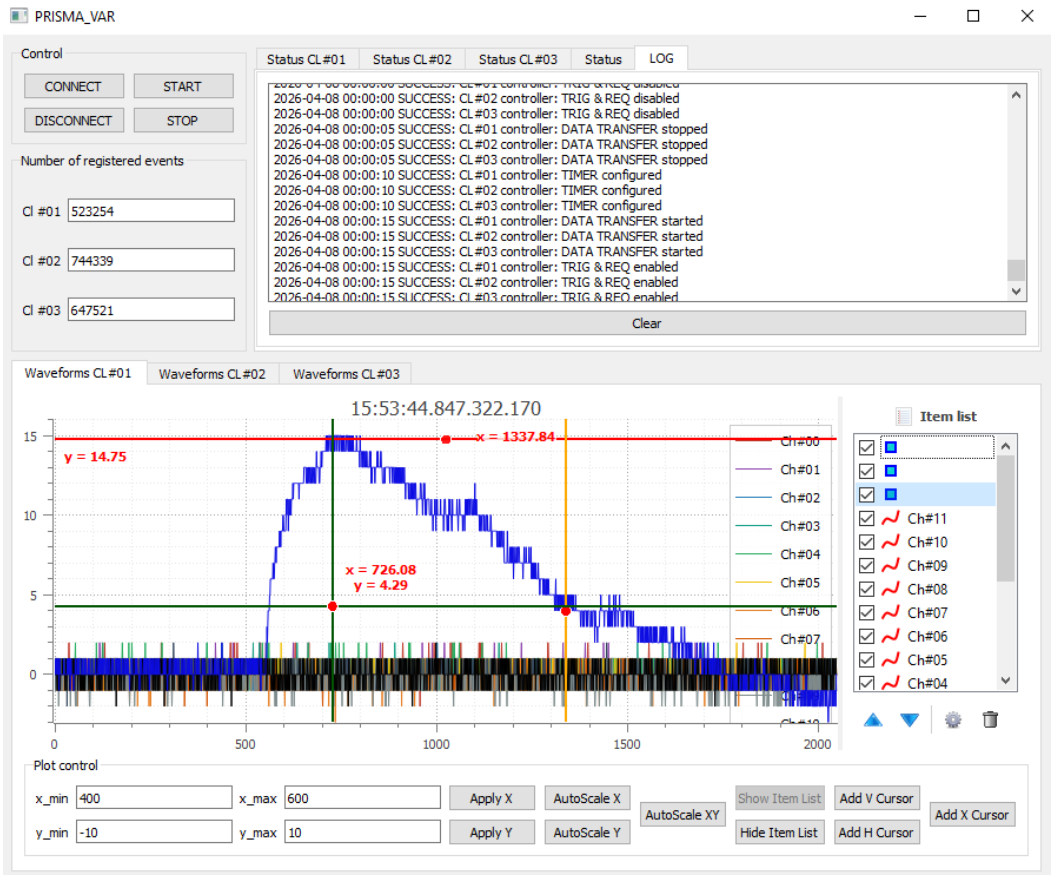


Fig. 4. Graphical interface of the "Server" program for the PRISMA-36.

3.3. Software interface: Online Client

In the development process, we followed the classical principles of Gestalt psychology, namely: proximity (grouping of detectors by clusters), similarity (uniform representation of

elements of the same type), and figure-ground segregation (inactive detectors merge with the gray background, thereby not diverting attention) [30]. Additionally, the principle of redundancy is employed—critical information is duplicated in numerical tooltips.

The interface was developed iteratively in accordance with the technical specifications provided by the physicists responsible for the facility, and was repeatedly revised based on their feedback.

The "Online Client" interface consists of 3 main blocks (Fig. 5): program control, graph display, and cluster status display.

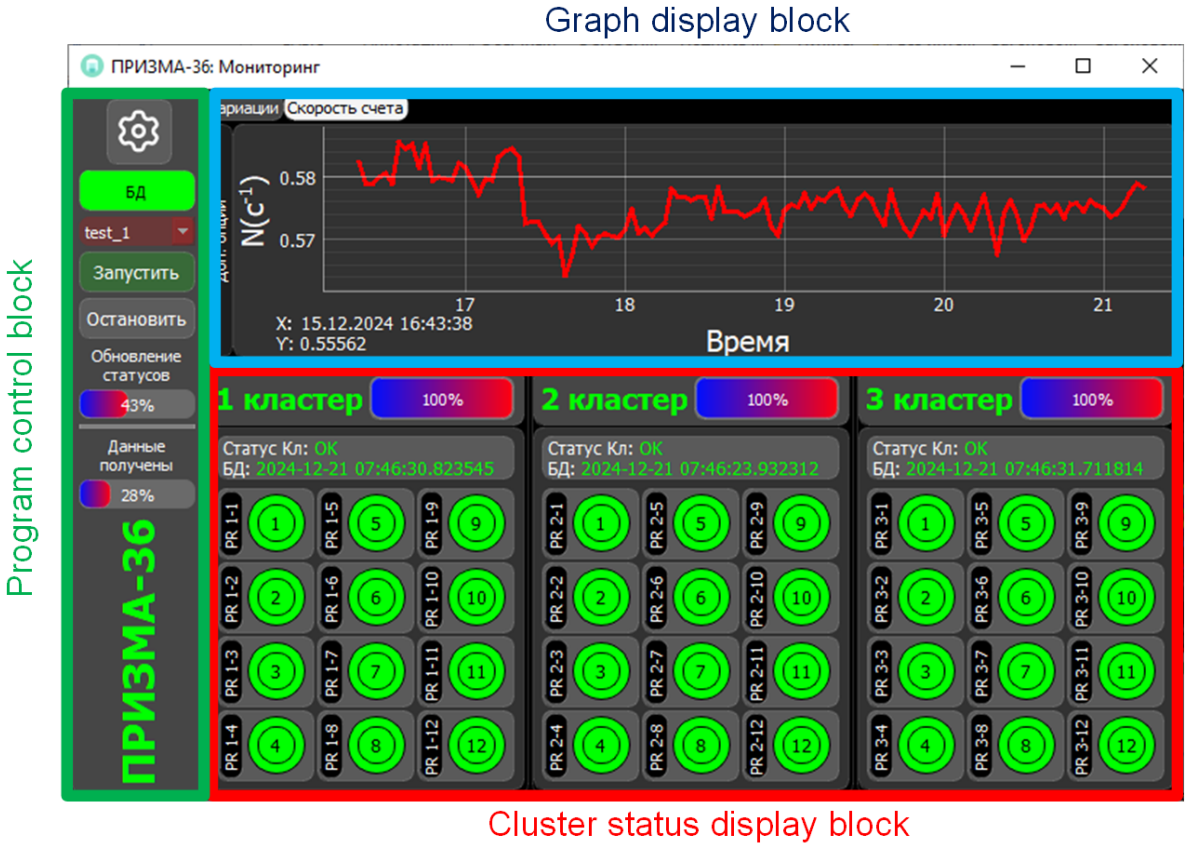


Fig. 5. Graphical user interface of the “Online Client” for the PRISMA-36.

The program control block (Fig. 6) contains: a button to call the program parameters window, a DB connection status indicator, a dropdown list for selecting the analyzed DB table, buttons to start and stop the program operation in online mode, an indicator bar to present the progress of the cluster status information updating, an indicator bar to show the progress of the graph plotting, and a facility (program) operation indicator.

The DB connection status indicator has two states: flashing green/white during normal program operation with an established DB connection; flashing red/white when the DB connection is lost.

If the DB connection is established, the list of experimental tables available in the database is automatically loaded. After selecting the table corresponding to the current measurement, the monitoring of the PRISMA-36 facility operation can be started.

The program parameters window (Fig. 10) allows setting threshold conditions and selection criteria (see Section 2), which are taken into account when analyzing experimental data, for each detector of the facility.

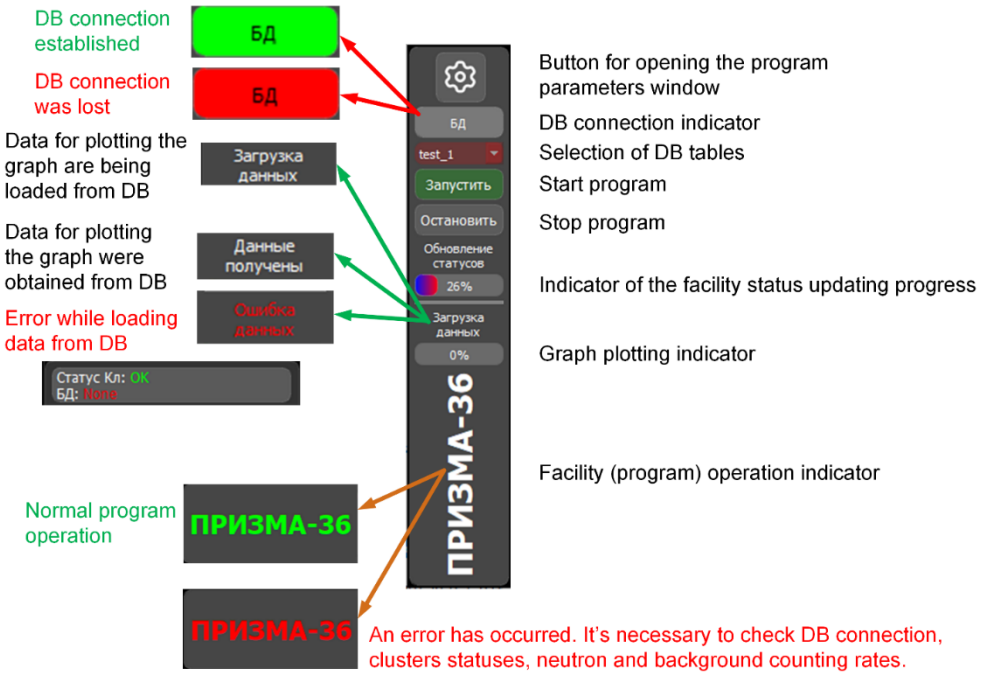


Fig. 6. Program control block of the "Online Client".

During monitoring, the data are periodically (the interval is set in the configuration file) exported from the DB in automatic mode. After analysis, the graphs and cluster statuses are updated.

The indicator (bar) of the facility status updating progress shows the time remaining until the next update.

The graph plotting indicator consists of a text field and a bar. The text field can take the following values: "Loading data"/"Загрузка данных", "Data received"/"Данные получены", "Data error"/"Ошибка данных". The bar shows the time until the next graph update.

The facility (program) operation indicator has two states: flashing green/white during normal facility (program) operation; flashing red/white when the DB connection is lost, when neutron and background counting rate values for individual detectors go beyond the specified range, or when no new data appears in the DB for more than 5 minutes from the current time.

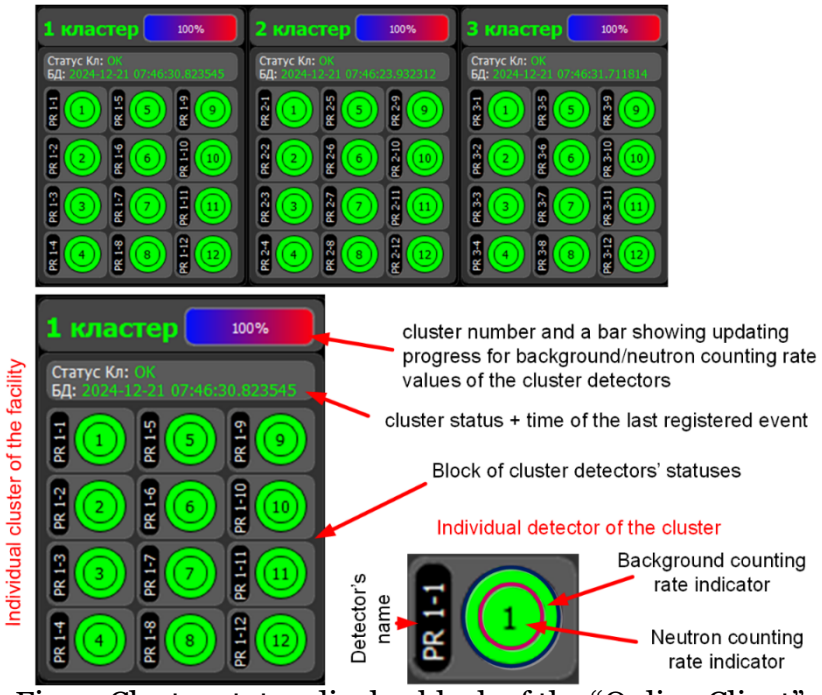


Fig. 7. Cluster status display block of the "Online Client".



Fig. 8. Indicators of detector and cluster statuses.

The cluster status display block (Fig. 7) includes a set of "cluster" widgets (three widgets for PRISMA-36). Each such widget consists of: a cell with the cluster number and a bar showing updating progress for background/neutron counting rate values of the cluster detectors; a cluster status cell indicating the time of the last registered event; a block of 12 cells symbolically representing the statuses of the cluster detectors.

The circular form factor was selected for three reasons: compactness when displaying 36 or more detectors on a single panel, high-speed state recognition via peripheral vision, and visual correspondence to the circular geometry of detectors within the clusters.

The detector cell indicates the detector number (in this case, "PR 1-1" means "first detector of the first cluster of the PRISMA-36 facility"). A background/neutron counting rate is presented by outer/inner circle of indicator. Hovering the mouse pointer over the indicator displays the corresponding background/neutron counting rate averaged over one minute since the last data update.

The status of each detector is represented using a traffic-light color code (green for nominal performance, orange for pre-critical deviations, and red for critical violations of preset thresholds). This coding convention is widely established in industrial process monitoring and, being intuitive, obviates the need for specialized user training.

Possible color options for detector and cluster indicators are: gray — disabled, green — normal operation, orange — warning mode, red — alarm mode. Variants of detector indication and cluster status are shown in Fig. 8. Threshold values for changing indicator colors are set in the program parameters window (Fig. 10).

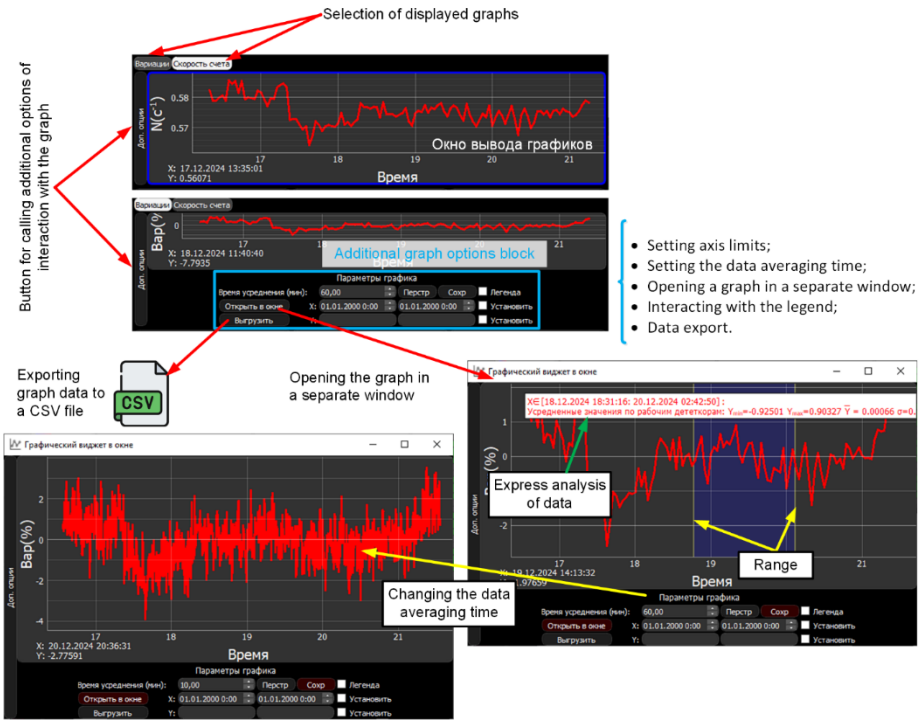


Fig. 9. Graph display block.

The graph display block (Fig. 9) consists of: a graph output window, buttons for selecting the type of displayed graph, and a button for calling additional functionality.

The graph output window displays a plot of the neutron counting rate averaged over all operating detectors of the facility, or a plot of its variations. The plots are rendered in a linear scale, since the ranges of all monitored quantities are known in advance and do not exceed one to two orders of magnitude. Logarithmic representation is not required, as operators are primarily concerned with absolute deviations from nominal values. The averaging interval is user-definable, enabling the display to be adapted to the specific task at hand—ranging from the detection of short-duration bursts to the analysis of long-term trends. The duration of the displayed time interval is set in the configuration file. It is possible to interact with the graph output window using mouse buttons: stretching/compressing the graph along axes, moving across the graph scene, calling the "range" express-analysis tool (the minimum, maximum, and average values, as well as the standard deviation of the displayed quantity are determined for the selected time interval).

Additional functionality of the graph display block, revealed by clicking the "Advanced options"/"Доп. опции" button, includes: setting axis limits, setting averaging time, hiding/showing the legend, and exporting the data presented in the window to a CSV file.

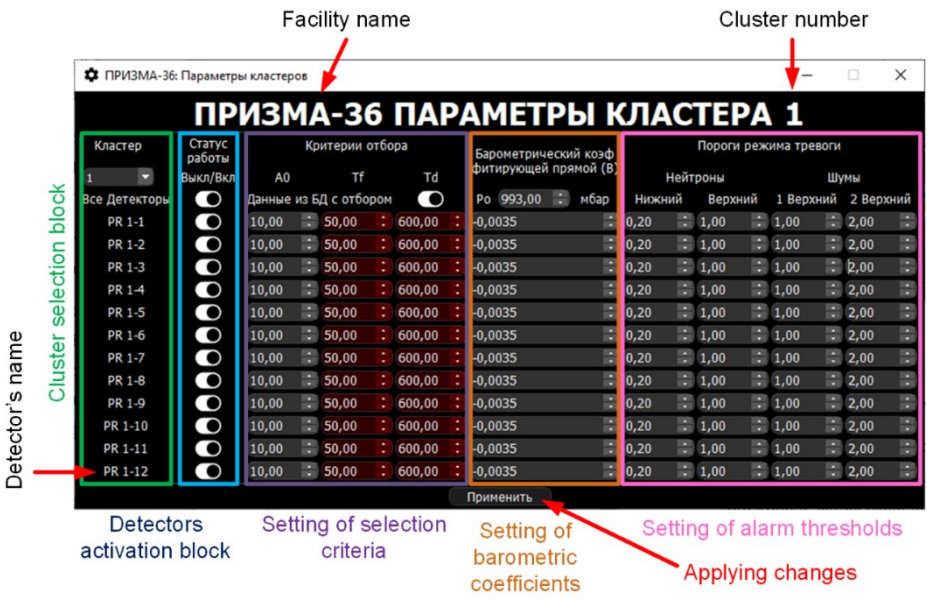


Fig. 10. Program parameters window of the “Online Client”.

The program parameters window (Fig. 10) consists of five blocks:

- a cluster selection block, including a dropdown list of facility clusters and a list of their detectors;
- a cluster detectors block for including/excluding individual detectors from analysis;
- a block for setting cluster event selection conditions and criteria for data analysis based on amplitude (A0), duration (Td), and rise time (Tf) of the signal;
- a block for setting barometric coefficient values for detectors and the mean atmospheric pressure Po for the cluster in mbar, which are taken into account when plotting graphs;
- a block for setting alarm thresholds, which are taken into account when coloring the neutron and background counting rate indicators for individual detectors.

3.4. Software interface: Offline Client

The graphical user interface of the "Offline Client" program consists of 2 main blocks (Fig. 11): DB interaction and graph display.

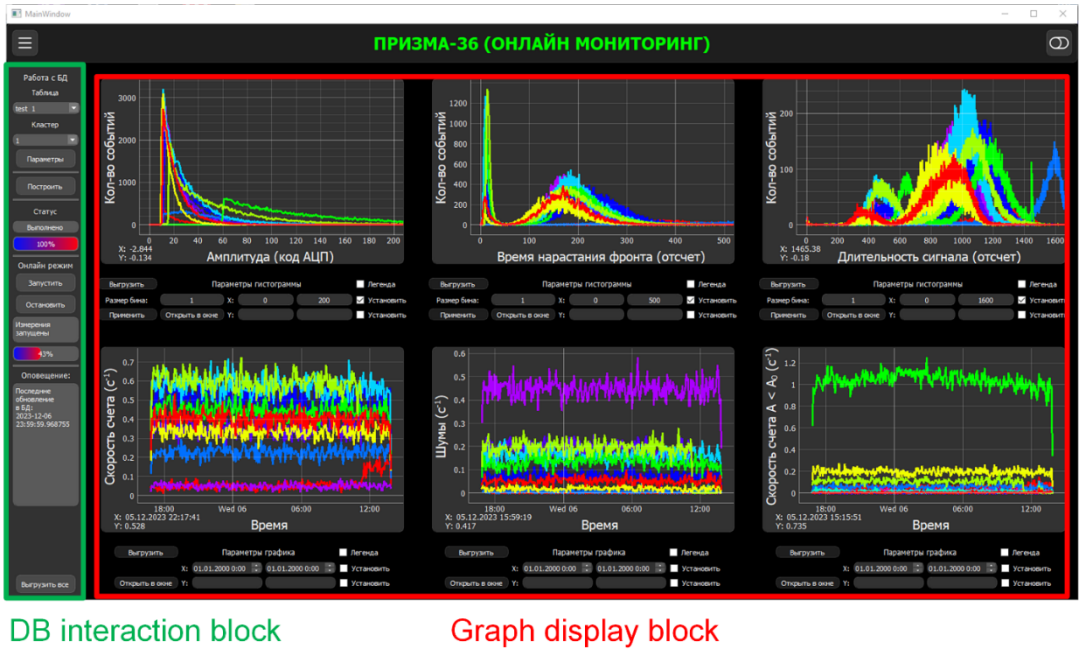


Fig. 11. Graphical user interface of the “Offline Client” for the PRISMA-36.

The graph display block contains 6 interactive graphical widgets (Fig. 12): three are used to display histograms of amplitudes, rise times, and durations of signals from detectors, and the others are used to display graphs of neutron and background counting rates, as well as amplitude-limited counting rates for each detector of one cluster. Interaction with the graphical widgets is similar to interaction with the “Online Client” graph display window (described above). Additionally, histogram widgets provides opportunity to change the bin width. Each graphical widget displays parameter values for 12 detectors of one cluster of the facility over a specified time interval.

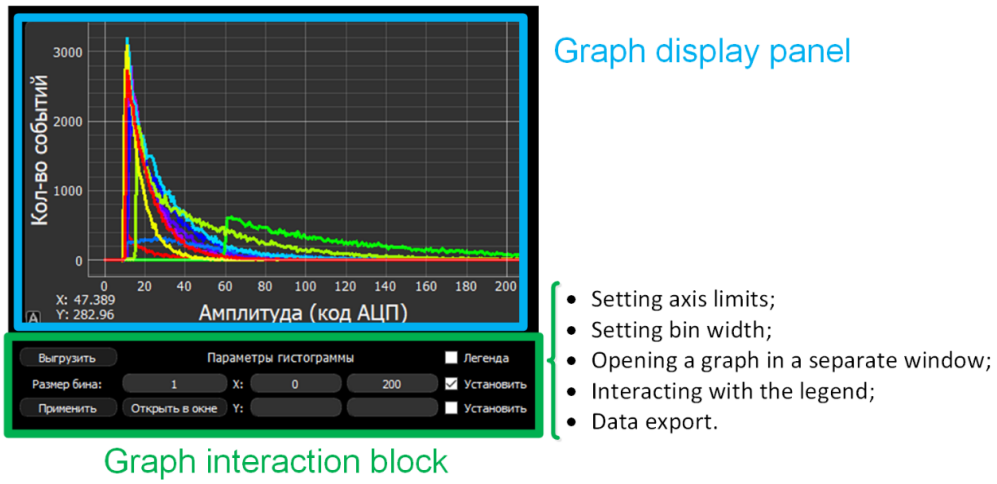


Fig. 12. Graphical widget (for histograms) in the “Offline Client” for the PRISMA-36.

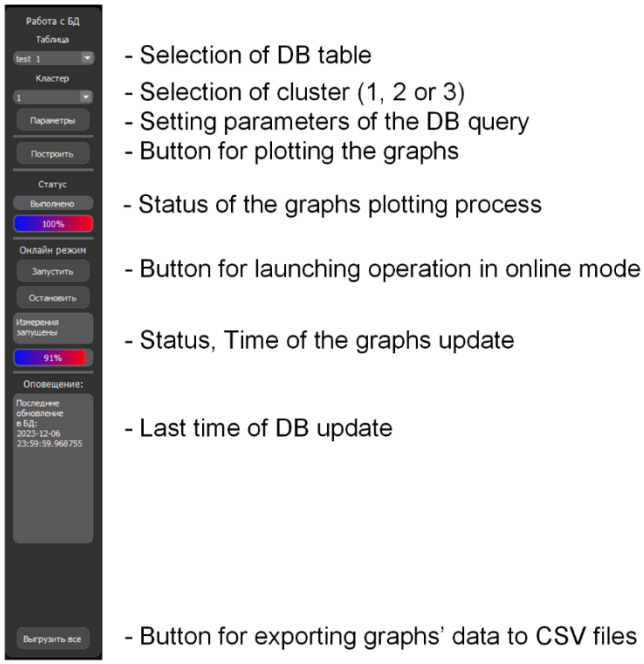


Fig. 13. DB interaction block in the “Offline Client” for the PRISMA-36.

The DB interaction block (Fig. 13) consists of 9 fields and allows user to:

- select a specific table from the facility DB and the cluster for which the measurement results will be displayed;
- set parameters for the query sent to the DB (Fig. 14);
- plot graphs with taking into account the set parameters;
- start online mode, in which the graphs are automatically updated at 1-minute intervals (a graph for the last 24 hours from the current time is displayed);
- obtain information about the time of the last DB update;

- export data processing results to a CSV file.

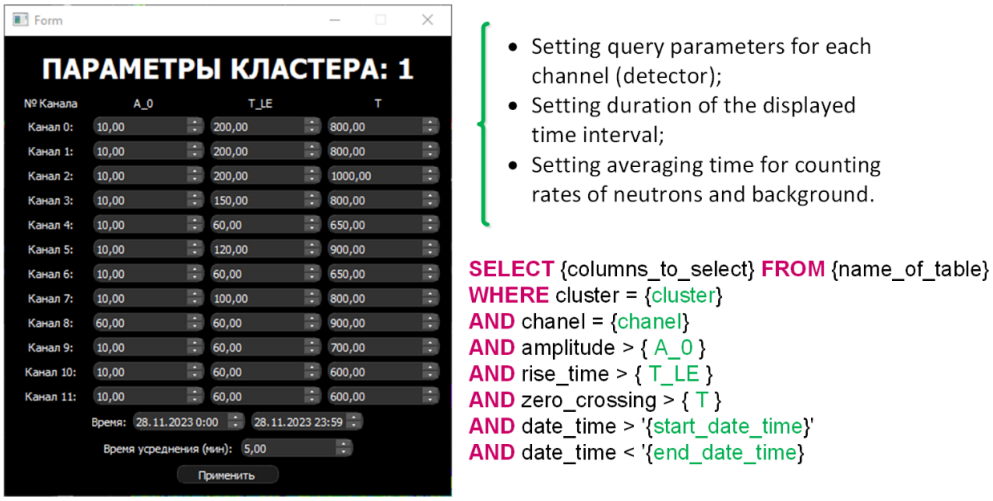


Fig. 14. DB query parameters.

When setting DB query parameters, the user inputs boundary values for amplitude, rise time, and signal duration. Based on these values, the query is subsequently formed, and neutron and background signals are separated.

If an error occurs in the program, the program title and the "Online mode" label flash red. Such errors may be caused by a DB server stop, loss of DB connection, or incorrect input of DB query parameters.

4. Implementation

Using the developed software, the GLE 77 event (a sharp increase in the number of protons in cosmic rays caused by a class X5.1 solar flare) was observed with the PRISMA-36 and URAN facilities in real time on November 11, 2025 [31]. The relative increase in counting rate reached a maximum of 20.1% ± 1.1% at the PRISMA-36 facility and 24.8% ± 1.3% at the URAN facility. The event was compared with observations from the neutron monitor (NM) network, which recorded an increase in neutron counting rate of about 20.9% ± 0.5% (for the Moscow NM) and 102.5% ± 0.1% (for the SOPO NM).

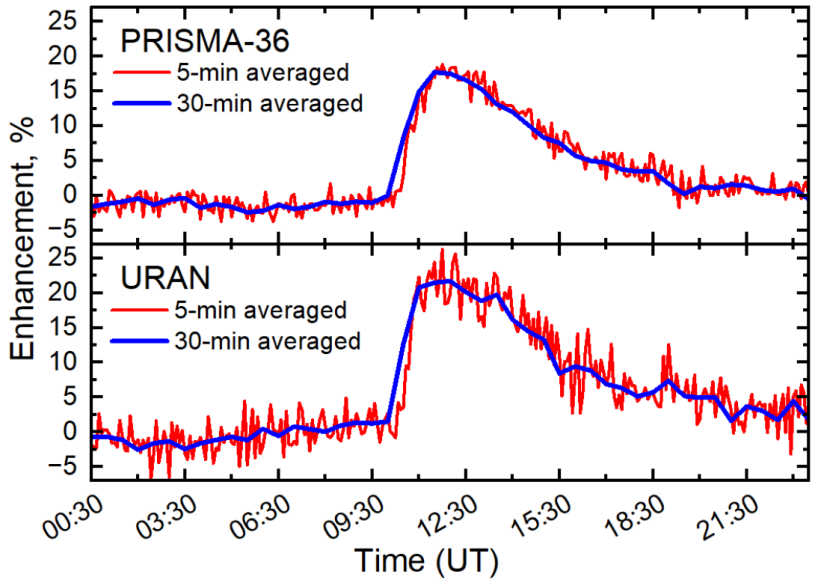


Fig. 15. Time profiles of a neutron flux enhancement observed by neutron detectors of the PRISMA-36 and URAN facilities.

5. Conclusions

A modern experiment in cosmic ray physics represents a comprehensive research toolkit that, in addition to complex recording equipment, includes specialized software for visualization and interpretation of experimental data.

The specialized software for studying variations in the intensity of the cosmic ray flux using the neutron facilities PRISMA-36, URAN, and "Neutron" of the Experimental Complex NEVOD has been developed in the Python programming language. The software allows observing changes in cosmic ray variations, monitoring the average neutron counting rate in real time, as well as offline monitoring of the parameters of individual detectors of the EC NEVOD neutron facilities and analyzing data from the facilities over a specified time interval in mode.

The approach to real-time visualization of data from the EC NEVOD neutron facilities enables fast identification of unique events in cosmic ray physics (powerful solar storms, Forbush decreases, etc.), and to study various periodic effects during the analysis of experimental data over long-time intervals in offline mode.

Acknowledgments

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