ISSN 1063-7788, Physics of Atomic Nuclei, 2024, Vol. 87, Suppl. 2, pp. S305–S313. © Pleiades Publishing, Ltd., 2024.

## ELEMENTARY PARTICLES AND FIELDS
### Experiment

# Muography Experiments in Russia with Emulsion-Based Detectors

**A. B. Alexandrov[1,2], P. A. Babaev[1], A. A. Gippius[1], S. A. Gorbunov[1], V. M. Grachev[3], N. S. Konovalova[1,2], Y. O. Krasilnikova[2], A. A. Larionov[3], A. K. Managadze[4], I. A. Melnichenko[2], N. M. Okateva[1,2], S. S. Paramonov[2], A. A. Petrukhin[3], N. G. Polukhina[1,2,3*], T. M. Roganova[4], Z. T. Sadykov[1,2], N. I. Starkov[1,2], E. N. Starkova[1], D. M. Strekalina[1], V. E. Tyukov[1], M. M. Chernyavskiy[1], V. I. Shevchenko[3], T. V. Shchedrina[1,2], D. I. Zainutdinov[1], and A. E. Volkov[1]**

[1]*Lebedev Physical Institute, Russian Academy of Sciences, Moscow, 119991 Russia*

[2]*National University of Science and Technology MISIS, 119049 Moscow, Russia*

[3]*National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, 115409 Russia*

[4]*Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, 119991 Russia*

Received November 25, 2024; revised November 26, 2024; accepted November 26, 2024

**Abstract**—The scientific and technological base of muography researches using emulsion detectors, including the equipment and software, is developed and actively used in Russia by the MISIS, NRU MEPhI, SINP MSU and LPI RAS collaboration. The article presents a number of experiments performed with the emulsion muography and illustrates the major stages of the method development and improvement.

**DOI:** 10.1134/S1063778824700935

## 1. INTRODUCTION

Muography is a tool for studying the density variations in large natural and artificial objects. The physical properties of atmospheric muons, such as speed close to the speed of light, the almost complete absence of strong interactions, and relatively large mass, allow them to reach the Earth's surface and penetrate hundreds of meters deeper. Due to the wide energy spectrum, the weakening of muon fluxes relates to the amount of the passed matter: muons from the low-energy part of spectrum stop in first meters of the soil, while the high-energy muons penetrate kilometers deep into the Earth's crust. Recorded by measuring devices, the atmospheric muon fluxes can be used as a tool for probing objects on the Earth's surface [1].

Electronic or emulsion detectors can be used as registering devices. The advantages of emulsion detectors include high space and angular resolution, long exposure time in various environment, small size and simple construction. Independence of power supplies and electronic reading systems, as well as the absence of the necessity of operative control over the experiment during the whole exposure period, provide more possibilities of emulsion detectors for muography applications.

The main disadvantage of the emulsion technique until recently was the labor-intensive processing of the tracks on the microscope. This drawback has been overcome by the use of scanning automated microscopes equipped with high-speed video cameras providing digital readout, high-speed image processing and track reconstruction within the detector volume. The new equipment can store data up to several terabytes. The first in Russia successfully functioning automated scanning complex PAVICOM (Fully Automated Measuring Complex) [2, 3] was created in Lebedev Physical Institute (LPI). Its facilities are used for processing data of track detectors of various types, in particular, to search for and digitize tracks and to perform primary data analysis.

The work being carried out by the MISIS, NRU MEPhI, SINP MSU, and LPI RAS collaboration since 2012 demonstrates the specific results of muography based on emulsion detectors and their scientific importance. The accumulated experimental base allowed for developing and improving the data processing and analysis tools, and to develop algorithm for vi-

*E-mail: polukhinang@lebedev.ru

sualizing the internal structure of the studied objects with account for the static and dynamic effects. The article presents the main stages of development and improvement of the muography method in Russia on the example of experiments using detectors based on photographic nuclear emulsion.

## 2. THE METHOD TESTING: SEARCH FOR KNOWN DENSITY ANOMALIES

The first stage of research was aimed at testing the method using detectors based on Russian-made nuclear emulsion and to find optimal and efficient technical solutions for its implementation. The object of the first test muography experiment was a massive steel column of 23 tons used as muon absorber creating a "shadow" in the incident atmospheric muons flux [4]. The goal of the study was to compare muon fluxes under different absorption conditions, i.e. when passing different distances through the object medium. Emulsion recorded tracks were differentiated by solid angles of particle arrival to analyze the inhomogeneity of muon fluxes corresponding to different path lengths in the absorber.

The GEANT4 software tool was used for simulation of the expected muon fluxes in the emulsion detectors located inside and outside the column body at different solid angles.

The experiment enabled to test the emulsion detector assembly and data processing methods. The obtained experimental data demonstrated full compliance with simulation results and the correctness of the taken approach. In addition, the experiment confirmed the high quality of the Russian-made nuclear emulsion produced by the Russian company Slavich Noya Technologies LLC.

The second test experiment was carried out on the equipment of the Research Institute of Tyre Industry in Moscow [5]. Two massive discs of a treadmill (an inertial element of the test bench) with diameter of 3 m and weight of 20 tons each were observed (Fig. 1*a*). The distribution of muon tracks over the azimuthal and zenith angles ($\varphi$ and $\theta$) obtained in detector clearly showed the "shadow" from a disc (Fig. 1*b*).

The next experiment was conducted in 2014 in an underground mine located on the territory of the Geophysical Service of the Russian Academy of Sciences in Obninsk [4]. The plan was to measure the difference in the intensities of atmospheric muon fluxes at ground level and at a depth of 30 m, and to detect a large cavity (elevator shaft) by registering the excess of muons in the corresponding direction (Fig. 2*a*).

For the result presentation, the angular variables $tx$ and $ty$ were used, which are the tangents of the track tilt angles in projections on the $xz$, $yz$ planes, where the $xy$ plane coincides with the plane of the detector and the ground surface, and the $z$ axis is directed vertically upwards. In these coordinates, the resulting representation is similar to a photographic image of an object in "muon beams." The variables are defined as $tx = \frac{dx}{dz} = \tan(\theta)\cos(\varphi)$, $ty = \frac{dy}{dz} = \tan(\theta)\sin(\varphi)$, where $\varphi$ and $\theta$ are the azimuthal and zenith angles of the track, respectively.

In the experiment, the excess of the muon flux at the ground level over the one at a depth of 30 m by about fifty times was fixed, which was in good agreement with the calculated estimates. The signal from the elevator shaft is highlighted with a frame on the experimental distribution in Fig. 2*b*.

Other soil density peculiarities observed in the distribution in Fig. 2*b* are related to the lens of marble-like limestone around the mine. It was the first muographic observation of an undeclared density anomaly in the studied area. Thus, the results of test experiments carried out by the muography method demonstrated the possibilities of the emulsion technique to obtain reliable data on the structure of the investigated objects.

## 3. LARGE-SCALE MUOGRAPHY STUDIES: SEARCH FOR PREVIOUSLY UNKNOWN CAVITIES AND HIGH-DENSE AREAS

A series of experiments on the study of monuments of cultural heritage of Russia were carried out by the muography method. An underground cross-domed structure of unknown purpose was studied in the architectural complex of the citadel of Naryn-Kala (Derbent, Dagestan), a UNESCO World Heritage Site. The research results made it possible to determine the size and density of the structure walls [6].

Another large-scale experiment was held in 2020 on the territory of the Holy Trinity Danilov Monastery in Pereslavl-Zalessky (Yaroslavl region), a historical and architectural site of federal significance [7]. Muography was applied as an alternative research method on the territory of a historical monument and functioning monastery, where traditional excavations were impossible. The monastery buildings and the area between them, where ancient underground burials and fragments of foundations of lost structures may presumably be located, were surveyed; 21 emulsion detectors were installed in the basements of the surviving buildings.

Processing of experimental data included the following steps: automatic scanning and online reconstruction of tracks in each separate emulsion plate; reconstruction of tracks through the entire emulsion detector (several emulsion plates); obtaining the

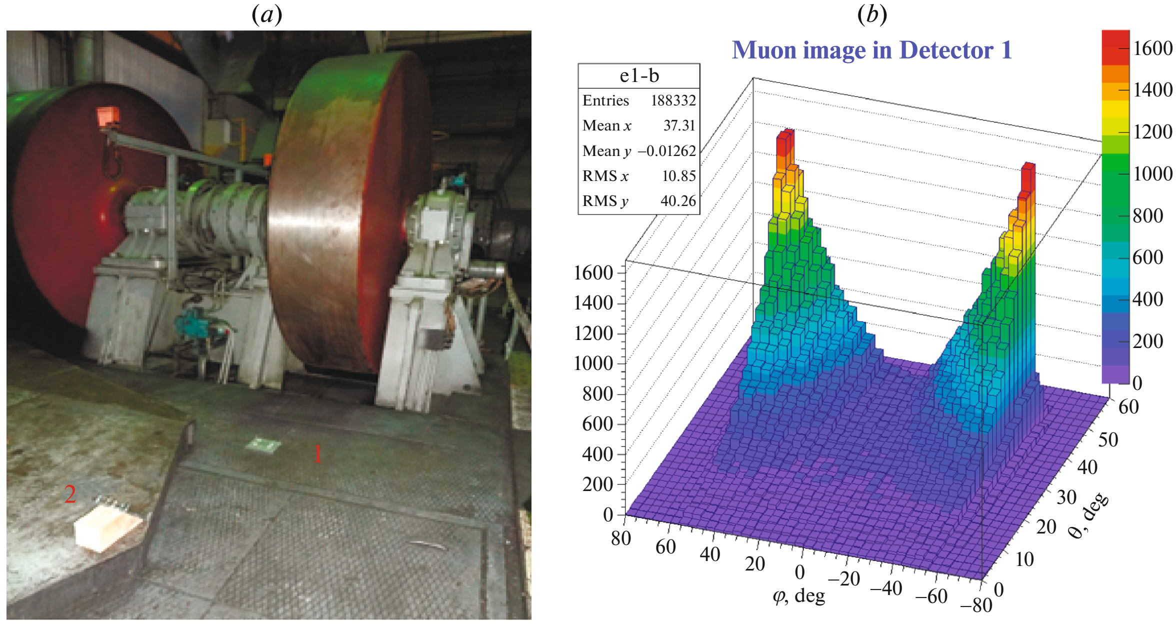


**Fig. 1.** Test experiment on the tyre bench: (*a*) position of emulsion detectors relative to the treadmill discs; (*b*) experimental distribution over angular variables $\varphi$ and $\theta$ of muon tracks registered in detector 1.

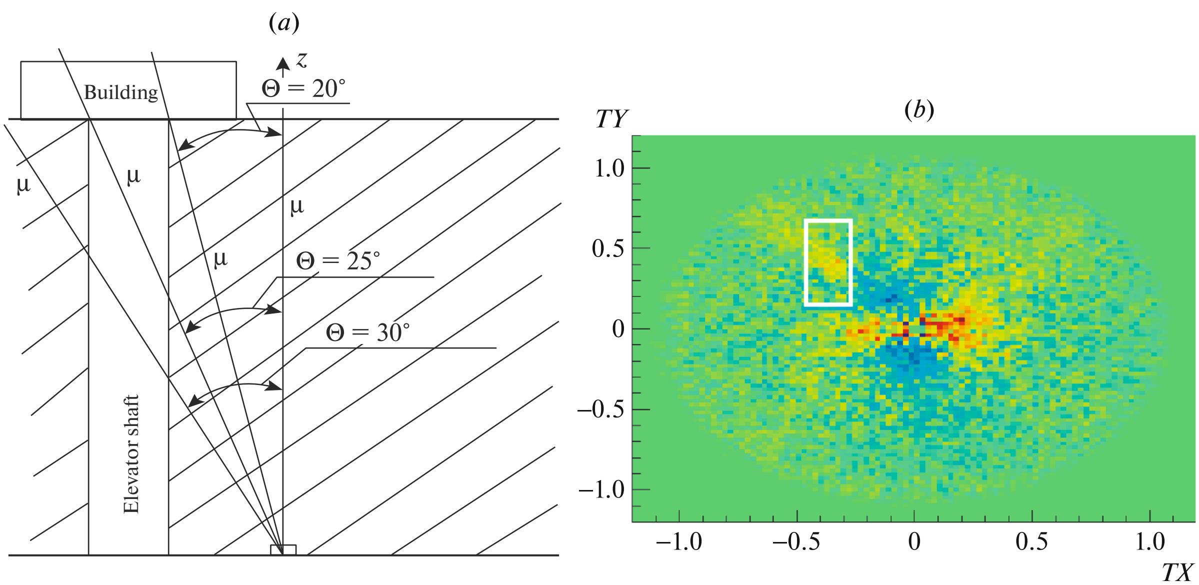


**Fig. 2.** (*a*) Scheme of the experiment in the mine at a depth of 30 m; (*b*) 2D distribution $(tx, ty)$ of the muon flux at a depth of 30 m; the frame highlights the signal from the lift shaft.

muon angular distributions in each detector; combining all detectors on the exposure into a single coordinate system; application of a unique algorithm for searching for local maxima to identify density anomalies of the studied objects; presentation of results in a comprehensible form by superimposing experimental data on geodetic and LIDAR survey data; construction of a 3D model of the detected anomalies.

Analysis of muon angular distributions of muon fluxes registered by each detector in terms of azimuthal angle $\varphi$ and zenith angle $\theta$ was performed by dividing the solid angle into elements $(\Delta\varphi, \Delta\theta)$ (bins) [8]. This distribution demonstrates the difference in the degree of muon absorption in different directions, and hence the difference in the distribution of the material in the survey sector. An applied visual representation of the data in the form of level lines, based on the determination of derivatives while smoothing, was more sensitive to irregularities in discrete distri-

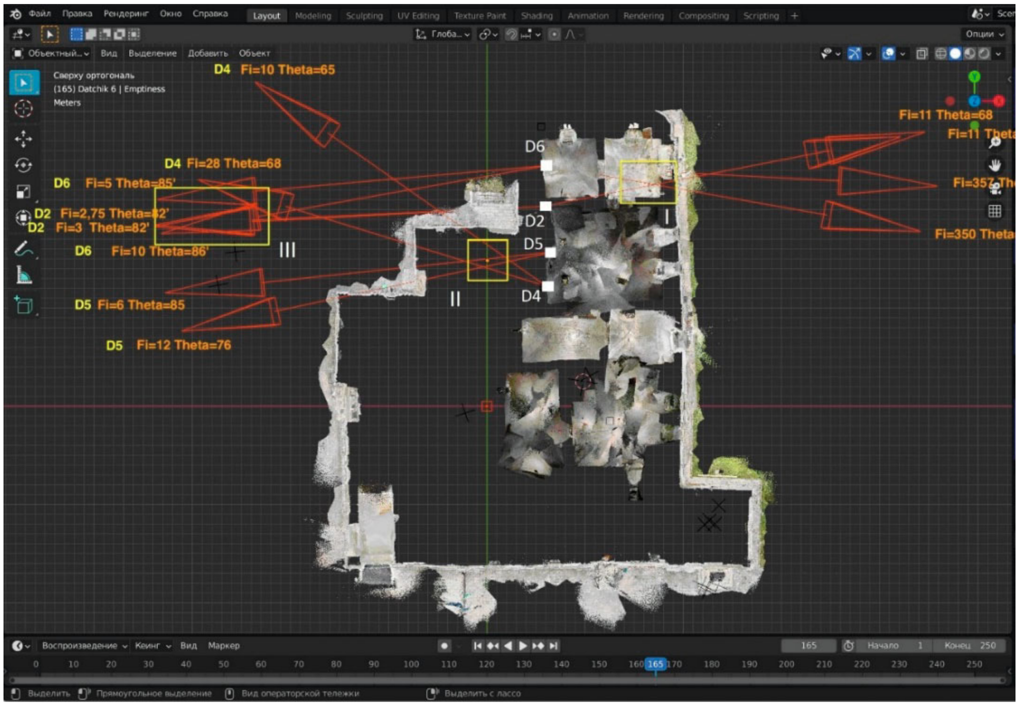


**Fig. 3.** Cavities detected by four detectors (nos. 2, 4, 5 and 6) on the territory of the Holy Trinity Danilov Monastery (indicated by yellow frames).

**Fig. 4.** General view of the Holy Dormition Pskovo-Pechersky Monastery obtained by aerial photography. The arrow shows the entrance to the cave temple.

butions, such as the number of muons in neighboring bins.

In this and subsequent experiments, the reliability of the developed data analysis algorithms was tested using visible architectural elements within the detectors' sectors of view (e.g. door and window openings, transitions between rooms, etc.). The results of the verification analysis demonstrated the correspondence between the features of the level lines of the experimental distributions and the directions to the visible building fragments [8].

To search for and explore inaccessible areas, such as hidden parts of basements, unknown burials or historical foundations, pairwise intersections of solid angles' intervals (beams) of detectors were used, in which features were observed on the level lines

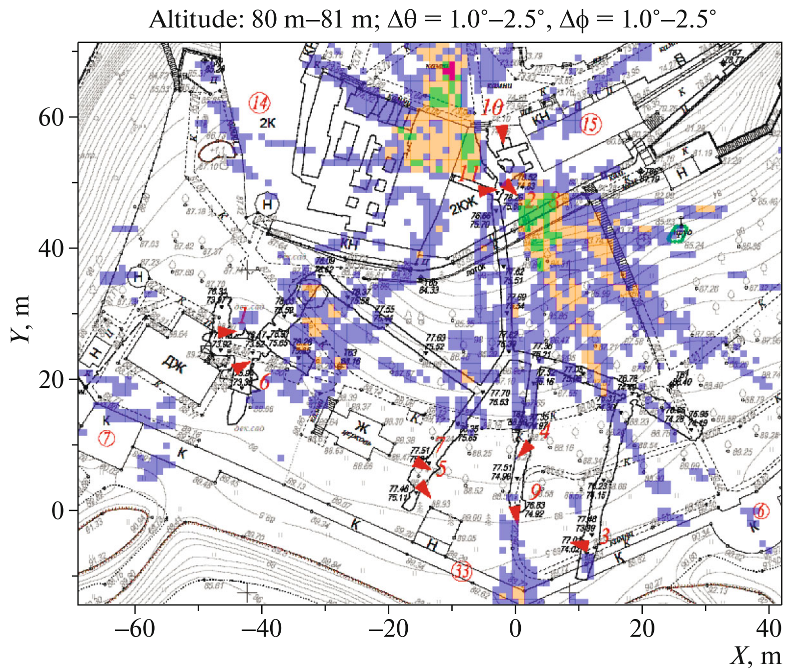


**Fig. 5.** The map of the local maxima intersections at a depth of $Z = 80-81$ m, obtained by emulsion detectors data.

(bulges corresponding to less dense areas, or depressions corresponding to denser areas). As a result, areas are identified in which fragments with abnormal density were presumably located.

To obtain a 3D image of each examined area, data of several detectors aimed at this area was used. One detector provided information about the presence of some structural peculiarity in the direction of only its own viewing sector, while the intersection of two or more sectors of different detectors provided the position of this peculiarity in space. Visualization of the obtained results was carried out by superimposing the emulsion detectors' processing data on LIDAR imaging.

One of the areas with reduced soil density (possibly an ancient burial site) was found underground between the buildings of two churches in the area of intersection beams of detectors nos. 2 and 6 (Fig. 3). This area is highlighted by a large yellow frame in Fig. 3. The smaller frame indicates a density anomaly detected in the basement of one of the temples by detectors nos. 4 and 5.

Based on the given algorithm, the alleged locations of previously unknown voids in the building basements, features of the foundation of one of the churches, and large voids underground, presumably ancient crypts were discovered [9]. The works on the study of the buildings and territory of the Holy Trinity Danilov Monastery in Pereslavl-Zalessky and the Naryn-Kala fortress were awarded the Metropolitan Makarii Prize for Natural Sciences for 2022.

The next large-scale muography experiment was held in the "God-built caves" of the Holy Dormition Pskovo–Pechersky Monastery, a temple complex located in underground galleries of karst (Fig. 4) [10]. The research was timed to coincide with the 550th anniversary of the founding of one of the largest and oldest monasteries in Russia, an object of cultural heritage. Seven known underground galleries ("streets") have a total length of more than 200 m and are located at a depth of 3 to 15 m under a sandstone hill. For the search for hidden voids in the galleries, 11 emulsion detectors were aimed at the possible positions of these voids. To combine the position of the installed detectors into a single coordinate system, a geodetic survey with the centimeter accuracy was carried out [11].

To process the obtained data, an original technique for searching for intersections for the local maxima (extremes) in the angular distributions of the recorded tracks, corresponding to the structure features, was developed. A local maximum indicates direction with a reduced amount of material (possible hollow), and a local minimum corresponds to direction with an increased amount of material or an area with higher density.

All the possible track directions in detector were sorted by angles $\varphi$ and $\theta$. To search for intersections of maxima recorded by each detector, the volume under study was conditionally divided into cubes with a side of 1 m. If the range of directions (bins) $(\varphi, \varphi +$

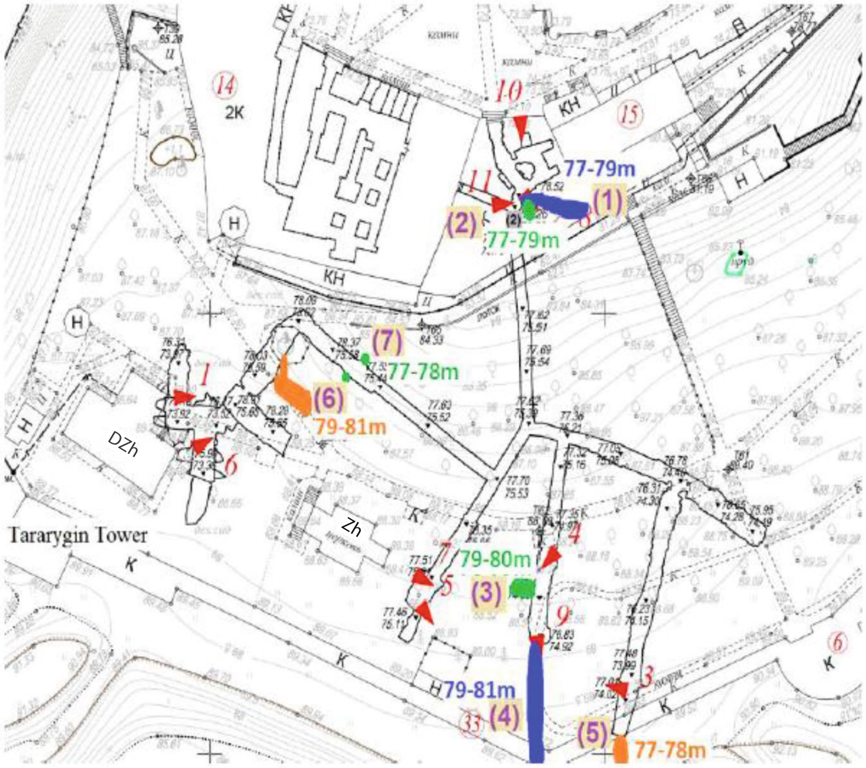


**Fig. 6.** A map of the detected voids with an indication of heights in the intersections of local maxima of muon fluxes recorded by emulsion detectors (detectors are indicated by red triangles, the acute angle of which is directed to the observation area).

$\Delta\varphi$) and $(\theta, \theta + \Delta\theta)$ corresponding to a local maximum of the track distribution on $\varphi$ and $\theta$ intersected this cube, it was plotted on the map of local maxima intersections. According to this scenario, a function $G(X, Y, Z)$ was constructed with an interval of 1 m for each spatial variable. If the volume element with coordinates $(X, Y, Z)$ intersected a local maximum of the muon flux registered by a single detector, the function $G(X, Y, Z)$ was assigned the value 1; if the volume element was intersected by the local maxima from two detectors, $G(X, Y, Z) = 2$, etc. The hidden cavities were the most likely positioned where the local maxima from the largest number of detectors intersected.

As an illustration to this algorithm, Fig. 5 shows a map of the local maxima intersections at the height of $Z = 80{-}81$ m (measured from the Baltic Sea level) on the map of the monastery. To increase reliability, Fig. 5 shows the sum of the $G$ functions obtained using the algorithm for four binning variants used in constructing distributions of the registered muons: $\{\Delta\varphi = 1.0°;\ \Delta\theta = 1.0°\}$, $\{\Delta\varphi = 1.5°;\ \Delta\theta = 1.5°\}$, $\{\Delta\varphi = 2.0°;\ \Delta\theta = 2.0°\}$, $\{\Delta\varphi = 2.5°;\ \Delta\theta = 2.5°\}$. Blue color corresponds to the function values $4 \le G(X, Y, Z) < 8$, orange—to $8 \le G(X, Y, Z) < 12$, and green—to $12 \le G(X, Y, Z) < 16$.

For clarity, the most probable underground voids predicted in the experiment are indicated on the cave map in Fig. 6. Numbers in Fig. 6 indicate the voids found in the experiment: *1*—a corridor with a width of 1 to 3 m and a length of up to 12 m branching off from a hidden crypt; *2*—the crypt behind the icon at the entrance to the Cave Temple, the size of which is estimated as $2.5 \times 2.5$ m$^2$; *3*—the chamber between the Bratskaya and Troitskaya streets; *4*—continuation of the Troitskaya Street along its main direction.

The data also indicate the presence of a void up to 3 m wide in the continuation of the Temple Street (cavity *5*) and another one of a similar section up to 12 m long extending from one of the caves behind the Pokrovsky Temple (cavities *6* and *7*). These voids, however, were detected less likely due to the smaller number of detectors aimed at the corresponding area.

Presently, processing and analysis of the data of a new experiment for search for hidden density inhomogeneities on the territory of the Kamenny Monastery, located on Kamenny Island in Kubensky Lake (Vologda region), has been completed (Fig. 7). Primarily, the objects of the research were the basements of the destroyed in the mid-1930s Preobrazhensky Cathedral, where a crypt with the remains of the disgraced patriarch of the Russian

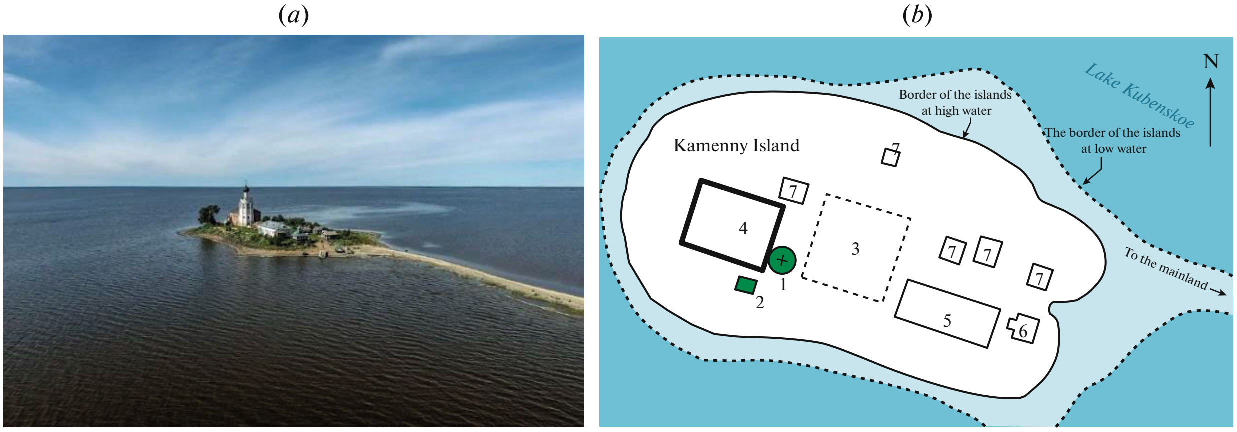


**Fig. 7.** (*a*) The Spaso-Kamenny Preobrazhensky Monastery; (*b*) the map of the monastery buildings: 1—the bell tower of the Church of the Assumption of the Blessed Virgin Mary; 2—the chapel of All Vologda Saints; 3—the Transfiguration Cathedral (in ruins); 4—the church and the fraternal building; 5—the hotel building; 6—the rescue station; 7—outbuildings (5 objects).

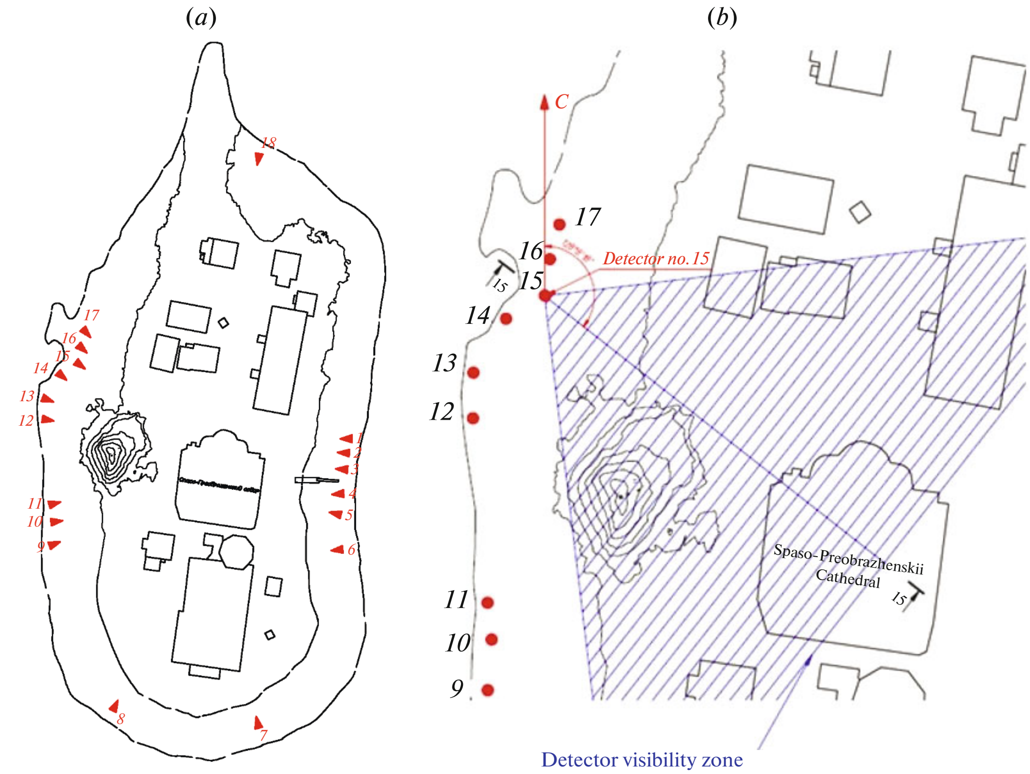


**Fig. 8.** (*a*) The layout of the detectors on Kamenny Island; (*b*) the directional viewing angle of detector no. 15.

Church Metropolitan Varlaam (†1533) is presumably located.

Eighteen emulsion detectors were installed on Kamenny Island oriented so that their view sectors intersected in the central part of the island in the area of the remains of the Preobrazhensky Cathedral (Fig. 8*a*). The relative spatial location of the installed detectors was determined using geodetic data obtained with the Sokkia electronic tacheometer. The directional viewing angles of all detectors were plotted on the topographic map of the monastery on a scale of 1 : 500. As an example, Fig. 8*b* shows the directional viewing angle of detector no. 15.

The first stage of the experiment traditionally consisted in verifying the reliability of the expected results on the visible objects in the studied area. Such observable objects as the burial of the monastery researcher A.N. Piligin and two septic wells on the territory of the island were registered.

The results of data processing of all detectors of

**Fig. 9.** Intersections of local maxima under the ruins of the Transfiguration Cathedral at a depth of 1.5–2.0 m indicating possible cavities under the altar and in the area of the columns.

the main experiment showed the following previously unknown objects: underground cavities under the destroyed temple (Fig. 9), underground cavities between the bell tower and the fraternal corps and under the fraternal corps, and four additional cavities on the monastery territory.

The marked areas in Fig. 9 correspond to the intersections of the maxima recorded in 3–4 detectors. The cavity under the altar may be the burial place of Metropolitan Varlaam. Two of four alleged cavities indicated in Fig. 9 for a depth of 1.5–2.0 m also observed at a depth of 2.0–3.0 m may correspond to the gaps between the foundations of columns or walls.

## 4. CONCLUSION. FACTORS OF THE METHOD DEVELOPMENT

The following main factors set in development of the muography in Russia:

1. The experiments use nuclear emulsion produced at the Russian company Slavich Noya Technologies LLC. It should be noted that the nuclear emulsion production in Russia was completely lost in the 90s. With the participation of the authors, in 2010th this complex technology was restored and is being constantly improved. Emulsion films with different pouring areas and different grain sizes are currently produced in Russia. The quality of the produced double-sided nuclear emulsion films is of the same quality as the product of its only competitor Nagoya University (Japan).

2. Detector design and assembly methods are being continuously improved. Currently, the layers of the nuclear emulsion are packed into light-tight envelopes using a vacuum machine, which eliminates the displacement of the film inside the package and ensures high accuracy of the coordinate reference of the layers. Depending on the size of the emulsion films, specially designed structures are used to mount the detectors at the site. The spatial binding of the detectors to a single terrestrial coordinate system is carried out using geodetic and LIDAR surveys, which provide the centimeter accuracy of the binding necessary for coordinating detector readings and 3D reconstruction of the studied areas. The optimal location for each detector is determined with the account for its observation angle ($\pm 45°$ from perpendicular to the emulsion plane). The number of detectors used is related to the task of reliable "viewing" of the studied areas. In addition, duplicate detectors are sometimes used, depending on the possibility of their installation, the complexity of mounting at the exposition site, or seasonal time constraints (as in the case of the Danilov Monastery, where in spring water flooded the basements to a level of half a meter).

3. In Russia, the modern level of processing and analysis of emulsion data has been achieved at LPI on the Completely Automated Measuring Complex (PAVICOM) allowing for restoration particle tracks in the detector volume in the range of zenith angles up to 75 degrees. The tool base and software of the complex are constantly being upgraded and improved [3, 12], expanding its scanning capabilities for emulsion films of different size at a high speed reaching 190 $cm^2/h$.

4. New methods of data analysis and visualization of the results obtained using modern computer technologies are continuously being developed and implemented. Registration of known architectural elements and objects on the territory under study confirms the validity of the technical and analytical solutions and the reliability of the obtained results. A method for searching and estimating the dimensions of the density anomalies using intersections of local maxima of muon fluxes recorded by several detectors has been developed.

New author's design solutions concerning emulsion scanning techniques, innovative original algorithms for recognizing the hidden three-dimensional structure of the objects under study and confirming the reliability of the results obtained have been developed and successfully applied. The development of the technique allows for studying complicated objects of different nature with a high degree of reliability. The authors of the article are the single scientific group in Russia successfully implementing the large-scale muonographic studies based on the emulsion technique.

## FUNDING

This work was supported by the Russian Science Foundation, project no. 23-12-00054 project no. 23-12-00054 under the program "Conducting Basic Scientific Research and Search Scientific Research by Individual Scientific Groups."

## CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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