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Research Article

Cosmic Muon Detection for Geophysical Applications

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A portable cosmic muon detector has been developed for environmental, geophysical, or industrial applications. The device is a tracking detector based on the Close Cathode Chamber, an MWPC-like technology, allowing operation in natural underground caves or artificial tunnels, far from laboratory conditions. The compact, low power consumption system with sensitive surface of 0.1 m^2 measures the angular distribution of cosmic muons with a resolution of 10 mrad, allowing for a detailed mapping of the rock thickness above the muon detector. Demonstration of applicability of the muon telescope (REGARD Muontomograph) for civil engineering and measurements in artificial underground tunnels or caverns are presented.

1. Introduction

Cosmic accelerators provide the highest energy particles which continually hit our Earth. These primary particles are mostly protons and He nuclei which strongly interact with nuclei (N, O, He, etc.) of the upper atmosphere and generate secondary particle showers at an altitude of typically 20–30 km. Secondary particles at the end of the decay chains are mostly muons, highly penetrating charged particles, which can reach the surface of the Earth and enter to underground.

Since the middle of *XX*th century, cosmic muons have been measured extensively and applied for geophysical [1], archaeological [2], geological [3], and speleological [4] researches. All these kinds of measurements are based on the energy loss of high-energy particles—mainly muons with cosmic origin—in matter. Since the muon flux is steeply decreasing as a function of the energy, therefore passed matter above the detector modifies the threshold energy for the detectable particles and correspondingly the flux. Due to this fact, the measured muon flux correlates with the density length of traversed material, which is the key issue in the aforementioned various applications.

Muon tomography and radiography detectors are usually trackers, which record the direction of the incoming muons with sufficient precision. Our portable Muontomograph is a tracking detector as well, similar to that used in high-energy physics laboratories. However, the design was especially developed and built for geophysical applications with the main emphasis on power efficiency, durability, and portability [5, 6]. These features are providing the possibility of tomographic mapping of rock thickness by measuring the angular distribution of cosmic muons from an observation point well below the structures to be investigated.

The present paper introduces the basic structure of the REGARD (Eötvös Loránd University and Wigner RCP collaboration for R&D of gaesous detectors) Muontomograph, a portable and durable tracking-detector based on Close Cathode Chamber (CCC) technology [7, 8]. An industrial (civil engineering) application is described: surveying an unmapped artificial cavern system in Kőbánya, Budapest, Hungary. The angular distribution of high-energy cosmic muons was measured, analysed, and compared to the rock thickness above the detector measured by high-precision GPS.

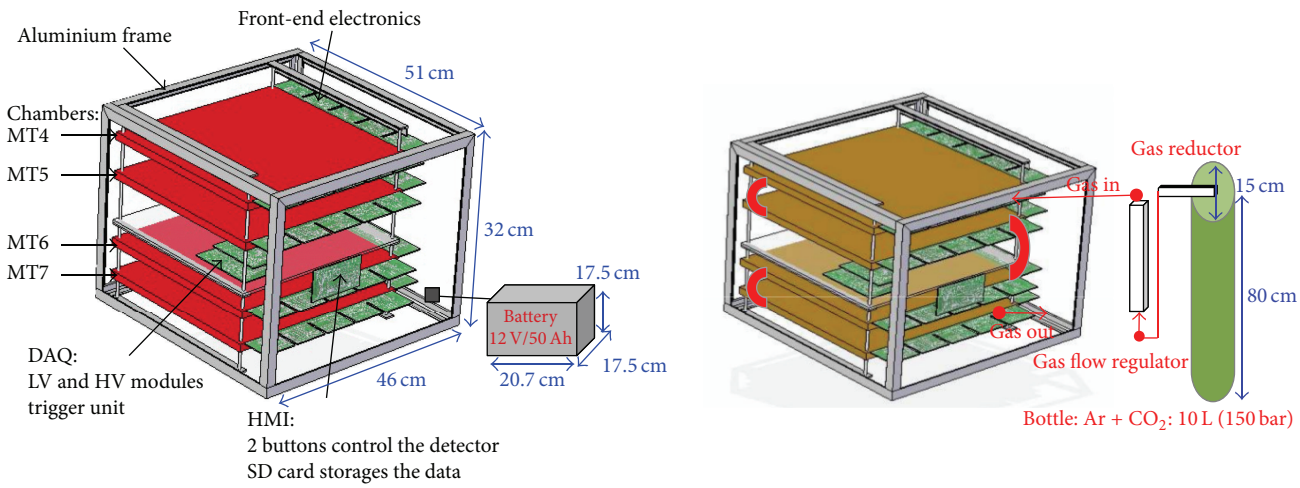

Figure 1: The layout and structure of the REGARD Muontomograph, including the power supply (a) and the gas system (b) based on [5, 6].

2. Structure of the Muontomograph

During the design of the detector, our aim was to optimize the sometimes contradicting aspects of effective sensitive surface, angular resolution, detection efficiency, portability (weight, resistance to mechanical shocks), resistance to high humidity, low power consumption, and cost efficiency. The final design of the REGARD Muontomograph turned out to be well adapted for the experimental purposes mentioned before.

2.1. The Basic Detector Outline. The most substantial parameter of a cosmic muontomograph is the sensitive surface of the detector.

In order to acquire the best statistics during the shortest possible measurement period, the surface of the cosmic ray detectors needs to be maximized. On the other hand, overly large size is prohibitive if actually someone would like to measure the interior of unexplored underground places, such as natural caves or artificial channels which may be difficult to access. These places require human handling of the equipments, which limits size and weight of a detector. In our case, the size of the detector was designed to fit into the caverns of the Ajándék Cave, Pilis, Hungary, described in [5, 6]. The detector can be safely handled manually by a single person: size of the final system is $51 \times 46 \times 32\,\text{cm}^3$, with total weight of about 13 kg. The muon telescope is housed in a plexiglass box, which, besides giving mechanical support, provides environmental isolation as well.

2.2. The CCC Detector Layers. The Muontomograph consists of four parallel sensitive detector layers of Close Cathode Chambers (CCC), denoted by "MT4," "MT5," "MT6," and "MT7" as in Figure 1 from top to bottom. The detector layers have been instrumented with segmented cathode and sensitive field-shaping wire structure as shown in Figure 2. The Close Cathode Chamber is an asymmetric multiwire proportional chamber, where the lower cathode plane (on ground potential) is much closer to the wire plane than the upper cathode plane as plotted on Figure 2(b). There are two types of wires forming the proper electric field in the chamber: 21 μm sense (anode) wires and 100 μm field shaping wires with 2 mm distance between them. The lower cathode is segmented into 4 mm wide strips (pads) perpendicular to the wires. The distance between the wire plane and the closer pad plane is 1.5 mm, the total thickness of the sensitive gas volume is 10 mm, and the area is $320 \times 320\,\text{mm}^2$.

The electric field within the chamber was obtained from simulations, shown in Figure 2(a). The individual field wires as well as the pads are simultaneously read out by high-gain front-end electronics, which provides two-dimensional position information about the muon hits in each layer—as clusters.

In contrast to traditional Multiwire Proportional Chambers (MWPCs), the CCC structure does not require weighty outer support frames (see Figure 3), which is the key advantage in sense of portability. The chosen detector technology therefore optimizes weight, position resolution, and efficiency aspects. This specific version of MWPC-like layout has advantage in high tolerance against the mechanical inaccuracies (100–200 μm) and other influences such as vibrations and shocks during transfer to deployment position.

The detector system, similarly to most gaseous tracking detectors, requires continuous gas flow during data taking. In our case, the gas is a nonflammable mixture of Ar and CO_2 in 82 : 18 proportion. As presented on Figure 1(b), the gas after pressure reduction goes into the flow regulator and flow meter first and then enters the CCC chamber volumes sequentially from top to bottom. Before the exhausting, the gas is redirected into the plexiglass housing box in order to reduce the inner humidity by 30–50%. During the measurements in the Kőbánya tunnel system, a standard 10-liter bottle (with 150 bar filling pressure) was sufficient for 20 days of continuous operation at ~3 l/h flow.

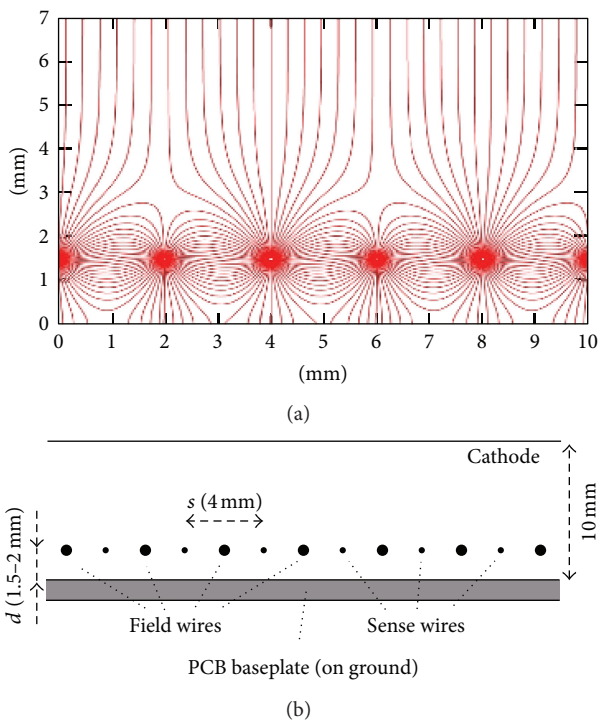

Figure 2: (a) The electric field in a Close Cathode Chamber, based on simulation. (b) The inner structure of a CCC chamber in a cross section [7, 8].

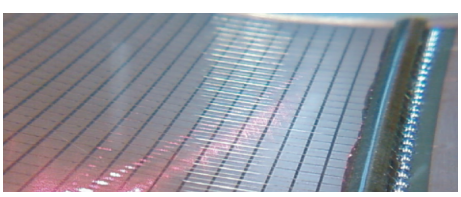

Figure 3: Photo of the inner pad and wire structure of a Close Cathode Chamber.

2.3. Data Acquisition System. A PIC32 microcontroller-based data acquisition (DAQ) system was applied in the Muontomograph, which is a small size ($12 \times 8 \times 8\,\text{cm}^3$) unit between the middle CCC layers, as drawn in Figure 1. The main functions are integrated into a common system plan (see Figure 4). Three main modules are distinguished: a processor board (motherboard) controls the data acquisition, including the low-voltage power system (LV), a high-voltage module (HV) to operate the chambers, and the Human-Machine Interface block (HMI) for maintenance and data storage access.

The high-voltage parts are housed in a separated board with appropriate protection against electric shocks. Two HV lines are supplying the chambers with typical values of +1100 V and −600 V. The low-voltage power supply of the auxiliary electronics, the trigger subsystem, and the environmental sensors were placed on the processor board near the PIC32 type microcontroller. The detector is supplied through a single line, nominally at 12 V DC. Based on direct measurements, the total current consumption of the complete Muontomograph system, including all subunits, does not exceed 380 mA, which is maximal while writing the SD card. We used a standard 50 Ah battery which allowed the detector to run for uninterrupted periods of more than 5 days.

The interconnected anode wire signals from the CCC layers were exploited to form the DAQ trigger. This means that no additional subdetectors were needed (e.g., a pair of scintillator planes) which would add weight and power consumption. A coincidence circuit has been implemented into the trigger module of the DAQ, which provides the trigger condition: the coincidence of one of the upper two and one of the lower two chambers [5].

The individual field wire and pad signals (carrying the position information) were amplified and discriminated by CMOS-based front-end electronics (FEEs). The FEEs receive the trigger signal from the DAQ and store the bits in shift registers. FEEs are connected in series, which allows the multiplexed data readout through a single data line. One event contains 640 bits.

The processor also monitors the analogue environmental parameters (humidity, temperature, and pressure) event-by-event, allowing the reconstruction of the whole timeline of each measurement. The recorded data are written to a standard SD (Secure Digital) card. For example, a single portable memory card of 2 GB capacity enables approximately a full year of measurement time in 50-meter rock-equivalent depth.

2.4. Offline Data Analysis. Standard high-energy physics procedures have been used in the offline data analysis. The analysis initiates with the alignment of the CCC layers. Event-by-event (track-by-track) analysis procedures have been performed independently for the two (pad and field wire) directions. The particle hits are found by a cluster finding algorithm. Typical cluster sizes (the number of adjacent fired pads or field wires) are 2–4, which are corresponding 8–16 mm cluster widths. The noisy pads and field wires (less than 1% in fraction) have been excluded from further analysis.

Straight line particle trajectories are found by a combinatorial tracking algorithm. Multiple tracks were rare (<2%) in the underground sample and have been neglected for further analysis. The slope of the tracks with the necessary acceptance and efficiency corrections have been applied for cosmic muon flux calculation (see more in [5]).

A Monte Carlo simulation has been designed to study specific capabilities and limitations of the detector system, such as efficiency loss (local or overall), position resolution, or noise effects (clusters or individual noisy channels). The simulation confirms that the noise has little (<1%) systematic effect on tracking performance, and it also provides a reliable angular resolution estimation of 11 mrad, which is close to the value extracted from data directly [5]. Such angular resolution corresponds to a well-resolved cavity of 1 m diameter seen from 50-meter distance.

3. Geophysical and Industrial Applications

In this section, we present how the REGARD Muontomograph can be used in geophysical, civil engineering, or industrial applications. These cases all require to place the

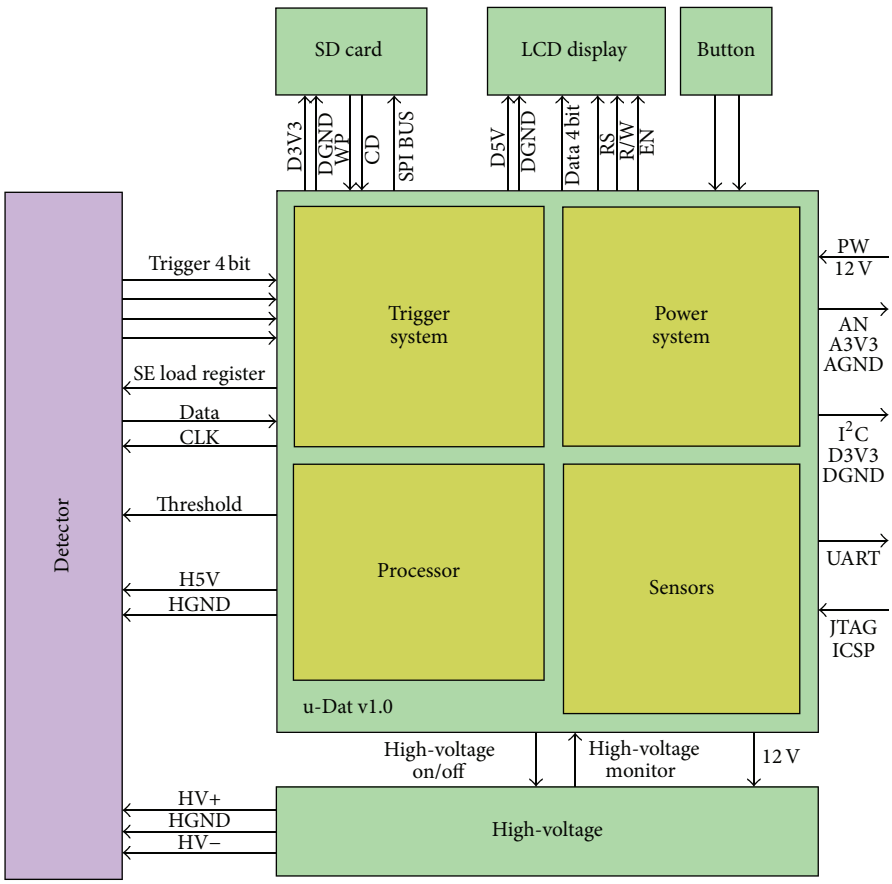

Figure 4: The schematic plan of the electronics system of the Muontomograph, including data acquisition, low- and high-voltage power system, and Human-Machine Interface block (LCD display, control buttons, and SD card access) [5, 6].

detector under the would-be-observed area, which immediately turns our attention to underground objects such as channel networks, caves and caverns, artificial tunnels, or large-scale buildings. Here we present test measurements in the artificial tunnel system in Kőbánya, Budapest, Hungary, with the aim to demonstrate the evidence for a clear correlation between underground tunnel and vent structures and local cosmic muon flux.

3.1. Measurement of Cosmic Muon Angular Distribution. The cosmic muon flux has been measured at different depths as a function of the zenith angles. The boxlike detector geometry implies a "natural" coordinate system along the detector axis, which has been translated to the usual angular variables, taking into account a correction for the angle-dependent detector effective surface (acceptance).

The measured muon yield at a given rock thickness (assuming homogeneous soil) can be correlated with the geometrical data measured by a high precision GPS device. Inhomogeneities such as underground cavities will appear as excess flux in the given direction.

3.2. Measurements in the Kőbánya Tunnel System. The main aim of our measurements in Kőbánya tunnel system was to test the applicability of the muon telescope for civil engineering. Here we investigated a poorly mapped, Swiss-cheese-like underground structure of an urban area with $1.8 \pm 0.1\,\mathrm{g\,cm^{-3}}$ average rock density, which might be dangerous in sense of urban planning and recultivation as well as for developments. In this section, we will show evidence that in finding hidden caverns the muon tomography is a complementary method relative to standard geophysical measurements in disturbed, noisy, urban areas.

The in-use artificial tunnels at some places are equipped with air-flow systems, which are vertical (zenith) tunnels with 1 m diameter and 10–20 m length and open to sky at the zenith direction. Here, as a known tunnel, the large-scale soil inhomogeneities can be tested by such holes. However, we note that, under the local area of the blowholes, there may be further, unknown, nonhomogeneous rock structures. Three measurements have been done approximately at the same depth relative to the ground level (15–20 m, whereas the rock thickness was reduced by the considerable height of the tunnels), at different detector positions. These measurements had the main purpose to test the surface reconstruction and/or estimate soil inhomogeneity.

3.2.1. Mapping a Narrow Blowhole. The first batch of measurements was done with duration of about 1 week in the

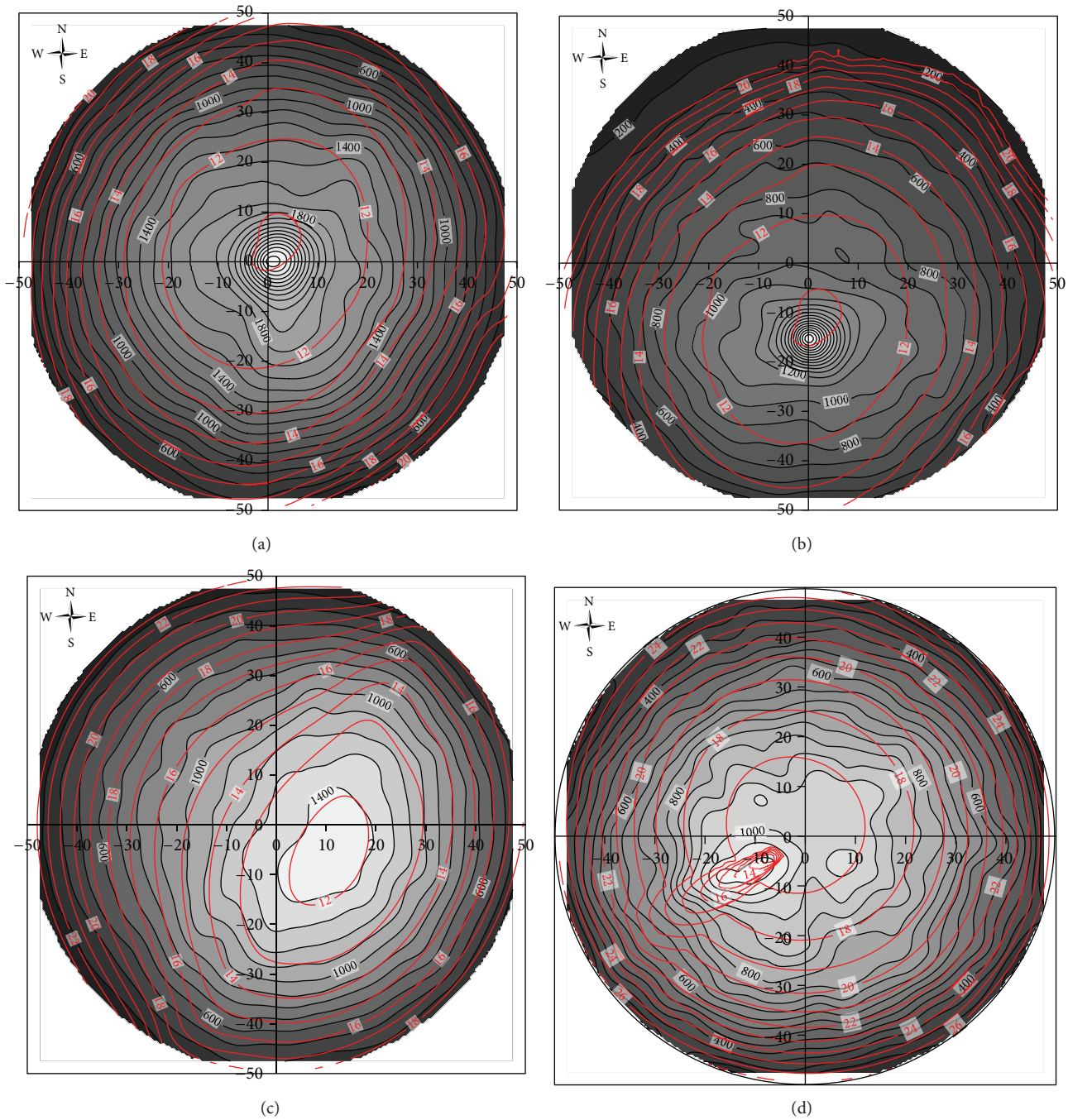

Figure 5: Measurements taken at Kőbánya at different places of the artificial tunnel. *Upper row*: Detector was exactly under the axis of the blow hole (a), 15° tilted detector at the same position (b), next to the wall of the tunnel (c), and the shifted detector position (d). *Solid red lines* are for the rock's length to the given direction in angles; *shading* is for the muon distribution after geometrical correction.

3rd tunnel of the Kőbánya system. The detector was placed precisely under the axis of a vertical 1 m diameter tunnel open to the sky, giving a large excess yield from the direction of the zenith. During this measurement, 330 k muon tracks have been detected by the Muontomograph.

Disregarding the hole, the shortest rock length was at the zenith direction with about 12 m length. Based on the knowledge on the local geological situation, we can assume homogeneous rock structure with an average rock density.

The result of the measurement is shown in Figure 5(a). The horizontal axis shows the West-East zenith angle, and the vertical axis shows the North-South zenith angle in degree units. *Solid red lines* indicate the calculated thickness of the soil/rock at given zenith/azimuth directions based on our local GPS measurements on the surface and the polygon

method used under the ground. *Solid topographical lines* connect the points with the same thickness (disregarding the hole). The measured muon distribution is drawn at given directions by *topographical shading* on the same plot. Both were generated by SURFER 9.0 [9] which is a standard 3D contouring and surface plotting program and both include geometrical corrections. The calculated thickness of the rock and the measured muon yield correlates well, and the open sky is seen as a bright spot at the origin. (Note that the information is contained in the appearance of the sharp maximum but not its peak flux, since not only the muon but also the electron component is measured for the very small effective material at the zenith for this case.)

3.2.2. Tilted Measurement. A measurement was performed at the same detector position as the one presented in Section 3.2.1. The duration of the data taking was about 1 week. Here the Muontomograph was tilted with ~15° from the zenith towards the South. The calculated rock thickness and measured muon flux are shown in Figure 5(b) with the same notations as before.

The tilt can be clearly seen in the *upper panel* of Figure 5(b) as the muon flux maximum, originating by the open sky from the hole, is shifted to the South with the expected ~15° in the coordinate system fixed to the detector.

3.2.3. Measurement Next to the Wall. The detector has been placed as close as possible next to the sidewall of the approximately 6 m high tunnel, which is directed 205° compared to North. Here we took data for about 1-week duration. In Figure 5(c), GPS-data-based rock thickness is compared to the muon angular distribution (*shaded*). The correlation is strong between the GPS-based rock thickness and the muon flux. The direction of the tunnel is well visible.

3.2.4. Imaging a Shifted Blowhole. The measurement presented in Figure 5(d) was taken in another cavern, (5th) of the Kőbánya tunnel system with the blowhole horizontally shifted about 2 m away from the vertical axis of the Muontomograph. This data recording took 6 days. The Muontomograph was placed at the same depth as earlier measurements (see Figures 5(a)–5(c) at about −20 m), but the ceiling of this 5th tunnel was lower with ~15–18 rock-equivalent meter above. The detector was directed to North–East and faced to the zenith similar as in Section 3.2.1.

The measured muon flux is correlating to first order with the calculated thickness of the rock, and the vertical tunnel is shifted to South-West direction as contours drawn in upper panel of Figure 5(d).

3.3. Summary of the Test Results. In all of the previous cases, the effect of the vertical tunnel and the wall can be seen clearly with the Muontomograph. Correlation between soil thickness and muon flux is strong as exhibited on the panels of Figure 5. One can conclude that the detector with the given parameters, especially the limited size to ensure portability, is applicable for search of underground rock inhomogeneities, such as hidden caverns at shallow, ~10–20 meter-rock-equivalent depths with relatively short time duration, ~1 week (see Table 1).

Table 1: The summary of the test measurements with the detector positions, depths, measurement times, and detected tracks.

Detector position	Depth meter	Time day	Detected tracks $\times 10^3$
Exactly under a blowhole	12	7	330
Tilted with 15° under a blowhole	12	7	225
Next to a wall	12	6	220
2 meters far from a blowhole	17	6	130

We note, however, that the results can be made more conclusive and uncertainties of the estimated thickness reduced exploiting a real tomographic measurement—that is measurements from multiple points of view—for definite localization of the small scale inhomogeneities.

4. Summary and Conclusions

The paper presented the capabilities of the REGARD Muontomograph on measuring and determining rock inhomogeneities. Several test measurements have been performed at the tunnels of Kőbánya in an urban area under about 10–20-meter rock equivalent. Muon tomography measurements can also be performed at larger depths, at the cost of increased measurement time due to the limited acceptance. As an example, about 7 weeks of measurement time provides 5% precision of the muon flux in 70 by 70 mrad^2 angular bins, at ~60-meter rock equivalent depth; that is, a cavity of 3-meter size in all directions can be safely observed. One must also note that the detection area of the present setup is typically by an order of magnitude smaller than that of other recent realizations with scintillator technology [9], and furthermore, the choice of MWPCs requires a gas supply. However, the reliable tracking performance, low power consumption, and the fair angular resolution, which may be a challenge for scintillators, make the presented setup highly competitive with any other outline. The results clearly demonstrate that underground structures are well visible, and therefore this kind of tomographic approach is promising in environmental, geophysical, or industrial applications.

Acknowledgments

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References

[1] E. P. George, "Cosmic rays measure overburden of tunnel," *Commonwealth Engineer*, pp. 455–457, 1955.

[2] L. W. Alvarez, A. J. Anderson, F. El Bedwei et al., "Search for hidden chambers in the pyramids," *Science*, vol. 167, no. 3919, pp. 832–839, 1970.

[3] K. Nagamine, M. Iwasaki, K. Shimomura, and K. Ishida, "Method of probing inner-structure of geophysical substance with the horizontal cosmic-ray muons and possible application to volcanic eruption prediction," *Nuclear Instruments and Methods in Physics Research A*, vol. 356, no. 2-3, pp. 585–595, 1995.

[4] E. Caffau, F. Coren, and G. Giannini, "Underground cosmic-ray measurement for morphological reconstruction of the "Grotta Gigante" natural cave," *Nuclear Instruments and Methods in Physics Research A*, vol. 385, no. 3, pp. 480–488, 1997.

[5] G. G. Barnaföldi, G. Hamar, H. G. Melegh, L. Oláh, G. Surányi, and D. Varga, "Portable cosmic muon telescope for environmental applications," *Nuclear Instruments and Methods in Physics Research A*, vol. 689, pp. 60–69, 2012.

[6] L. Oláh, G. Barnaföldi, G. Hamar, H. G. Melegh, G. Surányi, and D. Varga, "CCC-based muon telescope for examination of natural caves," *Geoscientific Instrumentation, Methods and Data Systems*, vol. 1, pp. 229–234, 2012.

[7] D. Varga, G. Hamar, and G. Kiss, "Asymmetric multi-wire proportional chamber with reduced requirements to mechanical precision," *Nuclear Instruments and Methods in Physics Research A*, vol. 8, no. 1, pp. 163–167, 2011.

[8] D. Varga, G. Kiss, G. Hamar, and G. Bencédi, "Close cathode chamber: low material budget MWPC," *Nuclear Instruments and Methods in Physics Research A*, vol. 698, pp. 11–18, 2013.

[9] "SURFER 9.0," 2013, http://www.ssg-surfer.com/.