Underground muography with portable gaseous detectors

G Hamar[1], G Surányi [2], D Varga[1], G Nyitrai[1], L Oláh[3], Á Gera[1], Sz J Balogh[1], and G G Barnaföldi[1]

[1] Wigner Research Centre for Physics, Budapest, Hungary
[2] MTA-ELTE Geological Geophysical and Space Sciences R.G., Budapest, Hungary
[3] Earthquake Research Inst. Tokyo University, Tokyo, Japan

E-mail: `hamar.gergo@wigner.hu`

Abstract. Muography is a novel imaging technology based on particle physics instrumentation to reveal density structure of hill-sized objects. The cosmic muon flux is attenuated while penetrating into the ground, thus the differential local flux correlates with the overburden density-length. Underground muography exploits the close-to-zenith flux, while main challenges became portability, low power consumption, and robustness against the out-of-the-laboratory environment. Various fields could benefit from this non-invasive imaging, eg. speleology, mining, archeology, or industry. Portable gaseous tracking detector systems have been designed, built, and successfully used in several underground locations. This paper presents the designed portable muography systems, the main requirements, and measurement campaigns for calibration, natural caves, and cultural heritage.

1. Introduction

As cosmic radiation enters the atmosphere of the Earth, they produce hundreds of new particles in high-energy hadronic collisions, where the end of the decay chain the pions, thus the muons stand, that can actually reach the surface. These muons penetrate the soil loosing slowly their energy, thus the differential local flux depends on the integrated density and length in a given direction. Muography is based on the measurement of this attenuated flux, and computing the corresponding density-length, and resulting a density image of a large-scale object.

The idea was introduced by Alvarez to search for hidden chambers in a pyramid [1]. The progress in technology and instrumentation of particle physics detectors made these kind of muograph systems accessible for practical applications, thus in the last decades Muography emerged.

Interesting targets are the volcanoes [2], where the on-surface experiments shall deal with close-to-horizon extreme-low flux, thus large detector systems are required [3]. Underground muography can target speleologic research [4], mines and ore-bodies [5], industrial applications [6, 7] or cultural heritage targets like for Alvarez [1].

The main challenges for underground muography are the portability and autonomity of the detector. As the entire device shall be carried into the natural or artificial caves, usually hard to access, the muograph shall be lightweight and compact. Not only the main elements, but the data acquisition and all the used electronics has to comply, while low-power operation is required as well (as usually there is no electricity in the field).

Various detector technologies are used for muography, like emulsion films eg. [8], scintillator systems eg. [9] or gaseous trackers eg. [10].

2. Multiwire based Gaseous Muon Trackers

Gaseous detectors [11] could be excellent candidates for layers in muography trackers. The micro-pattern technology can reach excellent position resolution [12], the RPC family could use sub-nanosecond time resolution [13], while the special modified wire-chambers, presented in this paper, do combine optimal resolution, portability, low-power operation, and cost-efficient construction.

The developed Close Cathode Chamber technology [14] has low material budget while keeping gain uniformity across the chamber even if bulging or sagging appears [15]. (This low-occupancy detector has been developed for a CERN ALICE upgrade the VHMPID [16] and HPTD detectors [17].) The assembled lightweight detector-stack equipped with simple data acquisition system was successfully used in natural caves, detailed in the next section.

For larger area muographs the CCC technology is usable, however even more simplified design has been developed, thus the construction of the roughly square-meter-area units are uncomplicated, while keeping the high performance [18]. These kind of chambers are used for large-area underground muographs, and for volcano muography in the Sakurajima Muography Observatory [3]. Photo of the smaller and the larger muograph next to each other can be seen on figure 1.

The data acquisition is a crucial part of a muograph tracker, it is responsible for triggering, readout of the front-end electronics, storage of recorded data, control of measurements, supply of low and high-voltage for the detectors, and monitor environmental parameters; all while its power consumption shall be kept as low as possible. Our developed DAQ is controlled by a RaspberryPi microcomputer, using its GPIO pins with custom protocols adapted to the low-power FEEs. The full system runs with 6-10 W power, a photo with its main parts can be seen on figure 2

Most recent development is an extra-small-sized muograph, that could be used for bore-hole experiments [19], in our case down to 100 mm diameter, the first photos of the gaseous muograph system is shown on figure 3.

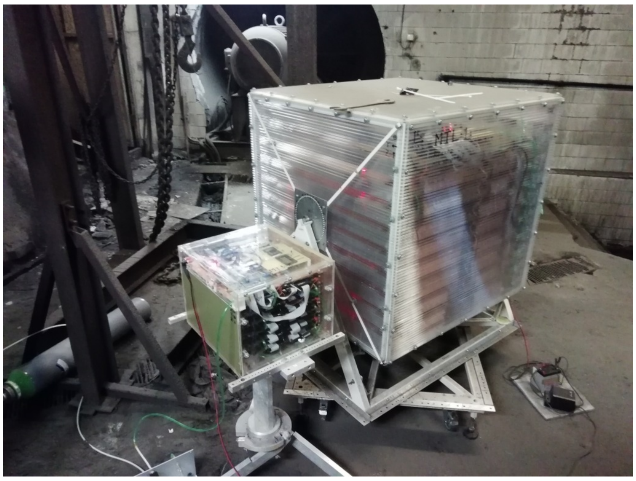

Figure 1. The Small (25 cm) and the Large (80 cm) Muograph next to each other in a tunnel below the Castle of Buda.

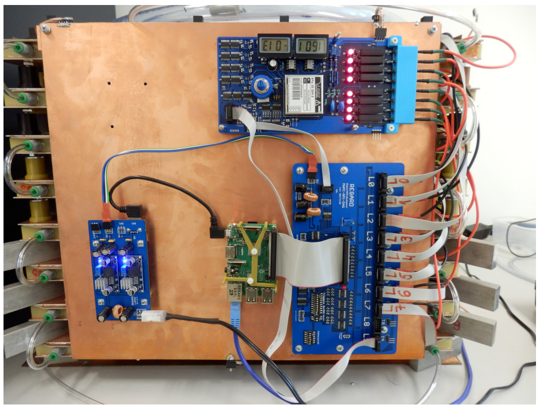

Figure 2. The Data Acquisition Systems of a muograph detector mounted onto a muograph; the eight chambers are visible behind the DAQ.

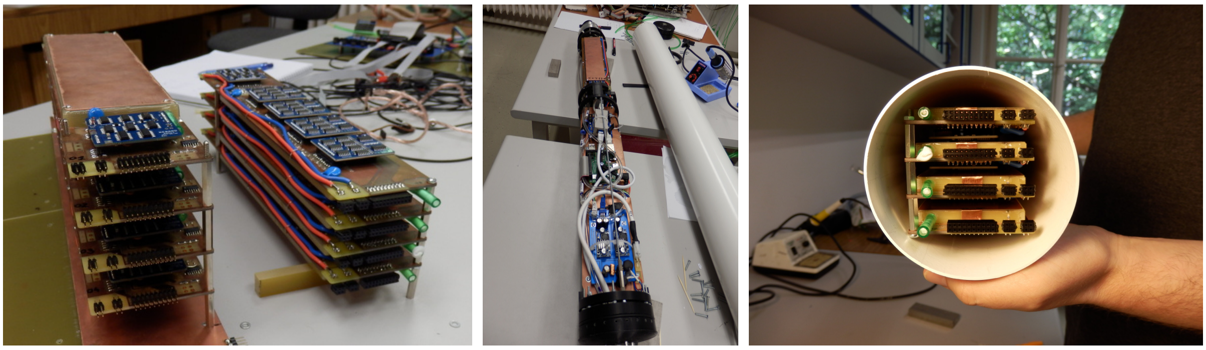

Figure 3. BoreHole-sized CCC based Muograph system. The photos show detector-sets' top and bottom side, the system with full DAQ and the container-tube, and the side-view of the assembled muograph.

3. Underground Muography Campaigns

Our Group has started several underground muography campaigns in Hungary, mostly focused for search for unknown caves in natural cave-systems, and similarly in archeology the disclosure of hidden medieval tunnels.

While the individual chambers and the full detector undergoes detailed tests in the laboratory, and the muography capabilities of the fully assembled system shall be measured, the underground system checks are most important. The electron components of the cosmic showers are well suppressed even in shall depth, thus realistic tracking/background validations are achievable. In the KFKI Campus in Budapest there is a 30 m deep pit of 3 levels with 1+2+3 tunnels, that is excellent for underground crosschecks, and can be used as reference via examining the tunnels above the measurement site [20].

The first in-cave measurements with CCC-based muograph has been done in the Molnár János cave, which is the feed of most hot springs around Budapest. While more than 90% is underwater, the accessible site was limited and extra humid; however the muograph survived the extreme climate [4]. In case of the Ajándék cave in the Ariadne system the electro-resistive measurements showed a large anomaly, however if that arose from a cave or a crack could not be defined. The muography measurements provided solid proof that the overburden rock-density is roughly homogen, thus no cave is hidden there [4].

Figure 4. Inside and installation of the Large Muograph into the cave of Sátorkőpuszta system.

The same muograph system has been successfully used to measure the directional cosmic background, and thus optimize the location of a planned underground laboratory in Felsenkeller, Dresden [21]. Similar underground laboratory exploration has been carried out in the Mátra mountain, as in search for most optimal location of a novel gravitational detector [22].

Most recent measurements located in Sátorkőpuszta, where the expected connection-caves are searched for; and inside the tunnels of Esztramos system, in search for anomalies. Some photographs of the installation and the environment are shown on figure 3.

Disclosure of hidden or forgotten tunnels are in interest of archeology as well, exemplary are the well-known pyramid experiments of Alvarez [1] and a recent exploration at Giza [8]. Our muographic tracker system is now used underneath the Castle of Buda, where hidden medieval tunnels are expected. The proof-of-concept measurement took place under a known tunnel, and the power of muographic imaging was excellently demonstrated. The measured flux is shown on figure 5, while the computed thickness of the missing rock on figure 6, where the slightly-rotated tunnel is clearly visible.

The most extensive campaign was the search for concealed caves and chambers in the Királylaki cave and tunnel region, where we have explored the overburden rock structure with few dozens of measurements along the known parts. Using several muographic image localization of anomalies could be done in three dimension, thus in theory a tomographic-like figure could be achieved [23], this method is usable for cavities [9, 24] or dense structures as well [5]. From the data analysis of the Királylaki campaign we have located several anomalies [25], first as for disclosing unknown regions, while the proof by drilling is scheduled for late 2021.

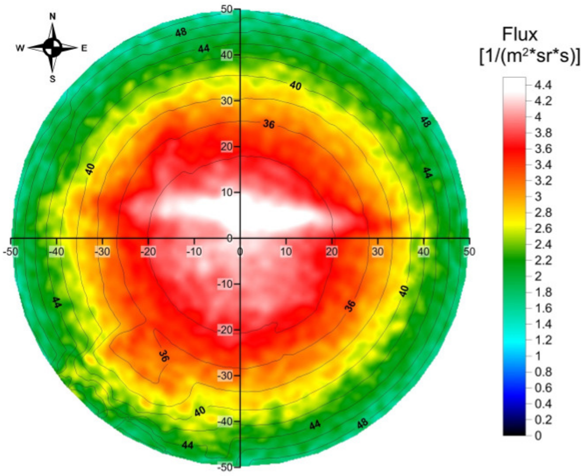

Figure 5. Measured muon flux under the Castle of Buda, with the portable muograph in 30 days.

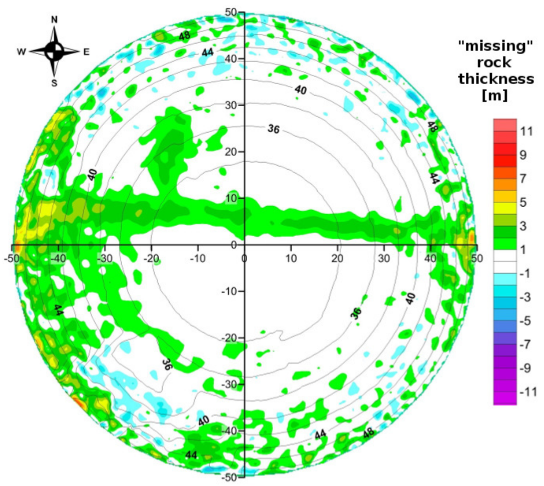

Figure 6. Calulated missing rock thickness, the above-crossing service tunnel is clearly visible, giving proof-of-concept.

Acknowledgments

The authors would like to acknowledge the support of the Hungarian OTKA Grant FK-135349 and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences. The authors would like to thank the work and support of the members of the REGARD Detector Physics Research Group of the Winger RCP.

References

[1] L.W. Alvarez et al. 1970 Search for hidden chambers in the pyramids *Science* **167** 832

[2] Tanak H K M et al. 2013 Development of a two-fold segmented detection system for near horizontally cosmic-ray muons to probe the internal structure of a volcano *Nucl.Instrum.Meth.* A **507** 657

[3] Oláh L, Tanaka H K M, Hamar G and Varga D 2019 Muographic observation of density variations in the vicinity of Minami-dake crater of Sakurajima volcano *Journal of Disaster Research* **14** 701

[4] Oláh L, Barnaföldi G G, Hamar G, Melegh H G, Surányi G and Varga D 2012 CCC-based Muon Telescope for Examination of Natural Caves *Geosci. Instrum. Method. Data Syst.* **1** 229

[5] Schouten D W and Ledru P 2018 Muon tomography applied to a dense uranium deposit at the McArthur River mine *Journal of Geophysical Research: Solid Earth* **123** 8637

[6] Thompson L F et al. 2020 Muon tomography for railway tunnel imaging *Phys. Rev. Research* **2** 023017

[7] Oláh L, Hamar G, Miyamoto S, Tanaka H K M and Varga D 2018 The first prototype of an MWPC-based borehole-detector and its application for muography of an underground pillar *Geophysical Exploration* **71** 113

[8] Morishima K et al. 2017 Discovery of a big void in khufu's pyramid by observation of cosmic-ray muons *Nature* **552** (7685):386

[9] Cimmino L et al. 2019 3D Muography for the Search of Hidden Cavities *Scientific Reports* **9** 2974

[10] Barnaföldi G G, Varga D, Oláh L, Hamar G, Melegh H G and Surányi G 2012 Portable Cosmic Muon Telescope for Environmental Applications *Nucl.Instrum.Meth.* A **689** 60

[11] Blum W and Rolandi L 1993 *Particle Detection with Drift Chambers* (Springer-Verlag)

[12] Bouteille S et al. 2016 A micromegas-based telescope for muon tomography: the watto experiment *Nucl.Instrum.Meth.* A **834** 223

[13] Carloganu C et al. 2013 Towards a muon radiography of the Puy de Dome *Geosci.Inst.Meth.Data Syst.* **2** 55

[14] Varga D, Hamar G and Kiss G (2011) Asymmetric multi-wire proportional chamber with reduced requirements to mechanical precision *Nucl.Instrum.Meth.* A **648** 163

[15] Varga D, Hamar G, Bencédi G and Kiss G 2013 Close Cathode Chamber: Low material budget MWPC *Nucl.Instrum.Meth.* A **698** 11

[16] Acconcia T V et al. for the VHMPID Collaboration 2014 A Very High Momentum Particle Identification Detector *Eur.Phys.J.Plus* **129** 91

[17] Boldizsár L et al. for the VHMPID Collaboration 2009 High-p(T) trigger detector development for the ALICE experiment at CERN *Nucl.Phys.Proc.Suppl.* **197** 296

[18] Varga D, Nyitrai G, Hamar G and Oláh L 2016 High efficiency gaseous tracking detector for cosmic muon radiography *Advances in High Energy Physics* **2016** 1962317

[19] Bonneville A et al. 2018 Borehole muography of subsurface reservoirs *Phil. Trans. R. Soc. A.* **377** 20180060

[20] Oláh L, Barnaföldi G G, Hamar G, Melegh H G, Surányi G and Varga D 2014 Applications of Cosmic Muon Tracking at Shallow Depth Underground *ICATPP* **2013** 280

[21] Oláh L, Surányi G, Barnaföldi G G, Bemmerer D, Hamar G, Melegh H G and Varga D 2015 Cosmic background measurements at a proposed underground laboratory by the REGARD Muontomograph *Journal of Physics Conf.Ser.* **665** 012032

[22] Ván P et al. 2017 First report of long term measurements of the MGGL laboratory in the Márta mountain *Classical and Quantum Gravity* **34** 114001

[23] Lesparre N, Cabrera J and Marteau J 2017 3-D density imaging with muon flux measurements from underground galleries *Geophys. J. Int.* **208** 1579

[24] Guardincerri E et al. 2017 3D cosmic ray muon tomography from an underground tunnel *Pure Appl. Geophys.* **174** 2133

[25] Surányi G, Molnár G, Barnaföldi G G, Hamar G, Melegh H G, Oláh L and Varga D 2016 Locating of density anomalies using highly penetrating cosmic muons *Karsztfejlődés* **2016** 203