Research on Novel Muographic Imaging
OTKA-FK-135349
Scientific Project Summary

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1 Introduction

Cosmic rays create a hard, penetrating muon radiation on the surface of Earth. Muography is an emerging interdisciplinary field of research and development, where these muons are used for imaging of the interior structure of large objects. The methods can lead to breakthroughs in instrumentation in geo-sciences, industry, and surveillance of large man-made structures.

The project aimed to investigate the underlying physics processes, allowing for efficient high resolution muographic imaging, including detection technology, data analysis, reconstruction; and investigating alternative muongraphy technologies via measurment of scattering and production of secondaries.

2 Scientific Achievements

The following brief summary lists our research results, the bibliography contains purely our published papers (A) proceedings (B) and conference presentations (C) connected to this Project.

As Muography is a novel and interdisciplinary field of research with various applications in geology and industry, several overwiew talks were given to specific audiences in speleology, volcanology, mining industry, and geologists as introductory for this modern technology, and its usability for their field of work. [C1] [C2] [C3]

Muography requires particle physics detectors to be operated in out-door conditions, being resistive to temperature variations, high humidity, rough transportation, while shall keep their good performance as muon detectors. We have developed a set of muographs: large-area detectors for mines and surface-based measurements, one-man-carry sized for tunnels and caves, and cylindrical borehole-fit devices as well, all with low-power electronics and environmental robustness. [A1] [B1] [C4] [C5]

Custom electronics and special RaspberryPi based readout system made our muographs excellent and cost-efficient devices. Special mobile/android app has been developed for simple control for collaborators and experts, thus starting data taking, downloading, or quick analysis can be parformed via a mobile phone. Low-power and low-gas operation is essential for long-term and natural-area campaigns, therefore dedicated studies resulted in defining and limiting the required gas flow, where our MWPCs has proven extreme-low-flow operability. [A2] [B2] [B3]

The planned software chain for analyses of raw data to physics quantities and geological data to anomaly has been established, and became a standard for internal usage, collaborative presentation and preparation for publications as well. The steps of analysis with corresponding plots are shown on Fig.1.

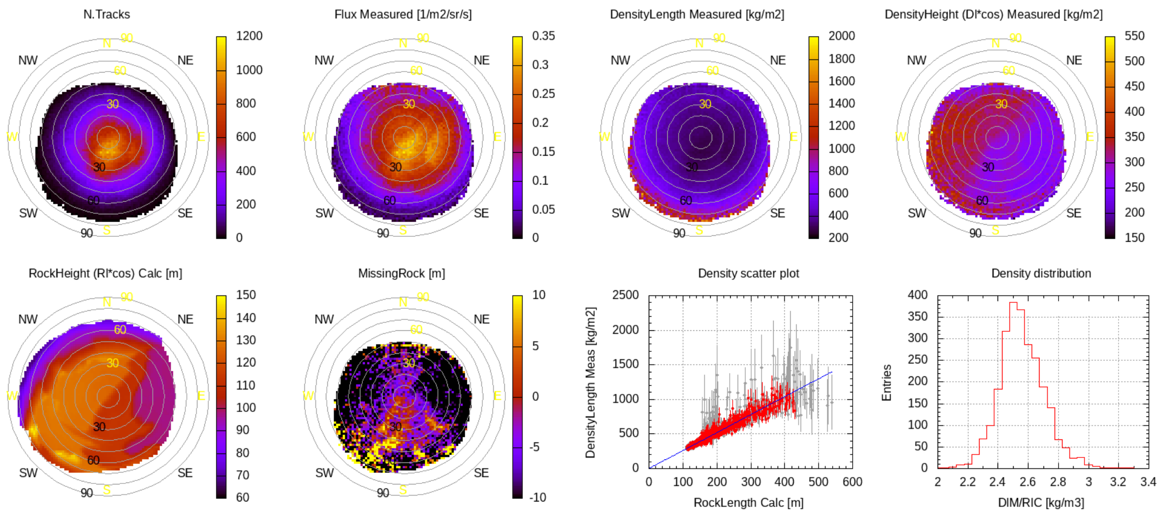

Figure 1: Example of the chain of our data analysis steps for a muogram, with data recorded in Esztramos mine in Hungary. The plots (counted from from top-left) show the following steps: The measured number of muons (1) shall be corrected for efficiency and acceptance to get the muon flux (2), from which the density-length (3) can be calculated. The surface-projected density height (4) and the LIDAR-measured rock-height (5) shall be correlated (7) or and histogram of their ratio (8) gives the average density. Using these information the anomalies can be visualized as missing rock (6).

The main part of the Project was to investigate and carry out underground muography measurements with gaseous tracker detectors. We have proven the applicability of our developed technology in real condition, and have shown the density-mapping and cavity-search usability with these devices in topical conferences. [B4] [C6] [C7]

We have initiated several new underground muography campaigns and continued the existing ones with the support of the Project and some connected calls. General summary of the developed methods and applicability were presented as a book chapter and on several conferences. [A3] [B5] [C8]

In Hungary we do cave search in the Királylaki tunnels, and the abandoned Esztramos mine (paper in preparation). The worlds most extensive muography campaign has been carried out underneath the Castle of Buda, where more than 80 muograms were recorded and evaluated; in the high-resolutiuon images even the building-walls and fine structures are visible. [B6] [B7]

Recent mining-connected muography measurements include 700m deep-underground usability (Poland), ore exploration in active mine (Bosnia-H.) and survey of rock relocation (Bulgaria), from which the publications are in preparation. Trackers for general mining applicability has been investigated within collaboration. [B8]

Muography is capable of three-dimensional reconstruction of the density structure if multiple measurements are present. Inversion method is well known for medical and geophysical evaluation, however in case of muography the few measurement-points and the large binned uncertainties makes it a true challenge on real data. Our Baysian inversion methods with the excellent measurements from the Királylaki tunnels has proven to reveal even low-density zones as well. [A4] [C9] [C10] [C11]

Machine learning and deep neural networks are gaining more interest in sciences, thus we have tested its applicability for background suppression in muographic measurements. Understanding of the NN results are key point in scientific use, where the SHAP values were shown to highlighting the most important part of the ML inputs. Investigating simulated Geant4 data and real muography measurements has proven that classical chi-square fit filtering could be enhanced with ML if low-energy cut is required. [A5] [B9] [B13] [C12] [C13]

The MuonSecurity experiment is our muon scattering tomography setup, extended with several iron absorber/scatter layers, thus momentum of the cosmic muons can be estimated. Using a momentum-binned information, the detection of lower-Z materials could became possible. [B11] [C14].

Our unique experiment of imaging via COsmic Muon Induces Secondaries (COMIS) got developed under this Project, the construction and pilot measurements were superb to the previous system operated in our Serbian-Hungarian collaboration. Photo of the setup is shown in Fig.2-Left. Material identification and self-absorption has been proven, and simulations got upgraded to check identification issues; while with the older MUCA setup the data taking were continued and possibilities presented. [B12] [C15] [C16] [C17]

While the initial proposal did not include direct surface-based measurements, the developed MWPC-based muograph systems were very well adaptable to such needs. Campaigns in Sicily (Italy) and the continuation of the Sakurajima experiment (Japan) enriched our portfolio, and deepened our knowledge on both technological issues on background suppression, conversions, and applicability to volcanology and monitoring. [A6] [A7] [A8] [A9] [B13] [C18] [C19] [C20]

Recently a new way of muon-utilizing has been invented, muon-positioning or "muometry" uses the coincidence information of cosmic muons to locate underground detectors. Our gaseous trackers were excellent upgrade for the initial system, giving vector-based information and thus increasing the applicability of the method. [A10]

The developed muon trackers could be of use for future particle physics experiments as well, the CERN ALICE3 Muon Identification Detector has two candidates, scintillator and MWPC technology, wereas our trackers excelled at the beam tests. [A11]

Educational talks on muography and detector technology were given by G.Hamar at the Researcher's Night programme for several years, while a muography related summary has been published in Hungarian to geoscientists [A12].

Figure 2: Left: Photo of the COMIS experiment in Budapest, secondariese are detected in the surrounding plastic scintillators, while the underlying trackers give position information. The combined DAQ system makes it compact and simple.
Right: Our 80cm wide MTL3 muograph 275 meters underground inside the active chromium/iron mine in Kemi, Finland.

3 Financial summary and justification

Personnel cost covered the supplementary wages of the PI (G.Hamar) and a PhD student (G.Nyitrai), and salary for twice a third of a year for a technician (D.Moncz). Supplementary for PhD and the other technician-months were covered by other projects. Students involved in the project as researchers (M.Gerlei, B.B.Gaál,B.A.Stefán) or engineers (B.Hertelendy, V.Tarnóczy) for a given task was awarded as well. For specific electronic and programming issues engineers (B.Gyöngyösi, M.L.Kapta) were hired for short jobs. The per-diem for the conferences and installations were less used as we got extra funds for specific travel expenses. The total personnel cost was underspent within 10 percent of the planned one.

Cost of consumables was a dominant part of the expenses as custom electronic components and special equipments were required for the laboratory works for R&D of particle detectors, the over-expense on these items were balanced by the reduced personnel costs. Travel expenses include conferences and in-field installations, these were partially reduced by the involvement of the special calls and partner institutes, thus we could support conference presentations for several students as well.

As we could use the existing Laboratory infrastructure, the equipment costs were low, only a few laboratory devices (eg. heat-camera) and computer parts were required.

4 Initiated projects

The Group and the project excelled in muography technology, connected research and development of detectors, and achievements got well respected in the international community. This success funded the basis for further specific national and European projects, and extended our range on collaborations.

The Eötvös Loránd Research Network (predecessor of HUN-REN) called for short application related projects (Kiemelt Téma / Highlighted Projects), which we got in 2021 (SA-88/2021) for "Application of Novel Muographic Imaging Technology in Local and International Projects" for two years. The ELKH-KT and the OKTA projects mutually supported each other, extending our reach to realistic applications in geophysics, geology, and archaeology. The international collaborations got boosted via two bilateral funds: With Catania University in Italy from 2021 the TÉT-2020-00224 : "Application of Multi Wire Chamber Based Tracking System for the Muography of the Etna Volcano" , and with the Novi Sad University in Serbia from 2021 the TÉT-2020-00223 : "Imaging via detection of comic muon induced secondary particles". Realizing the emerging need for high technological-readiness-level devices, the Group submitted and won the call of TKP-2021 of the NRDIO with the topic of "Developent of Muographic Instruments", for four years from 2022. This way could cover the full chain of fundamental research, and development, and applications.

The success on the international level and integration into the muographic community got well visible as we are partners in H2020 and HE projects as beneficiaries and contractors. In the AGEMERA and the MINE-IO European mining projects WignerRCP is main partner for muographic research and measurements.

Further research plan on detector development and muography has been submitted to the NRDIO as A-149679 "Tracking Detectors for Fundamental and Applied Science" including the extension of muographic research and applications, and usage of the developed tracking technologies for CERN experiments.

5 Impact and Innovation

The application of gaseous trackers for muography initiated a set of detector developments and muographic campaigns, all leading towards the industrial and geological applicability of this novel technology. Research collaborations lead to international proposals (H2020,HE) and specific agreements with various institutes and industrial partners. Main partner in Europe is Muon Solution Oy (Finland) while in Asia is Nippon Electric Company (Japan), who are collaborators in proposals, and purchase detectors and licence our patents as well. Horizon programmes initiated collaboration and measurement with industrial partners: Outokomptu Oy (Finland), KGMH Co. (Poland), SABO (Japan), Asarel M. JST (Bulgaria), BX Stone doo (Bosnia H.).

Based on the research on muographic devices WignerRCP has taken part in a connected intellectual property patent, the Vector Muon Positioning System together with the University of Tokyo.

During the project we have succeeded in training and education of students, two colleages (G.Nyitrai and G.Galgóczi) have fished their PhD studies in muography, while within the project framework I have hosted 5 BSc and 3 MSc thesis (and further 2+1 in progress), from which two of them have continued in our group as PhD students.

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