International Workshop on Cosmic-Ray Muography (Muography2021)

Report of Contributions

https://indico.cern.ch/e/muography2021

Contribution ID: **1** Type: **Plenary talk**

Assessing the rock density distribution of a volcano lava dome with a 4-panel scintillator-based muon detector

Thursday 25 November 2021 10:50 (20 minutes)

The intense hydrothermal activity occurring at La Soufrière de Guadeloupe, French Lesser Antilles, is a major concern for volcanologists at the Volcanological and Seismological Observatory of Guadeloupe (OVSG) and the local population that lives nearby. Partly hosted within the andesitic lava dome, this hydrothermal system, continuously fueled with meteoric waters, is indeed responsible for both violent phreatic eruptions (last major event occurred in 1976-1977), and fast rock alteration due to hot and acid fluid circulation that worsens the risk of a partial volcano flank collapse.

Since 2015, the deployment of particle trackers built in IP2I, Lyon, to perform dynamic muon imaging of the lava dome structure has allowed to increase the knowledge of the hydrothermal system dynamics. Recently a new generation of particle hodoscopes equipped with 3 and 4 plastic scintillator matrices have been installed around the volcano to scan different areas of the lava dome.

Here we will present a new versatile method to process the data acquired by these detectors, and estimate the corresponding density radiographies. Our method relies on particle trajectory reconstruction by performing a fit of the recorded hits in the impacted scintillator bars using a *Random Sample Consensus algorithm* (RANSAC). This algorithm is specifically built for discriminating outliers points ("noisy" hits) in the data. Thus, it allows to significantly improve the muon signal/noise separation, and obtain higher quality estimates of the particle trajectories. The analysis of the RANSAC-reconstructed events has started to offer promising results in terms of average density maps. In particular, here we will present primary analysis results from 6 months of data ($\sim 20.10^7$ reconstructed events) recorded in a telescope, equipped with four 16x16 scintillator bars matrices, located at the volcano south-west. This configuration allows notably to increase precision on the 2D density radiography of the central part of the scanned region, plus offers two more 3-panels sub-configurations, which leads to three different radiographies.

The 2D density radiographies will then be combined to serve as input for numerical modelling, conjointly with other geophysics data sets (e.g from gravimetry surveys), in order to obtain a 3D bulk density distribution model of the lava dome at an expected unprecedentedly high resolution thanks to the uniqueness of the different data sets available and the quality of the event reconstruction. This will lead to a better characterization of the hydrothermal fluid circulation impact on rock alteration and the resulting partial flank collapse hazard.

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Session Classification: Data analysis and image reconstruction

Track Classification: Data analysis and image reconstruction

Contribution ID: **2** Type: **Plenary talk**

The MURAVES experiment : study of the Vesuvius Great Cone with Muon Radiography

Thursday 25 November 2021 11:10 (20 minutes)

The MURAVES experiment aims at the muographic imaging of the internal structure of the summit of Mt. Vesuvius, exploiting muons produced by cosmic rays.
Though presently quiescent, the volcano carries a dramatic hazard in its highly populated surroundings. The challenging measurement of the rock density distribution in its summit by muography, in conjunction with data from other geophysical techniques, can help the modeling of possible eruptive dynamics.
The MURAVES apparatus consists in an array of three independent and identical muon trackers, with a total sensitive area of 3 square meters. In each tracker, a sequence of 4 XY tracking planes made of plastic scintillators is complemented by a 60 cm thick lead wall inserted between the two downstream planes to improve rejection of background from low energy muons. The apparatus is currently acquiring data. Preliminary results from the analysis of a first data sample will be presented.

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Session Classification: Data analysis and image reconstruction

Track Classification: Data analysis and image reconstruction

Contribution ID: **3** Type: **Plenary talk**

The simulations chain of the MURAVES experiment

Thursday 25 November 2021 09:40 (20 minutes)

The MUon RAdiography of VESuvius (MURAVES) project aims at the study of the summital cone of Mt. Vesuvius, an active volcano near Naples, Italy. This muographic profile combined with the data from gravimetric and seismic measurement campaigns will be used for better defining the volcanic plug at the bottom of the crater.
We report on a series of simulation studies that are being conducted to investigate the effects of the experimental constraints and to perform comparisons with the actual observations. The simulation setup is developed using Geant4 and for the generation of cosmic showers, a study of particle generators (including CORSIKA and CRY) has been conducted to identify the most suitable one for our simulation framework. To mimic the real data, Geant4 raw hits are converted to clusters through a simulated digitization: energy deposits are first summed per scintillator bar, and then converted to number of photoelectrons with a data-driven procedure. This is followed by the same clustering algorithm as in real data. After application of the same tracking code as in real data, we quantify tracking inefficiencies, the effect of dark noise and other nuisances, and the effect of the lead wall in terms of absorption and scattering as a function of momentum. We also report on the examination of muon transport through the mountain using PUMAS and Geant4.
We will elaborate on the rationale for our technical choices, including trade-off between speed and accuracy, and on the lessons learned, which are of general interest for similar use cases in muon radiography.

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Session Classification: Simulation tools and studies

Track Classification: Simulation tools and studies

Contribution ID: **4** Type: **Poster**

Unveiling triangular correlation of angular deviation in muon scattering tomography by means of GEANT4 simulations

Thursday 25 November 2021 16:00 (5 minutes)

The angular deviation commonly represented by the scattering angle generally serves to provide the characteristic discrimination in the muon scattering tomography. The regular procedure to determine the scattering angle compromises the collection of exactly four hit locations in four detector layers among which two top detector layers are utilized to construct the first vector, whereas the second vector is built by using two bottom detector layers. Although this procedure acts to classify the target volumes in the tomographic systems based on the muon scattering, the scattering angle obtained through the usual methodology founded on four detector layers is dubious for not yielding any information about the position of target volume. Nonetheless, the same set of four detector layers also imparts the possibility of splitting the scattering angle into two separate angles by creating a triangular correlation in such a way that the scattering angle is referred to an exterior angle, whereas the separate angles are considered the interior opposite angles that are not neighboring this exterior angle. In this study, we first show that a combination of three detector layers out of four fulfills the calculation of the interior opposite angles. Then, by employing the GEANT4 simulations over our tomographic configuration composed of three plastic scintillators in either section, we demonstrate that the interior opposite angles differ towards the vertical spatial variation, while the exterior angle approximately remains constant, thereby implying a beneficial feature to be used for the image reconstruction purposes.

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Session Classification: Poster session

Track Classification: Data analysis and image reconstruction

Contribution ID: **5** Type: **Plenary talk**

The Cosmic Muon Images demonstrator within the REINFORCE project

Thursday 25 November 2021 14:40 (20 minutes)

Cosmic Muon Images is a muon tomography citizen science framework developed within the EU-funded (GA-872859) REINFORCE project (Research Infrastructures FOR Citizens in Europe). REINFORCE aspires to decrease the knowledge gap between research and society. Citizen scientists will engage in the process of scientific discovery by analyzing detector data from four major physics domains.

Muon Tomography, Gravitational Waves, Neutrino Astronomy and High Energy Physics join forces with people from all over the world to do science and discuss detection techniques, signal vs background discrimination, environmental effects on measurement, and broadcast the impact of fundamental research on everyday life and on societal progress. In this effort we want to reach the broader audience possible, and this means also making our data accessible to as many people as possible. SonoUno is a user centered software developed within REINFORCE that allows people with different sensory styles to explore scientific data, both visually and through sonorization.

Cosmic Muon Images utilizes the Zooniverse website to bring muon tomography to the general public and the citizen science community. Muon telescope data are visualized with 3D and 1D plots with the goal being the identification of patterns through a series of lines and points on these plots. The results of this pattern identification will be used to train machine learning (ML) algorithms to discriminate between signal and background events. We will then evaluate the performance of these ML algorithms to more traditional track reconstruction and event selection algorithms that are already in use. The key factor being how they compare with respect to speed and pattern recognition accuracy. Furthermore, a large dataset catalogued by eye will act as a stepping-stone towards other studies like background identification and Monte Carlo simulation development.

Citizen scientists will benefit through their exposure to calibration and detection techniques for muon telescopes to make their scientific contributions more robust. This will also provide a more fulfilling experience by learning new staff which are for the most part reserved for higher education audiences. They are going to learn about the different applications of muon tomography in fields like volcanology, archaeology, civil engineering, hazard monitoring and others. A great effort is made towards the inclusion of school students through a series of schools and seminars co-organized together with other EU-funded projects (e.g. FRONTIERS Summer School 2021) since young people have much to gain from learning about interdisciplinarity between sciences and how scientists from different domains collaborate towards a common goal.

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Session Classification: Science communication and outreach

Track Classification: Science communication and outreach

Contribution ID: **6** Type: **Plenary talk**

Impact of geodesic parameters on the muon flux simulated by CORSIKA

Thursday 25 November 2021 09:20 (20 minutes)

Muon tomography is a non-invasive technique able to scan the internal density of large structures. This technique infers the density of an object by tracking the number of muons received by a detector, before and after traversing a structure. The amount of density met by a muon on its path minimizes its survival probability in a predictable manner, hence diminising the average flux received by a detector 1. The incident direction (defined by the zenital angle) of the detected muons is reconstructed by means of a detector composed of a 3 scintillators panels 2,3, allowing to produce 2-D density images.

To evaluate the degree of absorption caused by the density of structure, there are two key components: (1) the input flux (open-sky flux) which is infered theoretically, and (2) the output flux, measured by a detector. Both play an important role in estimating the density map of a structure. However, due to the dependancy of the open-sky flux on many factors (zenith angle, detector altitude, geographic positioning, and upper atmosphere state), it is challenging to estimate it properly. The goal of this study is to improve the current way in which this estimate is done.

Two approaches are generally possible to estimate the open-sky flux. The first is based on semi-empiric models (Tang [4], Shukla [5], Gaisser [6]...). The parameters of these formulations are calibrated using data sets recorded at specific locations and elevations. Analytical or empirical correction factors are then used to extrapolate these values to the desired survey elevation (z) with a simple formula [7] and take into account the atmospheric conditions influence on muon production [8],[9]. The second approach makes use of CORSIKA, a Monte Carlo driven Nuclei-Hadron interaction model used for cosmic shower simulation [10]. It has been used to simulate the influence of the temperature and the density of the atmosphere on the production and buffering of muons, as well as the effect of the geomagnetic field and the detector elevation. Both of these approaches have to overcome issues with extreme zenital angles.

We have evaluated the discrepancies between the analytical models, the CORSIKA fluxes, and laboratory measurements. Inter-comparision of these different approaches are used as a mean to validate our CORSIKA numerical experiment. Then, we analyze the geodesic effects on the muon flux in terms of energetic composition with varying magnetic field, altitude and density distribution of the atmosphere. General mechanisms governing the ground-level muon flux are then discussed.

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Session Classification: Simulation tools and studies

Track Classification: Simulation tools and studies

Contribution ID: **7** Type: **Plenary talk**

Borehole Muon Telescope for Underground Muography

Wednesday 24 November 2021 14:40 (20 minutes)

Muon radiography applies to different situations and is
particularly suitable for subsoil imaging. The methodology can be used in order to carry out civil and archaeological investigations. This kind of applications need the muon telescope to be installed below the region to be investigated. The shape and size of such a muon detector have to reflect this necessity.
A novel borehole cylindrical detector has been realized and tested to be used in harsh conditions and installed in tight spaces. It is built with two types of scintillators of different geometry, in the shapes of bar and arc. The size was chosen to fit inside holes greater than 25 cm in diameter, typically realized at standard costs. The commissioning of the detector and preliminary test results will be shown."

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Session Classification: Instrumentation

Track Classification: Instrumentation

Contribution ID: **8** Type: **Plenary talk**

Novel Muon Tomography Detector for the Pyramids

Wednesday 24 November 2021 15:50 (20 minutes)

Cosmic-ray muons which impinge upon the Earth's surface can be used to image the density of geological and man-made materials located above a muon detector. The detectors used for these measurements must be capable of determining both the muon rate and angle of incidence. Applications of this capability include geological carbon storage, natural gas storage, enhanced oil recovery, compressed air storage, oil and gas production, tunnel detection, and detection of hidden rooms in man-made structures, such as the pyramids. For these applications the detector must be small, rugged, and have operational characteristics which enable use in remote locations, such as low power requirements. A new muon detector design is now being constructed to make measurements on the Khafre pyramid to look for unknown voids that might exist in the structure. The new detector design uses plates of scintillator with fiber optic readout to obtain position information. This design will meet the operational requirements, while also providing a geometry which can be modified for different measurement conditions.

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Session Classification: Instrumentation

Track Classification: Instrumentation

Contribution ID: **9** Type: **Plenary talk**

Muon imaging and monitoring applied to hydrogeological studies at the Mont Terri Underground Rock Laboratory, Switzerland

Thursday 25 November 2021 11:30 (20 minutes)

In this work we analyze the data sets of two muon imaging and monitoring experiments carried out using a portable muon detector conceived for geosciences applications at the Mont Terri Underground Rock Laboratory (URL), Switzerland. This underground facility is located in the Jura Mountains in north-western Switzerland, at a depth of ˜300 meters below the Earth's surface. The region hosts two aquifers separated by an aquitard. The objective of these experiments is to evaluate the potential of muography to quantify groundwater variations.

Each of the data set consists of more than 1 year of measurements acquired in a specific location and detector orientation in the underground facility. This results in different opacity distributions for each experiment (˜700 and ˜1000 meters water equivalent, respectively). The two experiments together represent more than 2 years of muon data. From each data set we computed a radiography of average mass density along the registered muon trajectories, and we found that they are consistent with each other and with the geology of the site.

Previous large particle-physics experiments have shown that muon rate variations registered in underground facilities are sensitive to regional middle-atmosphere temperature variations. Our results show that the sensitivity to these phenomena is not only limited to large, expensive, and immobile muon detectors often associated to neutrino experiments and high-opacity conditions. We found that changes in the thermal state of the atmosphere represent a major cause of muon rate variations registered in both experiments conducted at the Mont Terri URL.

To evaluate the feasibility of employing muography methods to perform hydrogeological studies, we first study the influence of the middle-atmosphere temperature variations in each data set to remove it from the muon rate variations time series. After eliminating this effect, we compare the resulting muon rate variations time series with meteorological and hydrogeological data that estimate the groundwater content in the study region. In addition, by merging adjacent axis of observation of the portable muon detector, we found different zones of the rock volume above the site that exhibit characteristic behaviors. Finally, we discuss the implications of our observations for geosciences applications aiming to characterize density variations in the subsurface with muon data.

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Session Classification: Data analysis and image reconstruction

Track Classification: Data analysis and image reconstruction

Contribution ID: **10** Type: **Plenary talk**

COMMAND: a COmpact and Multi-purpose Muon And Neutron Detector

Wednesday 24 November 2021 14:00 (20 minutes)

Applications of both cosmic-ray (CR) muons and neutrons have grown in numbers in the last decades. Measurements of flux attenuation (radiography) and scattering angles (tomography) of CR muons have been successfully applied to the inspection or monitoring of large natural and civil structures, to the search for heavy metals in container and trucks, to the control of nuclear wastes, and much more. Measurements with CR neutrons have instead been used for the determination of the snow-water equivalent, the soil moisture estimation and climate studies (sometimes together with CR muon measurements). In this talk we present COMMAND, a new compact detector for both muons and neutrons, which is currently in a late stage of development. It consists of 5 independent and removable modules: 3 for the detection of muons, based on scintillating fibers coupled to SiPMs, and 2 for the detection of neutrons, based on lithium enriched phosphor detectors, read by a matrix of SiPM. Several innovative solutions have been implemented in the making of COMMAND, from the use of additive manufacturing, to the design of the electronics, which is based on COTS devices and features realtime time-stamping and triggering, programmable bias for SiPMs, and low-noise/high-speed analogue front-end. An overview of the detector, its current state of development (completion due by the end of the year) and its possible applications are presented.

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Session Classification: Instrumentation

Track Classification: Instrumentation

Contribution ID: **11** Type: **Plenary talk**

Muography in the university and in the museum

Thursday 25 November 2021 14:20 (20 minutes)

The LouMu team joins together specialists in particle detectors and in cosmic ray analyses, geophysicists and science communicators to muograph an underground gallery of an old mine, now open to visitors of a science museum. The muon telescope is made of Resistive Plate Chambers developed to operate stably and with low consumption at remote locations, and it has been tested in the Coimbra University, before being moved to the Science Center of Lousal, Portugal. In parallel to the scientific goals of surveying the geological faults around the gallery, comparing and combining the information from muography and other techniques, and testing and possibly upgrading these detectors for muography, the project aims to engage students at several levels and the interested public at large. The telescope was thought to operate in front of visitors, all the project phases will be documented, and the muographic data collected in the university building and the mine gallery will be made available for educational use. Providing an almost online update of simple and complex muographies is a challenge but provides an opportunity for a valued interaction of the public with our usually distant work.

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Session Classification: Science communication and outreach

Track Classification: Science communication and outreach

Contribution ID: **12** Type: **Plenary talk**

Muography for Underground Geological Surveys: ongoing application at the Lousal Mine (Portugal)

Wednesday 24 November 2021 09:15 (30 minutes)

The feasibility of muography for geological survey and mining exploration has been demonstrated in many works around the world, since the first steps of muography. It was in 1955, as documented, the first use of muons was to measure the ice thickness above the tunnel of a mine in Australia.
Muography with muon telescopes in an underground setting has an easy side due to the absence of the background radiation but, on the other hand, the muon flux is much lower compared to what is measured on the surface. It is a matter of geological and underground conditions, suitable muon detectors and the necessary time of exposition to carry the observation.
To innovate the geophysics methods panorama in Portugal, a collaboration has been established between the Institute of Earth Sciences (ICT) –University of Évora, the Laboratory of Instrumentation and Experimental Particle Physics (LIP) and the Lousal Living Science Center to develop muon telescopes and evaluate the muography potential in the Lousal Mine.
The Lousal Mine is no longer an exploration mine, it now functions as a mining museum integrated in scientific and educational activities. The upper gallery of the mine is the host of the muon observations, about 18 m below the surface. The telescopes, developed by LIP, use robust RPC detectors to observe the crossing muons in real time. The application aims to do a geological survey of the terrain between the upper gallery and the surface, to map structures and ore masses already known and to improve the existing information with new data, while putting to the test the muon detectors performance developed for the project.
Other geophysical methods, particularly seismic refraction and georradar (GPR) methodologies, are being used on the surface of the terrain to build a reference model. The goal is to use all the information gathered to build a 3D density model of the studied region, using muography as a central technique.

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Session Classification: Collaboration reports

Track Classification: Collaboration reports

Contribution ID: **13** Type: **Plenary talk**

Magnetic-field imaging by cosmic-ray muon (Magic-μ)

Thursday 25 November 2021 16:15 (20 minutes)

Cosmic-ray muon radiography, also called muography, can exploit the internal structure of an object that muons traversed. In the conventional absorption method, transmission or absorption ratio to background terrestrial muon flux can determine the density length. After the scattering method was invented, muography can inspect nuclear materials' existence in targets. The identification is possible because the nuclear materials have a large electron density to scatter muon at large angles. This study proposes new targets, "magnetic field imaging" and "magnetic flux density measurement." We call the project, Magic-μ, which is short for MAGnetic field Imaging by Cosmic-ray MUons. When a muon traverses in a magnetic field, they are deflected and change their trajectories with its velocity and charge. In other words, the magnetic field must distort the muography image from its original (non-magnetic field condition) image only around the magnetic field. The distortion is detectable with the same process as anomaly detection in the absorption muography. This technique is promising to detect the degradation of a superconductive coil of a fusion reactor because it can find a weak magnetic field region. Next, let us move toward magnetic flux density measurement. In standard muography, muon charge identification is not necessary, but it is mandatory for the magnetic flux density measurement. We will install a muon charge identifier to a standard absorption muography detector. Also, a novel data analysis technique is required to determine the absolute value of the magnetic flux density from the distorted image. We will start with the so-called template matching method, which can find displacement from a template image, a muography image without a magnetic field. We will estimate the magnetic flux density from the displacement. It is useful to understand the magnetic field applied by multipole electromagnets using for Fixed-Field Alternating Gradient accelerator. Additionally to these overviews, simulation results for the feasibility study will be shown in the workshop.

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Session Classification: New Ideas

Track Classification: New ideas

Contribution ID: **14** Type: **Poster**

Simulation Studies for Muography of the Pyramids

Thursday 25 November 2021 16:00 (5 minutes)

Muography is an technique that can image objects by tracking cosmic-ray-produced muons, which are unstable leptonic particles with a mass of 207 MeV and a mean lifetime 2.2 μs. Muography ispotentially useful for discovering voids inside the Great Pyramids. Our computer simulation of muography focus on studying the great Pyramid, "Khufu,"to discover voids inside it using an advanced muon detector designed with a suitable geometry that measures the angular dependence of the cosmic muon flux inside the pyramid. The simulation results will be validated using previous simulations. This will be useful for developing an algorithm that can also be used for discovery within the second great pyramid, "Khafre".

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Presenter: Ms ALY, Shereen (Helwan University and Canadian Internaational College)

Session Classification: Poster session

Track Classification: Simulation tools and studies

Contribution ID: **15** Type: **Plenary talk**

Imaging of the inner zone of blast furnaces using the muon radiography: the BLEMAB project

Friday 26 November 2021 09:40 (20 minutes)

The aim of the BLEMAB project (BLast furnace stack density Estimation through on-line Muon ABsorption measurements) is the application of the muon radiography techniques in order to obtain the imaging of a blast furnace inner zone. In particular, the goal of the study is to charachterize geometry and size of the so called "cohesive zone", i.e. the spatial region where the slowly downward moving material begins to soften and melt, that plays such an important role in the performance of the blast furnace itself.

Thanks to the high penetration power of natural cosmic ray muon radiation, muon transmission radiography could be an appropriate non invasive methodology for the imaging of large high-density structures such as a blast furnace, whose linear dimensions can be up to a few tens of meters. A state of the art muon tracking system derived from the technology developed for MIMA and MURAVES detectors (used in muography applications in the field of Archaeology, Geology and Civil Engeneering) is currently in development and will be installed at a blast furnace on the ArcelorMittal site in Bremen (Germany), in order to start a continuos test of data collection.

Hundreds of muons are expected each day, for each angular bin with a size of 2 deg in azimuth and 2 deg in elevation, thus allowing a continuos measurement of the average density distribution keeping statistical fluctuations at less than ten percent. Muon radiography results will also be compared with measurements obtained through an enhanced multipoint probe and standard blast furnace models.

In this contribution the project, its development status and the expectations based on preliminary simulations are presented and briefly discussed.

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Session Classification: Applications

Track Classification: Applications

Contribution ID: **16** Type: **Plenary talk**

Towards portable high-resolution muon detector based on RPCs

Wednesday 24 November 2021 11:35 (20 minutes)

The use of conventional imaging techniques becomes problematic when faced with challenging logistics and confined environments. In particular, such scenarios are not unusual in the field of archaeological and mining explorations as well as for nuclear waste characterization. For these applications, even the use of muography is complicated since the detectors have to be deployed in difficult areas with limited room for instrumentation, e.g., narrow tunnels. Within this context, our group has developed a portable muon detector (muoscope) based on mini glass Resistive Plate Chambers (mini-gRPCs) following a design similar to the one developed by the CALICE collaboration at CERN, but with smaller active area of 16×16 cm^2. The specific design goals taken into consideration while developing our first prototype are portability, robustness, autonomy, versatility, safety and low cost. We are currently in the process of developing an improved second prototype, which will have a new electronic chip for readout. In line with our design goals, we also plan to switch the sensitive units from strips in the old prototype to pixels for the new one. This will help further improve our design goal of portability by reducing the overall weight of the setup by half since a single RPC layer provides bi-dimensional information with pixels. However, for performing high resolution muography, the number of readout units per layer also increases significantly, leading to increase in the overall cost and power consumption of the muoscope. To mitigate these issues, we are developing a novel 2D multiplexing algorithm for reading out several pixels with a single electronic channel. In this talk, we will give an overview of the detector development, focusing mainly on the design goals and the choice of detector technology. Furthermore, the details of the expected changes in the new prototype as well as some preliminary results from the 2D multiplexing study will also be presented, along with the results from the performance studies of the current prototype.

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Session Classification: Instrumentation

Track Classification: Instrumentation

Contribution ID: **17** Type: **Plenary talk**

Recent results from Canadian Nuclear Laboratories' work on muon tomography for nuclear security and safeguards

Thursday 25 November 2021 11:50 (20 minutes)

During the last decade, Canadian Nuclear Laboratories (CNL) has been accumulating considerable experience in the development of muon radiography techniques with a focus on potential applications for nuclear security and safeguards. A unique muon tomography system with the ability to measure muon momenta, the Cosmic Ray Inspection and Passive Tomography (CRIPT) detector, has been operational at CNL since 2013. Building on that expertise, CNL has constructed and is commissioning a compact portable muon tomography system for field use. Recent advances at CNL in detection systems and data analysis techniques for muon radiography and practical applications will be presented including the three main achievements highlighted below.

A clustering-based algorithm that uses a nonparametric statistical test based on a reference case to determine the presence of high-density high-Z material, such as illicit nuclear material hidden inside a shipping canister, has been developed. The technique provides a single output –a simple 'yes'or 'no'–to confirm the presence of nuclear material. In contrast to other muon-based imaging methods, it does so without the need for a detailed visual reconstruction or human interpretation. The performance of the algorithm was demonstrated using experimental data obtained with the CRIPT detector. This new algorithm has the potential for many important applications in nuclear safeguards, including the security of nuclear facilities and nuclear materials controls (e.g., nuclear treaty verification efforts).

A novel attenuation-based muon computed tomography algorithm has been developed to enable imaging of large nuclear infrastructure using measurements from a single muon tracking module. The performance of the algorithm has been evaluated for seven different reconstruction techniques from the computed tomography literature. A muon-tomography reconstruction of a simplified simulated reactor core is able to accurately reproduce the geometry, including the identification of missing fuel channels, and can produce reasonable estimates of average stopping powers in high-density voxels.

Statistically differentiating lead and ceramic UO_2 (commonly found in reactor fuel) has been demonstrated for the first time using CNL's CRIPT detector. These two materials have comparable radiation lengths, which makes measurements of the scattering angle distributions difficult to resolve. The inclusion of muon momentum information, provided by the momentum spectrometer, has enabled this first-of-a-kind measurement. This serves as a demonstration of the capability of muon scattering tomography as a non-intrusive inspection tool for nuclear safeguards applications.

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Session Classification: Data analysis and image reconstruction

Track Classification: Data analysis and image reconstruction

Contribution ID: **18** Type: **Plenary talk**

A muon generator for cosmic-ray muon applications

Thursday 25 November 2021 09:00 (20 minutes)

Cosmic-ray radiation, thanks to its high penetration capability and relative abundance, has been successfully used in scientific research and civil applications for a long time. For example, techniques based on the attenuation of cosmic-ray muons (muon radiography) or on their angular scattering (muon tomography) have been used to study the inner structure of volcanoes, to search for hidden chambers in Egyptian pyramids, to inspect nuclear waste containers and to monitor blast furnaces. In addition to these imaging techniques, cosmic ray muons have also been used for the detector alignment in large experiments in nuclear and elementary particle physics, and, more recently, proposed for the alignment and stability monitoring of mechanical structures.
Muon radiography applications are sensitive to the angular distribution of cosmic muons, and many applications of muon tomography are also sensitive to their momentum distribution. For these reasons, an accurate simulation of the dependency of the muon flux on momentum and direction is a key requirement for every generation tool targeting to such applications. Moreover, as the inspection of large structures requires a very large statistics, the generator has also to be fast.
A new Monte Carlo generator of cosmic-ray muons, called EcoMug (Efficient COsmic MUon Generator) and specifically designed for muon radiography and tomography applications, is presented. It is a header-only C++11 library, based on a parametrization of experimental data. Unlike other tools, EcoMug gives the possibility of generating from different surfaces (plane, cylinder and half-sphere), while keeping the correct angular and momentum distribution of generated tracks. The main features of EcoMug, its mathematical foundation, as well as applications to selected study cases are presented.

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Session Classification: Simulation tools and studies

Track Classification: Simulation tools and studies

Contribution ID: **19** Type: **Plenary talk**

Muography at Low Background Noise Underground Research Laboratory of Rustrel.

Wednesday 24 November 2021 16:10 (20 minutes)

Muon trackers are used for both scattering and transmission muography. When the properties of the object change over time, event timestamping is essential to study the temporal dynamics of the system. In addition, underground measurements present supplementary deployment constraints in terms of volume, weight and gas management, among others. The T2DM2*project at the Low Background Noise Underground Research Laboratory of Rustrel (LSBB) has developed a compact muon tracker for dynamic tomography of density based on a thin time projection chamber with Micromegas readout to work under these conditions and with a performance analogue to classic geophysics methods.*
*This contribution presents (i) the working principle of the detector, (ii) a former study case as performance and application example, (iii) the recent detector hardware updates, (iv) the status of the project, (v) other Muographic activities at the LSBB and the (iv) short term objectives and valorization strategy.*Temporal Tomography of the Density by the Measurement of Muons.

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Session Classification: Instrumentation

Track Classification: Instrumentation

Contribution ID: **20** Type: **Plenary talk**

Muography in Colombia: simulation framework and instrumentation

Wednesday 24 November 2021 10:45 (30 minutes)

We describe the Muography Program to study the volcanoes ranging from the Colombian Andes. We discuss the developed simulation framework covering the cosmic rays impinging the upper Earth's atmosphere, the geomagnetic field modulation, the particle showering along the atmosphere, the muon flux passing through the volcano edifice, the particle-detector interaction and the detector response. We built a hybrid muon telescope (MuTe) based on a composite detection technique. It combines a hodoscope for particle tracking and a water Cherenkov detector to enhance the muon-to-background-signal separation due to extensive air showers' soft and multiple-particle components. MuTe also discriminates inverse-trajectory and low-momentum muons by using a picosecond Time-of-Flight system. We describe the structural –mechanical, and thermal– behaviour of MuTe. We discuss preliminary results from the background composition and the telescope-health monitoring variables. Finally, we implement optimization algorithms to improve the volcano internal density distribution measured by our instrument and machine learning techniques for background rejection.

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Session Classification: Collaboration reports

Track Classification: Collaboration reports

Contribution ID: **21** Type: **Plenary talk**

The use of muon radiography in the verification of nuclear geological disposal facilities

Friday 26 November 2021 10:50 (20 minutes)

The long-term disposal of nuclear waste is a pressing global problem. Most countries are following similar routes of developing one or more geological disposal facilities (GDF) deep underground. The potential role that muon tomography can play in the construction and operation of such a facility is currently under consideration across Europe. The presentation will focus on a number of aspects where muon tomography will provide a unique or valuable complimentary tool, such as repository verification, materials screening and package voidage. Results from initial simulations will also be discussed.

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Presenter: F. THOMPSON, Lee (University of Sheffield (UK))

Session Classification: Applications

Track Classification: Applications

Contribution ID: **22** Type: **Poster**

Monte Carlo simulation for background study of the Wudalianchi volcano with cosmic ray muons

Thursday 25 November 2021 15:30 (5 minutes)

Muon radiography can be a powerful tool to study the internal density structure of large objects at a few hundred meters scale. However, background noise can reduce significantly the efficacy of this technique if not adequately eliminated. In our cosmic ray muon radiography experiment to image the internal density structure of the Wudalianchi volcano in northeast China, the background noise pollution led to overestimate the muon flux, which seriously underestimated the density of the volcano. To estimate correctly the level of background noise and propose solutions to reduce it, we use the CRY code to generate the cosmic particles (electrons, protons and muons) and the Geant4 code to simulate the interaction of particles within the volcano structure. The results show that the background noise in muon radiography is mainly made of low energy particles (less of 1-2 GeV). To discriminate the background particles and eliminate them we study the feasibility of two methods; one is based on Time of Flight technique provided by fast time detectors to identify the particles, another is using the Multiple Coulomb Scattering method by placing absorber walls between detector layers. The two methods aim at separating low from high particles.
This study will be instructive for the next volcano experiment.

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Session Classification: Poster session

Track Classification: Simulation tools and studies

Contribution ID: **23** Type: **Plenary talk**

Simulation Study of Reinforced Concrete Blocks With Muon Imaging Techniques

Friday 26 November 2021 11:50 (20 minutes)

Ageing civil infrastructure poses a huge problem for the modern world. In the example of transport bridges, structural integrity defects can result in disruption, massive economic losses, and in extreme cases of failure, even tragedy. Inspection technologies in use today can hardly be called ideal: X-rays can provide high-resolution images but their usage is restricted by health and safety regulations; on the other hand ultrasound and ground-penetrating radar, are safer, but suffer from limited penetrating depth and/or poor resolution. There is an emerging technology that can be used to image these large structures: muon imaging. This technique does not have the drawbacks of the more conventional non-destructive testing methods. It is well known that the cosmic ray muon has a very high penetrative capability due to its high average momentum and its large mass. Muon imaging techniques are only reliant on background radiation and do not require hazardous man-made radioactive sources. In this paper, we developed Monte Carlo simulations to study the performance of muon imaging methods on thick reinforced concrete structures. Image reconstruction methods such as POCA, MLEM etc. were used with varying parameters (such as tracking detector resolution, diameter of steel reinforcement bar and thickness of the concrete structures) to assess the effects of outside factors on imaging performance. The effect of the tracking detector noise on the image quality was also investigated. The experimental result of a reinforced concrete block is also shown in this paper, and it agrees well with the simulation results.

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Session Classification: Applications

Track Classification: Applications

Contribution ID: **24** Type: **Plenary talk**

Application of muography to the industrial sector

Friday 26 November 2021 10:00 (20 minutes)

Muography can be utilized as a Non-Destructive Testing (NDT) technique to perform preventive maintenance of industrial equipment, quality control of production processes and risk assessment in the context of the heavy industry. The great penetration power of muons in matter makes this technique interesting to inspect large and dense industrial structures such as cauldrons, furnaces and pipes. At the same time, muography does not require to stop the production process allowing to decouple this kind of maintenance from the technical stops of the factories. This kind of application simplifies also the muon imaging algorithms since only small deviations with respect to a very well known nominal geometry are needed, allowing to solve the problem with parameter inference solutions. This talk will review and summarize the recent progress of the company Muon Systems on this topic ranging from detector considerations, reconstruction algorithms and new applications.

Primary authors: Mr ORIO, Aitor (Muon Systems); Mr DÍEZ, Carlos (Muon Systems); MARTINEZ RUIZ DEL ARBOL, Pablo (Universidad de Cantabria and CSIC (ES)); Dr GÓMEZ, Pablo (Muon systems)

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Session Classification: Applications

Track Classification: Applications

Contribution ID: **25** Type: **Plenary talk**

Absorption muographic challenges on the surface

Thursday 25 November 2021 13:40 (20 minutes)

Absorption muography has many applications, but it can typically be divided into two categories based on the detector location: underground or surface measurements. The latter case started in volcanological application, but nowadays multiple applications arise besides basic muographic researches e.g., archaeology, and building structural imaging. In my presentation, I would like to briefly summarize the MWPC-based Muography Observation System (mMOS) at the Sakurajima volcano and the plans of installation at Etna volcano as well (Budapest-Catania-Tokyo collaboration), furthermore I would like to show an imaging resolution measurement method at the Budapest Fairy Rock, and give an overview on different flux calculations, systematic errors, lead wall background suppressions, and challenges of the surface measurements.

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Session Classification: Data analysis and image reconstruction

Track Classification: Data analysis and image reconstruction

Contribution ID: **26** Type: **Poster**

Meiga, a dedicated framework used for muography applications

Thursday 25 November 2021 16:00 (5 minutes)

The design and development of detectors for muography is in constant demand of the usage of semiempirical models and simulations. In this contribution we present *Meiga*, a framework conceived for simulation and reconstruction of muography applications. This framework takes a simulated muon flux at ground level and propagates it through a given material where the detectors are located. It uses Geant4 as a toolkit for the simulation of traversing particles through the material and computes the signal produced when muons pass through any type of detector at the desired location. Both, simulated and reconstructed data are stored for an offline analysis. Meiga encompasses the need of simulating different scenarios to optimize detector design in a versatile and easy-to-use framework. In this contribution, we present the methods for simulating scintillator-based detectors intended for muography studies in addition to first results of validation with prototype detectors.

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Session Classification: Poster session

Track Classification: Simulation tools and studies

Contribution ID: **27** Type: **Poster**

Simulation of a first case study for magnetic field imaging with the Magic-μ technique

Thursday 25 November 2021 16:00 (5 minutes)

We present a feasibility study for a new muography technique, MAGnetic field Imaging by Cosmic-ray MUons (Magic-μ), whose general principles are introduced in another presentation. This new application exploits the charge of cosmic-ray muons, which causes them to shift their trajectory in response to magnetic flux density. As a first case study, we simulated the measurement of the field generated by a permanent magnet. In the first step, the magnetic field was calculated using the three-dimensional finite-element solution package AMaze. Then, the magnetic field flux density data were converted into a readable format for the PHITS Monte Carlo simulation code and muography images were obtained for two states of the magnetic field region ON and OFF. Positive and negative muons were generated using the PARMA model implemented in PHITS. The resulting image of the magnetic field ON is significantly blurred compared to the image of the magnetic field OFF. This blurred image can also be used for the analysis of the magnetic field. The simulation results are promising for the newly proposed application of cosmic-ray muons, the imaging of the magnetic field.

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Presenter: BASIRI, Hamid (Kyushu University)

Session Classification: Poster session

Track Classification: Simulation tools and studies

Contribution ID: **28** Type: **Poster**

Development of a non-destructive inspection method for trees using cosmic rays

Thursday 25 November 2021 16:00 (5 minutes)

We have developed a technique for non-destructive inspection of huge structures such as the Egyptian pyramids and nuclear reactors using cosmic rays, which have high material penetration ability. In this study, we proposed a new application of this technique to the cavity exploration of trees. We used nuclear emulsion as a cosmic-ray detector. The non-destructive inspection technique using cosmic rays was applied to trees for the first time, and the validity of this technique as a diagnostic method for giant trees was clarified.

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Presenter: Dr NISHIO, Akira (Nagoya University)

Session Classification: Poster session

Track Classification: New ideas

Contribution ID: **29** Type: **Plenary talk**

Muon Tomography Applications for Nuclear Waste Management and Decommissioning in the UK

Friday 26 November 2021 11:10 (20 minutes)

In the UK nuclear industry, muon imaging is gaining traction as a credible option in the toolkit of techniques for monitoring and inspection of waste packages arising from decommissioning activities across the UK nuclear estate. Since 2009, the National Nuclear Laboratory has collaborated with the University of Glasgow and Lynkeos Technology Ltd. to develop muon imaging techniques for such applications. In this paper we review our experiences in imaging typical waste-forms such as vitrified products and corroded sludge. The requirements and expectations of stakeholders and plant operators with regard to waste monitoring are examined, and the constraints and challenges of deploying and operating muon detection instruments on nuclear licensed sites are discussed.

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Presenter: Dr RYAN, Matthew (National Nuclear Laboratory)

Session Classification: Applications

Track Classification: Applications

Contribution ID: **30** Type: **Plenary talk**

A Novel Readout Scheme for Muon Tomography Application in Material Identification

Wednesday 24 November 2021 14:20 (20 minutes)

We plan to build a prototype muon tomography system for material identification utilizing multiple Coulomb scattering suffered by cosmic ray muons while passing through a matter. The resultant deflection from the original trajectory can be represented by a Gaussian distribution dependent on several physical properties of the matter (density ρ, atomic number Z) and also the muon momentum. Thus, the measurement of the scattering angle by tracking the pre and post-interaction muon trajectories enables one to identify the material. The tracking of the muons can be accomplished with multiple position-sensitive detectors placed along the direction of the muons which facilitate the reconstruction of the trajectories using the 2D position data obtained from each of them.

We plan to use RPCs for tracking muons due to their reasonable position and time resolution. An inexpensive novel multi-parameter readout scheme has been developed for collecting position data from the RPCs and subsequent track reconstruction 1. An 8-channel ultra-fast front-end preamplifier discriminator chip NINO has been used to obtain Time-Over-Threshold (TOT) outputs corresponding to the current signals induced on the readout strips of the RPC due to a muon event. Each NINO chip provides 8 pairs of LVDS signals which are suitable for low-power, high-speed transmission with better noise immunity. For parallel post-processing and to take advantage of this LVDS scheme, we have used an FPGA development board with ALTERA MAX 10 which can directly acquire LVDS analog signals using a PLL-controlled clock (500 MHz max) for sampling. This has led us to achieve 2 ns resolution for signal acquisition. The FPGA has been programmed to transfer the acquired data to the computer using UART protocol. The data for muon events as collected by a single NINO board followed by the FPGA have been analysed to estimate the position information and used for determining the efficiency of the RPC in muon detection in comparison to plastic scintillator. We plan to operate a Bakelite-RPC of dimension 30cm x 30 cm equipped with two orthogonal panels of readout strips of width 1 cm and pitch 1.2 cm for producing image of a lead block from the muon hits as acquired by the present readout scheme to examine its efficacy for implementing in building up the readout electronics of the full prototype tomography system.

Reference:
1 S. Tripathy et al., Precise tracking of cosmic muons using the Time-over-Threshold property of NINO ASICs, Journal of Instrumentation 15 (2020) C11013.

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Presenter: Mr DAS, Subhendu (Saha Institute of Nuclear Physics (IN))

Session Classification: Instrumentation

Track Classification: Instrumentation

Contribution ID: **31** Type: **Plenary talk**

Technological development and application of muography with nuclear emulsions

Wednesday 24 November 2021 15:30 (20 minutes)

We are developing nucelar emulsions for muographys at Nagoya University and applied to many targets. In this talk, I'll present current status and new progress.

Primary authors: MORISHIMA, Kunihiro (Nagoya University (JP)); Dr NISHIO, Akira (Nagoya University); Dr KITAGAWA, Nobuko (Nagoya University); Dr KUNO, Mitsuaki (Nagoya University); Mr MANABE, Yuta (Nagoya University); Mr IMANISHI, Tomoya (Nagoya University); Ms MIYATA, Fuyu (Nagoya University); Mr KODAMA, Hiroto (Nagoya University); Mr MORII, Kento (Nagoya University); Mr SHIMIZU, Kai (Nagoya University)

Presenter: MORISHIMA, Kunihiro (Nagoya University (JP))

Session Classification: Instrumentation

Track Classification: Instrumentation

Contribution ID: **32** Type: **Plenary talk**

Imaging and evaluation of defects in civil structures using Muon Scattering Tomography (MST)

Thursday 25 November 2021 14:00 (20 minutes)

MST is a major non-destructive technique to detect high-atomic number (Z) and high-density (⊠) materials by finding the deviation in muon tracks. Both numerical simulation and experimental activities are being carried out towards assembling a gaseous ionization detector-based MST system at SINP. A prototype setup has been simulated using Geant4. Based on scattering parameters, an algorithm namely, Pattern Recognition Method (PRM) has been devised which is able to distinguish high-Z and low-Z materials with more than 5⊠ accuracy 1. A practical application of MST, namely, detecting defects in common civil structures has been performed using the same numerical technique. A few basic concrete structures that are frequently used in civil construction, have been considered as test cases. The images of the test cases with and without the defect have been simulated for variable exposure of cosmic muons on the basis of their scattering from the composite concrete structures. The efficacy of the said method has been evaluated in terms of the PRM-score devised in this work as well as using the t-statistics. The limitation and advantages of the present application of the MST encompassing the imaging and image processing technique in non-destructive evaluation of concrete structures have been discussed 2.

1. S. Tripathy et al., 2020 JINST 15 P06029
2. S. Tripathy et al., The European Physical Journal Plus, 824(136) (2021)

Primary author: Mr TRIPATHY, Sridhar (SAHA INSTITUTE OF NUCLEAR PHYSICS)

Co-authors: DATTA, Jaydeep; MAJUMDAR, Nayana (Saha Institute of Nuclear Physics); MUKHOPADHYAY, Supratik (Saha Institute of Nuclear Physics (IN))

Presenters: Mr TRIPATHY, Sridhar (SAHA INSTITUTE OF NUCLEAR PHYSICS); MAJUMDAR, Nayana (Saha Institute of Nuclear Physics); MUKHOPADHYAY, Supratik (Saha Institute of Nuclear Physics (IN))

Session Classification: Data analysis and image reconstruction

Track Classification: Data analysis and image reconstruction

Contribution ID: **33** Type: **Poster**

Measurement of cosmic rays with emulsion chambers in water

Thursday 25 November 2021 16:00 (5 minutes)

Nuclear emulsion films packed in aluminum laminated sheet were installed in a 2.9m-deep-pool.We observed cosmic rays for 13 days, and then calculated the muon flux up to about 600 MeV.
In this session, we would like to discuss the measurement results of muon flux by comparing with the measurement data of BESS and the simulated data by PHITS, with considering the systematic errors from the contamination of electrons and the circumstances during observation.

Primary authors: Dr NISHIO, Akira (Nagoya University); Dr MORISHIMA, Kunihiro (Nagoya University); Dr KITAGAWA, Nobuko (Nagoya University); Dr KUNO, Mitsuaki (Nagoya University); Mr MANABE, Yuta (Nagoya University)

Presenter: Dr KITAGAWA, Nobuko (Nagoya University)

Session Classification: Poster session

Track Classification: Instrumentation

Contribution ID: **34** Type: **Poster**

Development of a borehole detector with nuclear emulsions

Thursday 25 November 2021 16:00 (5 minutes)

We are currently developing a borehole detector using nuclear emulsions. Because of the high resolution of nuclear emulsions, the detector can be inserted into the borehole whose diameter is 75mm without losing angular accuracy or other performance characteristics even if the size of nuclear emulsions is reduced. Furthermore, no power supply is required. In this poster, we will report the current status of the detector development.

Primary authors: NISHIO, Akira (Nagoya University); MORISHIMA, Kunihiro (Nagoya University); KITAGAWA, Nobuko (Nagoya University); IMANISHI, Tomoya (Nagoya University)

Presenter: IMANISHI, Tomoya (Nagoya University)

Session Classification: Poster session

Track Classification: Instrumentation

Contribution ID: **36** Type: **Poster**

Nuclear Waste Imaging and Diversion Monitoring using Muon Scattering Tomography

Thursday 25 November 2021 15:50 (5 minutes)

In addition to imaging an object, muon scattering tomography (MST) benefits from providing additional information, i.e. the Z of the scattering material, when interrogating the object. MST' s potential therefore to image the material inside nuclear waste drums is well-established. Here the technique is extended, using machine learning methods, to provide quantifiable metrics for in-drum material identification. The methods thus developed and the results obtained for a series of nominal material types and shapes in a simulated drum are presented. Results using the MST technique to determine whether or not materials have been diverted or replaced in the drum will also be presented.

Primary author: WEEKES, Michael

Co-authors: THOMPSON, Lee (University of Sheffield); VELTHUIS, Jaap; F ALRHELI, Ahmad; DE SIO, Chiara (University of Bristol); J BARKER, Dominic; KIKOLA, Daniel; KOPP, Anna (Albert-Ludwigs-Universitaet Freiburg (DE)); MHAIDRA, Mohammed; STOWELL, Patrick (Durham University (UK))

Presenter: WEEKES, Michael

Session Classification: Poster session

Track Classification: Data analysis and image reconstruction

Contribution ID: **37** Type: **Plenary talk**

Application of Portable Gaseous Detectors for Underground Muography

Wednesday 24 November 2021 12:15 (20 minutes)

The rapidly evolving field of Muography opens an outstanding way to reveal density anomalies inside hill-sized objects. The cosmic muons lose thei energy gradually and penetrate hundreds of meters into the ground, thus their differential local flux correlates with the density-length they traveled through.

In case of underground muography one exploits the low background and the higher flux in close-to-zenith regions, while sub-terrain operations face demanding technical requirements. The main field of interest of this non-invasive imaging are speleology, mining, and disclosure of cultural heritage targets.

The main challenges are the portability, low power consumption, and robustness against the out-of-the-laboratory environment. Portable gaseous tracking detector system has been designed and built, and successfully used for in the last years in several underground locations.

The presentation will focus on the designed portable tracking system, the main technical requirements, and successful measurement campaigns for calibration, exploration of natural caves, and examination of tunnels around the Buda Castle.

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Presenter: Dr HAMAR, Gergő (Wigner RCP, Budapest)

Session Classification: Instrumentation

Track Classification: Instrumentation

Contribution ID: **38** Type: **Plenary talk**

Muography developments within the MuAR project: advances in simulations and new detectors designs

Wednesday 24 November 2021 11:15 (20 minutes)

After the successful development of AMIGA and MuTe, both integrally designed, funded and built in Latin America, we created MuAr, a new collaborative project for the development of muography applications in geophysics, mining prospecting and safeguard.

We focus this project on the development of innovative muon detector designs, such as our two new muographers prototypes: *Mudulus*, a modular and portable detector, and *Musaic*, an innovative design based on fully autonomous, small, portable and independent tiles, that can be arranged in a panel with the desired size and shape. These designs are strongly supported by the development of *Meiga*, an intensive computational framework for muography.

In this contribution, I will briefly describe the current status of our developments within the MuAr project, the main scientific and technological motivations, some of the identified targets and our future perspectives.

Primary authors: ASOREY, Hernán (CNEA); Dr ALMELA, Alejandro (CNEA)

Presenter: ASOREY, Hernán (CNEA)

Session Classification: Collaboration reports

Track Classification: Collaboration reports

Contribution ID: **39** Type: **Plenary talk**

Construction and readout systems of gaseous muography detectors

Wednesday 24 November 2021 11:55 (20 minutes)

Muography instrumentation presents a wide range of practical challenges, since the implementation environment differs from the high energy physics laboratory conditions. The presentation will briefly overview the pros and cons of existing technologies, and gaseous detectors in particular. The practical challenges are partially environmental, such as thermal cycling or high humidity, partially connected to the installation such as mechanical shocks, and also include the human factor stipulating minimal non-expert maintenance and troubleshooting. The presentation aims to introduce various solutions to address these challenges, based on the examples of the detectors developed jointly by Wigner RCP and ERI at the University of Tokyo, with operational experience spanning five years.

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Presenter: VARGA, Dezso (Wigner Research Centre for Physics (Wigner RCP) (HU))

Session Classification: Instrumentation

Track Classification: Instrumentation

Contribution ID: **40** Type: **Poster**

Development of Mudulus, a muography detector based on double-synchronized electronics for geophysical applications

Thursday 25 November 2021 16:00 (5 minutes)

By taking advantage of our previous experiences in the development of muon detectors, such MuTe project in Colombia and AMIGA in Argentina, our group is developing detectors for muography and multi-purpose applications. Our prototype detectors use different modules of plastic scintillators with embedded optical fibres and 64 channel multi-anode photomultiplier tubes (PMT) with a common dynode, or arrays of Silicon Photomultipliers (SiPM).
In the case of Mudulus, each module is made of 12 scintillator strips of (4x1x100) cm3, and each extreme is connected to one of the PMTs channels. In this case, we can build panels with up to four of these modules. This modular configuration allows changing the panel geometries looking for an adaptive shape or size to the studied object and resulting in a faster or more detailed muography image.
The improvement in performance obtained with Mudulus is achieved by the combination of its modular design and the double synchronised detection at the end of each scintillator bar. We take advantage of the photomultiplier at each end to determine the muon flux using a model to account signal attenuation in each anode, and then determine the position of the incoming muons with a better discrimination and sub-pixel spatial resolution. In this contribution, we present the design, calibration, development and implementation of Mudulus.

Primary authors: CALDERÓN ARDILA, Rolando (Instituto de Tecnologías en Detección y Astropartículas); ASOREY, Hernán (CNEA); ALMELA, Alejandro (CNEA)

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Presenter: CALDERÓN ARDILA, Rolando (Instituto de Tecnologías en Detección y Astropartículas)

Session Classification: Poster session

Track Classification: Instrumentation

Contribution ID: **41** Type: **Poster**

Volcanic Eruption Forecasting using Cosmic Ray Muography and Artificial Intelligence

Thursday 25 November 2021 16:00 (5 minutes)

Machine learning algorithms have preliminarily been shown to have the potential to predict volcanic eruptions by training on muon data. The high-energy particles are used to map the interior of the volcano, chiefly due to muon's relatively high mass. In this poster, we discuss opportunities in this area. Challenges include curating the large-scale datasets that are necessary for deep learning applications like this one. We show intercomparisons between muography methods and traditional techniques like seismicity, deformation, and gas emission in terms of prediction efficacy.

Primary author: CHEN, Thomas (Academy for Mathematics, Science, and Engineering)

Presenter: CHEN, Thomas (Academy for Mathematics, Science, and Engineering)

Session Classification: Poster session

Track Classification: Applications

Contribution ID: **42** Type: **Plenary talk**

Thoughts about an ideal validation environment for muography applications

Friday 26 November 2021 09:00 (20 minutes)

Muography has many possibilities ranging from imaging volcanoes to observing civil infrastructures or even small scale objects. G.F. Knoll has laid out the fundamentals of radiation detection and measurement. However, what is still lacking is the testing and verification environments for muography detectors. In this work, we will present a few thoughts on such a possible muography test and method validation site.

As the target sizes for muography vary drastically, there is a need to have different detector technologies and assemblies. Most known applications of muography are linked to observing unknown (e.g., archaeological or geological target) or temporally changing (e.g., volcano monitoring) targets. There are also a lot of well-known but deteriorating targets within civil infrastructures. Data gathered from an alternative source(s), e.g., topographic maps, gravitational data, conductivity or magnetic field data, or seismic reflectivity data, to name a few, are used as reference material for the muography analysis. With Monte Carlo simulations, the muon background can be simulated and compared with the measured muon statistics to get a glimpse of what might be within the observed target.

For the data and method validation, an entry-level test environment is needed. It would be the most beneficial if it would be located on the surface, or at least relatively close to it, so that the muon flux measurements would be quick to carry out. Also, targets should be of high contrast compared with the surrounding environment, and the targets should be well-known objects what comes to their internal density profile and outer dimensions. For example, air against any liquid or solid target would create high contrast object and hence an ideal target for validating and testing muography detectors and imaging software. Using artificial targets such as 1 m3 concrete blocks or similar-size industrial containers filled with water, gravel, sand, or perhaps refined ore would provide an ideal object in size, cost and mobility. Additionally, a series of targets could contain integrated density anomalies (voids, denser structures) to enhance the validation tests related to contrast separation, angular resolution, inversion methods, and reconstruction of density profiles and tomographies. This could be called a micro-level validation environment.

At the macro level, the validation environment should be as authentic as possible. It should, for example, have access to a subsurface facility and known geological and infrastructural environment (e.g., a former underground mine with flat overburden would include all these qualities). In such a setting, the underground galleries, workings, and the tunnel network itself would make excellent muon radiography and muon tomography targets. Similarly, a micro-level validation environment would guide the validation process for testing the detector systems and the data reconstruction capabilities of the software. Additionally, it would be beneficial if there would be stockpiles of sand, gravel, etc., on the surface, and these would have variable sizes, or some of them could be reshaped or changed in terms of size. They could be used to validate both the spatial resolutions of the chosen detector assemblies and the threshold limits for observing the temporal changes.

We propose that the Callio Lab, a science and R&D site located at the 1.5 km deep Pyhäsalmi mine, Finland, offers an excellent opportunity to establish a micro and macro scale validation environment for the muography community. The underground mining is ending soon at this site, subsequently giving room for even 24/7 underground operations for other types of operators. However, the surface operation continues. The flat local overburden is ideal for both surface and

underground validation tests for muography instruments. Geology and the mine infrastructure are well-known and documented. From the infrastructure point of view, the underground has even a 1 Gb internet connection, and with secure remote access, long-term remote tests are also possible.

Primary authors: Mr HYNYNEN, Ilkka (Mining School, University of Oulu, Finland); Mr JOUTSENVAARA, Jari ((1)Kerttu Saalasti Institute, University of Oulu, Finland; (2) Virtual Muography Institute (global); (3) Arctic Planetary Science Institute, Finland; (4) Muon Solutions Oy, Pyhäjärvi, Finland); Mr HOLMA, Marko ((1)Kerttu Saalasti Institute, University of Oulu, Finland; (2) Virtual Muography Institute (global); (3) Arctic Planetary Science Institute, Finland; (4) Muon Solutions Oy, Pyhäjärvi, Finland)

Presenter: Mr JOUTSENVAARA, Jari ((1)Kerttu Saalasti Institute, University of Oulu, Finland; (2) Virtual Muography Institute (global); (3) Arctic Planetary Science Institute, Finland; (4) Muon Solutions Oy, Pyhäjärvi, Finland)

Session Classification: Applications

Track Classification: Applications

Contribution ID: **43** Type: **Plenary talk**

Civil Infrastructure Monitoring using Muon Radiography

Friday 26 November 2021 09:20 (20 minutes)

This presentation will focus on the application of muon radiography to the imaging of civil infrastructure, specifically its use in the location, characterisation and monitoring of hidden voids and shafts in railway tunnels. Results from a series of measurements made in railway tunnels on the UK's rail network in which a previously unknown void was located will be discussed alongside results from simulations of other features of interest. An overview of current and future instrumentation will also be presented.

Primary authors: STEER, Chris (Geoptic Infrastructure Investigations (UK)); GLUYAS, Jon (Durham University (UK)); THOMPSON, Lee (University of Sheffield (UK)); STOWELL, Patrick (Durham University (UK)); PIDCOCK, Richard (Central Alliance, Wakefield (UK)); BLANEY, Sean (Central Alliance, Wakefield (UK))

Presenter: STEER, Chris (Geoptic Infrastructure Investigations (UK))

Session Classification: Applications

Track Classification: Applications

Contribution ID: **44** Type: **Poster**

Muography, outreaching and transdisciplinarity

Thursday 25 November 2021 16:00 (5 minutes)

It can be reasoned that many emerging scientific disciplines arise when the conventional sciences cross paths in a manner not seen before. Events like these may lead to the rapid development of new methodologies, concepts, and technologies as the collaboration between previously separate research communities forms a fruitful background to further developments. This is the case also with muography which –at least occasionally –combines as varied fields of human activity as particle physics, detector designing, software coding, archaeology, arts, and a multitude of geoscience and engineering applications. It is the cross-pollination between the people with varied backgrounds that makes muography such an interesting and rapidly developing field of research and drives the emergent commercial activities.

Muography deviates from conventional particle physics by providing more visual results for the audiences. It also differs from conventional particle physics by being an applying method, rather than a fundamental and deeply theoretical science. A multitude of geophysical methods are used in geosciences, but only a few can be traced back to the quantum world of particle physics. Hence, the conventional curriculums of geophysicists and geologists, for example, are rarely preparing the graduating scientists for the requirements of muography. As muographers, it is within our responsibility to develop muography further, so that it will overcome the barrier that still separates it from other geophysical subdisciplines. This can be carried out by active collaboration between the different research groups working in the field of muography. However, as the applications of muography vary drastically from one to another, we also need effective communication with the researchers of other sciences. In addition, we need outreaching projects that let us be seen, heard, and experienced in the media, science parks and art installations by the other scientists and public alike.

Due to the fact that muography applications are so drastically varied, muography is intrinsically transdisciplinary in character. A transdisciplinary science approach is one that integrates or requires various disciplines, concepts, and methods in order to make research possible. When the research problem is relatively simple (from the viewpoint of modern curriculums), the conventional research fields are applied (e.g., astroparticle physics, instrumentation, and geoscience work and develop separately). However, when the challenges are more complicated, the different disciplines need interaction that can be described as multidisciplinary or interdisciplinary, depending on how much there is overlap. There are, nevertheless, also research fields that require even more interaction between different disciplines than either the multi- or interdisciplinary approaches can offer. We propose that muography falls into this fourth category, which is called transdisciplinary research. The reasons why we believe so are explained in the present work.

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Presenter: HOLMA, Marko (Muon Solutions Oy, Pyhäjärvi (Finland))

Session Classification: Poster session

Track Classification: Science communication and outreach

Contribution ID: **45** Type: **Plenary talk**

Muography and geology - Does it matter which continent you stand on?

Thursday 25 November 2021 10:00 (20 minutes)

The literature concerning muography has steadily increased in recent years, but so far very few publications have taken into account the true complexity of rocks in different continents, each continent having a different history and hence different geological features. The same is also valid for the question how deep underground muography can be applied. This is not straightforward because of rapidly reducing muon rate. Furthermore, we keep in mind that most people working in these fields are geologists, geochemists, geophysicists, and mining engineers.

In order to demonstrate the wide spectrum of different types of geological domains in the layered earth structure, we conducted a series of extensive simulations to be able to understand the differences in conducting muographic measurements in different parts of the world. Our simulations are based on the geological fact that different geological environments have different bulk rock compositions and density variation profiles.

Consequently, the present work introduces five continental geological models that differ from each other in terms of their density and rock chemistry. Clearly, both density and chemistry have a clear impact on the muon survival as it is known well that the attenuation of muons depends mostly on the density of the material the muons pass through before ceasing to exist.

We discuss the basic principles that must be taken into account while considering the maximum depth muography can be applied, but also highlight the key issues why this simple question is far from trivial, and why the answer always has some constraints that must be considered before planning and conducting muographic measurements deep underground.

The studied continental geological models were 1) upper continental crust, 2) bulk continental crust, 3) lower continental crust, 4) oceanic crust, and 5) oceanic upper mantle. In the latter two models, the oceanic rocks are tectonically thrust on the continental crust. The chosen five models differ from each other by both rock chemistry and density. Furthermore, water and standard rock were used as a reference as those are more familiar materials among astroparticle physicists. The simulation tools were Geant4 (attenuation) while the muon rate estimates were based on CORSIKA, Guan et al. (2015) (modified from Gaisser, 1990), Chirkin and Rhode (2016) (MMC code) and on the experimental data of Enqvist et al. (2005) extracted in the Pyhäsalmi mine, Finland.

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Primary authors: HOLMA, Marko (Muon Solutions Oy, Pyhäjärvi (Finland)); KUUSINIEMI, Pasi (Muon Solutions Oy, Pyhäjärvi (Finland)); ENQVIST, Timo (Muon Solutions Oy, Pyhäjärvi (Finland))

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Session Classification: Simulation tools and studies

Track Classification: Simulation tools and studies

Contribution ID: **46** Type: **Poster**

Trends in publishing muography related research results. The situation at the end of 2020

Thursday 25 November 2021 16:00 (5 minutes)

There is a wide variety of applications in muography. These include engineering, border control, tunnel detection, cave mapping, architecture, archaeology, volcanology, mineral exploration, mining, rock mechanics, water exploration, and many types of monitoring applications. As an application and a discipline, muography is currently shifting from its pioneering stage to a transdisciplinary research field (Holma et al., 2021). This is not only normal for a developing research field, but also a necessity for any research that provides tools for applied research. In this work, we will summarise the current development trends in muography by analysing the research publication data mined from the Web of Science database.

The data used in the analysis cover all data found in Web of Science published before 1 January 2021. The data screening is based on the following search words separated by the Boolean operator "OR": "muograph", "*muon radiograph*", "muon tomograph", *and* "*muon scattering tomograph*". The asterisk was used a multiple character wildcard search for finding the variable endings of a given root word. The searches were conducted by selecting the "All Fields"operator, as this operator searches all the searchable fields using one query. Note that the used set of search parameters is by no means the only option to study trends in muography related publications. However, the search results definitely support the general view according to which more and more publications have been published in the last ten years or so.

The above database search yielded a total of 556 publications. The oldest five publications were from the years 1987 (1 count), 1990 (1), 1996 (1), 1998 (1), and 2000 (1). Every year after 2001 (3) is represented by more than one publication. Based on the selected set of search parameters, the most intense year of publications is 2019 (68). The oldest paper in this search is that of Bondarenko et al. (1987) titled "Muon Tomography of a Rock Terrain", which is published in Russian in the journal "Izvestiya Akademii Nauk SSSR Fizika Zemli". According to Web of Science categories, this paper is multidisciplinary geosciences publication.

Although our parameter set used in the search failed to find older publications than Bondarenko et al. (1987), it is well known that there are several earlier publications that have collectively paved the road to the current surge of muography publications. Nevertheless, it is interesting to note that many of the early publications already noted the possibilities to use attenuation of cosmic-ray muons on rock characterisation (e.g., George, 1955; Malmqvist et al., 1978, 1979). As we now know, rock characterisation (e.g., volcanoes, mining), archaeology, border control, spent nuclear waste imaging, and other civil engineering applications are those that have earned most attention so far. We will present more results of our Web of Science analysis in our poster.

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Primary authors: JOUTSENVAARA, Jari (Muon Solutions Oy, Pyhäjärvi (Finland)); HOLMA, Marko (Muon Solutions Oy, Pyhäjärvi (Finland)); KUUSINIEMI, Pasi (Muon Solutions Oy, Pyhäjärvi (Finland))

Presenter: HOLMA, Marko (Muon Solutions Oy, Pyhäjärvi (Finland))

Session Classification: Poster session

Track Classification: Science communication and outreach

Contribution ID: **47** Type: **Plenary talk**

Muography of the active Sakurajima volcano: recent results and future perspectives of hazard assessment

Wednesday 24 November 2021 09:45 (30 minutes)

Sakurajima volcano is one of the world's most active volcanoes with over 3,000 of explosive eruptions during the last five years. A muography observatory is under construction in international collaboration since 2017 at a distance of approx. 2,800 m in south-west direction from the active craters, called Minamidake and Showa [1,2]. Currently, the Sakurajima Muography Observatory (SMO) is operating with 11 MWPC-based Muography Observation System (MMOS) that is covering a sensitive surface area of 8.25 square meters. We will briefly present the design of the MMOS system, the data collection and analysis procedures, and mainly focus on the volcanological observations:
- tephra deposition, and erosion of surface region due heavy rains and post-eruptive lahars were observed 3,
- magmatic plug formation was observed beneath the active craters after the deactivation of Showa in 2018 [4] and dormant period of Minamidake in 2020 [5],
- machine-learning-based processing of daily muographic images achieved a fair sensitivity of above 0.75 in eruption forecasting [6].
Future prospects of SMO and its application for hazard assessment will also be discussed.

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[4] L. Oláh et al.: Plug Formation Imaged Beneath the Active Craters of Sakurajima Volcano With Muography, Geophysical Research Letters, https://doi.org/10.1029/2019GL084784
[5] L. Oláh & H.K.M. Tanaka: Muography of Magma Intrusion Beneath the Active Craters of Sakurajima Volcano, Geophysical Monograph Series (accepted)
[6] L. Oláh & H.K.M. Tanaka: Machine Learning with Muographic Images as Input: an Application to Volcano Eruption Forecasting, Geophysical Monograph Series (accepted)

Primary authors: VARGA, Dezső (Wigner Research Centre for Physics, Budapest, Hungary); HAMAR, Gergő (Wigner Research Centre for Physics, Budapest, Hungary); TANAKA, Hiroyuki (Earthquake Research Institute, The University of Tokyo, Tokyo, Japan); OLÁH, László (Earthquake Research Institute, The University of Tokyo, Tokyo, Japan); NYITRAI, Gábor (Wigner Research Centre for Physics, Budapest, Hungary); OHMINATO, Takao (Earthquake Research Institute, The University of Tokyo, Tokyo, Japan)

Presenter: OLÁH, László (Earthquake Research Institute, The University of Tokyo, Tokyo, Japan)

Session Classification: Collaboration reports

Track Classification: Collaboration reports

Contribution ID: **48** Type: **Poster**

Measurement of the Low-energy Muon Spectra with the Rotatable NEWCUT Spectrometer

Thursday 25 November 2021 16:00 (5 minutes)

The precise measurement of low-energy muon spectra is required to improve muography of small-sized objects. We developed a 5-meter-length, rotatable, MWPC-based spectrometer to precisely measure the energy spectra of muons from 0.5 GeV to 5 GeV between vertical and horizontal directions 1. It is a consecutive series of nineteen detectors with a positional resolution of approx. 4 mm and lead plates. The structure of the spectrometer, data analysis methods, simulation and first mesurement results will be discussed.

1 L. Oláh et al.: Improvement of cosmic-ray muography for Earth sciences and civil engineering, PoS 358, https://doi.org/10.22323/1.358.0377

Primary authors: VARGA, Dezső (Wigner Research Centre for Physics, Budapest, Hungary); HAMAR, Gergő (Wigner Research Centre for Physics, Budapest, Hungary); GALGÓCZI, Gábor (Wigner Research Centre for Physics, Budapest, Hungary); SUENAGA, Hiroshi (Central Research Institute of Electric Power Industry (CRIEPI), Chiba, Japan); TANAKA, Hiroyuki (Earthquake Research Institute, The University of Tokyo, Tokyo, Japan); OLÁH, László (Earthquake Research Institute, The University of Tokyo, Tokyo, Japan); HAMAR, Gergő (Wigner Research Centre for Physics, Budapest, Hungary); MIYAMOTO, Shinichi (NEC Corporation (Global))

Presenter: OLÁH, László (Earthquake Research Institute, The University of Tokyo, Tokyo, Japan)

Session Classification: Poster session

Track Classification: Instrumentation

Contribution ID: **49** Type: **Plenary talk**

Muography activities at CEA-Saclay

We will review the different activities and recent developments of muography at CEA-Saclay. In the last year, several new telescopes have been manufactured thanks to the partnership with a PCB company. Up to 12 telescopes can now be run in parallel on various projects. The latest improvements include a spatial resolution lower than 200 microns and a gas consumption yielding about 2L/day only. On the software side, a 3D algorithm combining 2D projections was successfully tested on simulated and real data. An old nuclear reactor is currently being imaged in the South of France, with already 13 projections achieved. By March 2022, the number of projections will reach more than 30, perhaps the largest number ever obtained in muography of a single object. A muon metrology experiment was also recently conducted in lab, with another in preparation on a whole building.

Primary authors: PROCUREUR, Sebastien (Université Paris-Saclay (FR)); Dr ATTIÉ, David (CEA-Saclay); Dr GOMEZ, Hector (CEA-Saclay); Mrs LEHURAUX, Marion (CEA-Saclay); Dr MANDJAVIDZE, Irakli (CEA-Saclay); Mr MAS, Philippe (CEA-Saclay)

Presenter: PROCUREUR, Sebastien (Université Paris-Saclay (FR))

Session Classification: Applications

Track Classification: Applications

Contribution ID: **50** Type: **Plenary talk**

Atmospheric ray tomography for low-Z materials

Thursday 25 November 2021 16:35 (20 minutes)

Atmospheric ray tomography (ART) uses the muons and electrons for detecting objects and their composition. In this talk I will describe some new methods and **a proof-of-concept tomography system developed for the ART of low-Z materials**. Recently we introduced the Particle Track Filtering (PTF) and Multi-Modality Tomographic Reconstruction (MMTR) methods. Having Geant4 models we optimized the tomography system, the parameters of PTF and MMTR. Appling plastic scintillating fiber arrays in our tomography system, we achieved the spatial resolution 120 μm and 1 mrad angular resolution in the track reconstruction. We developed a novel edge detection method to separate the logical volumes of scanned objects. We showed its effectiveness on single (e.g. water, aluminum) and double material (e.g. explosive RDX and biological tissue) objects. **The tabletop tomography system we built showed excellent agreement between simulations and measurements**. We are able to increase the discriminating power of ART on low-Z materials significantly. This work opens up new routes for the commercialization of ART tomography in the security and custom field. I will discuss possible applications in industry and medicine. The talk is based on a recent preprint, https://arxiv.org/abs/2102.12542

Primary author: HEKTOR, Andi (GScan OÜ & KBFI)

Presenter: HEKTOR, Andi (GScan OÜ & KBFI)

Session Classification: New Ideas

Track Classification: New ideas

Contribution ID: **51** Type: **not specified**

Registration

Wednesday 24 November 2021 08:30 (30 minutes)

Session Classification: Opening

Contribution ID: **52** Type: **not specified**

Welcome

Wednesday 24 November 2021 09:00 (15 minutes)

Session Classification: Opening

Contribution ID: **53** Type: **Plenary talk**

Tomographic Muon Imaging of the Great Pyramid of Giza

Thursday 25 November 2021 16:55 (20 minutes)

In 1970 L. Alvarez et al. reported on the first experiment to use cosmic-ray muons to investigate the interior of a very large structure. This structure was Khafre's Pyramid at Giza. The group used, for that era, state-of-the-art instrumentation from the field of high-energy physics: spark chambers. In the intervening 40+ years, the technology used for determining the trajectories of elementary particles has advanced significantly. In November of 2017, the Scan Pyramids team used modern-day instrumentation to discover a new large void in the Great Pyramid. However, the size (˜ a few meter square) of this new system was not very much bigger than the one used by Alvarez's team. To apply true tomographic muon imaging to such large structures, a new approach must be taken. In this talk we describe an advanced concept for a high-resolution tomographic study of the internal structure of the Great Pyramid which will not only look for voids but investigate the ancient building techniques on a much more detailed scale than ever attempted.

Primary author: BROSS, Alan (Fermilab)

Presenter: BROSS, Alan (Fermilab)

Session Classification: New Ideas

Track Classification: New ideas

Contribution ID: **54** Type: **Plenary talk**

SilentBorder project: a new generation of custom and security scanners

Friday 26 November 2021 11:30 (20 minutes)

Only a small fraction of cargo is inspected and even smaller fraction of illegal goods are detected. Today, the most widely used technology for scanning vehicles, ranging from vans and trucks to railcars, is gamma-ray and X-ray radiography. Cosmic-ray tomography (CRT) is considered as beyond the state-of-the-art technology in cargo screening. We will bridge the major security gap for fast and safe inspection of large numbers of cargos by developing the Multi-Functional Passive Detection System. The detection capability is based on using plastic scintillating fibre arrays in combination with beyond state-of-the art tomographic reconstruction and material classification algorithms. The main objective of SilentBorder is to develop and validate a new high-technology CRT scanner for border guard, customs and LEAs that enables safe and fast screening, detection and identification of hazardous and illegal goods (e.g. SNM), contraband (e.g. tobacco or explosive) as well as hidden persons in up to 20'ISO containers. More information on the project,https://cordis.europa.eu/project/id/101021812 and more information on the technology applied,https://arxiv.org/abs/2102.12542.

Primary author: KIISK, Madis (University of Tartu)

Presenter: KIISK, Madis (University of Tartu)

Session Classification: Applications

Track Classification: Applications

Contribution ID: **55** Type: **Poster**

The MURAVES experiment at Vesuvius: geophysical implications

Thursday 25 November 2021 15:55 (5 minutes)

We describe the muography laboratory built on the slopes of Vesuvius in the context of the MURAVES project. The aim of the experiment is the detection of the internal structure of the upper part of the volcanic cone, where different eruptive regimes in the period 1906-1944 (eg: effusive or explosive) generated internal volumes with different density. The laboratory is located inside the Vesuvius National Park, it is powered by solar panels and data transmission is based on a WiFi radio bridge.

Primary author: MACEDONIO, Giovanni (INGV - Osservatorio Vesuviano, Napoli, Italy)

Session Classification: Poster session

Track Classification: Instrumentation

Contribution ID: **56** Type: **Poster**

Tomographic Muon Imaging of the Great Pyramid of Giza

Thursday 25 November 2021 15:55 (20 minutes)

In 1970 L. Alvarez et al. reported on the first experiment to use cosmic-ray muons to investigate the interior of a very large structure. This structure was Khafre's Pyramid at Giza. The group used, for that era, state-of-the-art instrumentation from the field of high-energy physics: spark chambers. In the intervening 40+ years, the technology used for determining the trajectories of elementary particles has advanced significantly. In November of 2017, the Scan Pyramids team used modern-day instrumentation to discover a new large void in the Great Pyramid. However, the size (˜ a few meter square) of this new system was not very much bigger than the one used by Alvarez's team. To apply true tomographic muon imaging to such large structures, a new approach must be taken. In this poster we describe an advanced concept for a high-resolution tomographic study of the internal structure of the Great Pyramid which will not only look for voids but investigate the ancient building techniques on a much more detailed scale than ever attempted.

Primary author: JAMIESON, Ishbel

Presenter: JAMIESON, Ishbel

Session Classification: Poster session

Track Classification: New ideas

Contribution ID: **57** Type: **Poster**

MUCH: an imaging Cherenkov telescope for volcano muography

Thursday 25 November 2021 15:55 (20 minutes)

In the last decades, several attempts have been made to investigate internal structures of large bodies, such as volcanoes, with transmission muography. High spatial resolution and reduction of the strong background noise due to protons, electrons and scattered low energy muons, are the main challenges for this technique. As a possible solution to fulfill these requirements, muography with Imaging Atmospheric Cherenkov Telescopes (IACTs) has been recently proposed and the feasibility demonstrated by our team using Geant4 simulations.

IACTs are telescopes dedicated to the gamma-ray astronomy consisting of an optical system that focuses the Cherenkov light into a high-sensitive and fast read-out camera. Muons with energy above about 5 GeV induce Cherenkov radiation which is emitted in a cone with a constant opening angle around their travel direction. As IACTs image in angular space, the Cherenkov light focused onto the camera forms a ring-shaped image centred at a distance from the focal plane centre proportional to the muon incidence angle. None of the previously mentioned source of background is expected to affect the IACTs muon signal.

Here we present MUCH, a lightweight and compact IACT design, specifically dedicated to volcano muography. The telescope design is based on a SiPMs camera working in the 280nm-900nm wavelength band, equipped with a fast read-out electronics with single photon counting capability.

The proposed Schmidt-like optical system is composed of a 2.5m aspheric mirror and a 2.5m Fresnel lens corrector. It results in a Field of View (FoV) of about 12°, an entrance pupil of 2.5m diameter and an angular resolution better than 0.2° throughout the entire FoV which allows us to determine the muon direction with a reconstruction precision better than a few tenths of degree.

A Geant4 framework for the simulation of Fresnel lenses and aspheric mirrors is currently being developed for the telescope prototype achievement.

Primary author: MOLLICA, Davide (INAF/IASF Palermo)

Presenter: MOLLICA, Davide (INAF/IASF Palermo)

Session Classification: Poster session

Track Classification: Instrumentation

Contribution ID: **58** Type: **Poster**

Muography Application in IFIN-HH

Thursday 25 November 2021 15:55 (20 minutes)

There are more than 20 years since cosmic ray muons have been studied in IFIN-HH. Starting as fundamental physics research, it continued later by putting muons to use, through applications. Muography is a new and emerging technique that interpret the muon flux in order to obtain information about the inner structure of dense objects. Different applications have been designed and are currently being implemented at IFIN-HH. Scanning dense objects at the ground level, in order to determine their composition, or using the technique to imagine the structure of underground tunnels or mines are in present under investigation.

Primary authors: BALACEANU, Alexandru; GHERGHEL-LASCU, Alexandru; DOBRE, Madalina; SMAU, Raluca; VANCEA, Catalin; STANCA, Denis; NICULESCU-OGLINZANU, Mihai; MOSU, Toma

Presenter: STANCA, Denis

Session Classification: Poster session

Track Classification: Applications

Contribution ID: **59** Type: **not specified**

Closing statements

Friday 26 November 2021 12:10 (10 minutes)

Presenter: TYTGAT, Michael (Ghent University (BE))

Session Classification: Closing