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ERMES: active TeV muon interrogation of piezoelectric stress fields for earthquake precursor monitoring

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Reliable earthquake forecasting remains limited by sparse and indirect observables, and by the difficulty of accessing stress evolution at seismogenic depths. Many proposed electromagnetic precursor methods rely on detecting signals after they propagate out of the Earth crust, where attenuation, scattering, and environmental noise complicate detection and signal interpretation. We propose ERMES (Earthquake Reconnaissance using Muon beam Evolution in Silicon dioxide) [1] as an active probing technique that targets the source region directly, measuring stress-linked fields in situ rather than inferring them from far-field emissions.

ERMES interrogates quartz-rich rocks around a known active fault using a collimated, high-energy muon beam. Tectonic stress induces piezoelectric electric fields within quartz fabrics; these near-field structures act on traversing muons and imprint stress information onto the beam transverse phase space (for example centroid shift and angular spread) measurable at an exit detector. Kilometer-scale penetration requires TeV-class muons: transport studies indicate that a 10 TeV beam can traverse about 3 km of crystalline rock while retaining analyzable phase-space signatures. To strengthen post-target diagnostics, we introduce a compact muonic lens concept to refocus and condition the transmitted beam before measurement, improving sensitivity to small stress-driven perturbations. Because this regime involves extremely thick targets where secondary production and energy-loss straggling matter, we cross-validated long-baseline transport and background predictions using independent Monte Carlo toolchains (FLUKA and Geant4). We also define a proof-of-principle path at existing facilities, using GeV-class muons through stressed granite slabs and a zero-generation surrogate test with 20-150 MeV electrons through single quartz crystals under controlled compressive load.

By enabling continuous, active monitoring of tectonic stress evolution at depth, ERMES could provide earlier and more reliable precursor observables to support seismic hazard assessment and civil-protection decision timelines.

[1] (Physical Review Research **7**, 043336)

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Simulation and Optimization of Muon Production Using Electron Beams and RPC Detectors

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The development of compact, high intensity muon sources is of growing importance for applications such as muography, non destructive inspection, and advanced particle detector studies. Electron driven secondary particle production offers a promising pathway toward laboratory scale muon generation and compact beamline development.

In this study, FLUKA Monte Carlo simulations are performed to investigate muon production from 2 GeV, 5 GeV, and 10 GeV electron beams incident on high Z targets. A comparative analysis of lead (Pb) and tungsten (W) targets is conducted, and the dependence of muon yield on beam energy and target thickness is systematically evaluated. Optimal target thicknesses are identified to maximize muon production while limiting secondary particle contamination.

To assess the feasibility of detection, a detailed geometry of the Resistive Plate Chamber (RPC) is implemented in the simulation framework. The muon fluence in the RPC active volume is quantified, and background contributions are analyzed. The results demonstrate the feasibility of electron driven muon production and confirm the suitability of RPC technology for characterizing secondary muon fields, providing guidance for the design of compact muon beamlines.

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Portable Glass-RPC Telescope for Muography and Future Applications at Laser Wake Field Accelerators

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To enable muography measurements in logistically challenging environments, we have developed a compact and transportable muon tracking detector. The system is based on glass Resistive Plate Chambers (gRPCs) and features a sealed, gas-tight design specifically optimized for field deployment. The telescope consists of two to four gRPC modules, depending on the use case, constructed with glass electrodes having an active area of 16 × 16 cm². Key design priorities include mechanical robustness, operational autonomy, flexible deployment, safety, and cost-effectiveness. Detector performance has been characterized using atmospheric cosmic-ray muons, demonstrating its applicability to muographic measurements in demanding settings. Additionally, in 2025 our team installed this telescope at the laser wake field multi-GeV electron accelerator ELBA at ELI Beamlines. The aim was to measure highly penetrating charged particles generated by the ultra-short (30 fs) pulsed (3.3 Hz) and high-power (1 PW) plasma-laser interaction. Tungsten was added before a concrete dump to increase muon production. This was the first use of a gRPC in a laser environment. The campaign demonstrated that gRPC detectors operate reliably and safely even under intense radiation and strong electromagnetic fields. While the collected datasets were statistically limited and affected by the parasitic nature of the data taking, they enabled a first characterization of the background and confirmed the detectors' stability and tracking performance even in such a complex environment. These results validate the feasibility of the approach and provide a solid foundation for a dedicated future run under optimized beam conditions, where muon detection sensitivity is expected to improve substantially.

This talk focuses primarily on the long-term stability and performance testing of these detectors, with particular attention to detection efficiency, timing response, and gas stability, alongside beam test results.

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Task-Driven Differentiable Optimization of Muon Scattering Tomography for Anomaly Detection

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Muon scattering tomography (MST) is a non-invasive imaging technique used to reconstruct the material constituents on enclosed volumes to identify high-Z materials. This technique leverages scattering information obtained from conventional PoCA reconstruction, which provides a density point cloud of the approximated scattering locations within the scanned volume. However, PoCA-based inference suffers from noise and limited sensitivity to improvements in detector design choice [1]. Moreover, detector and reconstruction parameters are typically optimized using surrogate metrics, such as tracking angular resolution, rather than task-level performance. We investigate learned voxel-wise radiation length inference from event-level scattering observables using TomOpt [2], a differentiable framework for MST detector design optimization. While the neural network improves the identification of high-Z targets, its performance does not generalize uniformly across lower-Z materials. Motivated by this limitation, we perform gradient-based co-design optimization of detector geometry and software parameters directly with anomaly-detection performance as the objective. The joint optimization converges toward configurations consistent with theoretical performance limits while directly maximizing detection utility, without requiring full 3D reconstruction.

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Muon4Earth: LHC Cosmic-Ray Muons as a New Atmospheric Observable Bridging the Earth Observation Scale Gap

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Earth observation systems face a critical scale gap: satellites provide broad coverage at coarse resolution, while meteorological stations deliver continuous measurements only at sparse locations. This lack of intermediate-scale observations (10–100 km^2) limits satellite validation, weather model calibration, and detection of mesoscale atmospheric phenomena that drive extreme events. Cosmic-ray muon flux provides a unique atmospheric observable through the positive temperature effect, where warmer stratospheric conditions increase meson decay probability, enhancing surface muon rates. The underground Main Injector Neutrino Oscillation Search (MINOS) experiment established correlation with stratospheric temperature and first detected sudden stratospheric warmings as muon rate excursions. The deep underground Large Volume Detector (LVD) at Gran Sasso revealed multi-year atmospheric cycles invisible to conventional proxies. The shallow-depth DANSS reactor neutrino detector and the underwater KM3NeT neutrino telescope confirmed similar modulations across detector configurations. However, these results remain confined to astroparticle physics, muon atmospheric observables have never been systematically integrated with satellite data or operational Earth observation workflows.

We present a proposal of a data integration framework transforming LHC experiments into dual-use atmospheric observatories. LHC detectors (CMS, ATLAS, ALICE,LHCb) opportunistically record cosmic muon tracks during routine maintenance and data taking periods for alignment, which can cover large areas at zero additional cost. As first implementation using CMS, we will start with comparing cosmic muon data during extreme atmospheric events (sudden stratospheric warmings, severe storms) against normal conditions, then cross-validate against satellite temperature sensors, atmospheric reanalysis models, and weather stations. Using Geographic Information Systems and standardized pipelines, we shall then align these datasets spatially and temporally to identify consistent atmospheric signals.

So, if the findings show enough sensitivity, we'll also try testing the idea of using the framework to check the historical accuracy of low-resolution satellite products from before 2012 using historical LHC data. Future work will extend this to other LHC experiments and connect to international Earth observation networks. It will also involve deploying portable surface muon detectors at strategic locations based on sensitivity requirements established from LHC analysis.

Keywords: Earth observation scale gap; cosmic-ray muons; LHC experiments; data integration framework; atmospheric monitoring; portable detectors

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Industrialised strategies for centimetre precision muon scattering muography

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Traditionally, high precision muon scattering tomography has required expensive detectors that are hard to deploy and often highly sensitive to environmental conditions. Furthermore, muon tomographic inversion software optimised to handle large amounts of data and high spatial resolution models, on the order of tens-to-hundreds of seconds, are not readily available. Muodim holds the keys to these issues within both the hardware and software domains. Scintillators with centimetre-scale bars on each observation axis are cheap to produce, easy to deploy and maintain, and may provide sufficient resolution for many practical imaging scenarios. Furthermore, recent developments in machine learning make algorithms designed for GPUs a trackable, scalable and flexible solution to muography inversion problems. Muodim deployed two scintillator detectors aligned vertically, above and below multiple targets, both for controlled laboratory experiments and client projects. Results confirm that centimetre precision scintillating bars are sufficient for centimetre precision imaging of target objects. Our inverse problem framework is scalable to problems of ~1 million events with ~1 million voxels deployed on a 4Gb laptop GPU and is executed on the order of minutes. The model can be extended to process events with an "out of memory"model, allowing the treatment of larger datasets at the cost of speed. In the Muodim framework, the scattering problem based on the MLSD algorithm (Schultz, 2007) can be interchanged for a bespoke method developed to solve the absorption tomography problem with comparable performance characteristics.

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PCA-Based Multivariate Analysis of Muography Time Series at the Sos Enattos Mine

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We analyzed a year-long muography dataset (2024–2025) acquired at the Sos Enattos mine in Sardinia, Italy, to investigate temporal variations in the overburden mass at the Sos Enattos site. This mine is a potential candidate site for the future European gravitational-wave detector, Einstein Telescope, and the characterization of its overburden is of major interest. Muography is a passive geophysical technique that exploits the attenuation of cosmic-ray muons to estimate the opacity of large geological structures. Muons are subatomic particles capable of traversing large amounts of matter. The flux of muons is measured along many distinct axes of observation, each corresponding to a specific trajectory through the overlying rock mass. Because muons are absorbed according to the amount of matter they encounter, changes in the measured flux along each axis can be interpreted as variations in overburden mass over time. This setup allows a single muon detector to investigate multiple regions simultaneously, providing spatially and temporally resolved information on overburden mass distribution.

A key aspect in analyzing muon time series is deciding how to group the signals from different trajectories to calculate the flux through distinct regions, since combining trajectories that are not coherent could mask meaningful variations. To address this, we applied a PCA-based multivariate analysis to jointly analyze the time series from all trajectories and identify spatially coherent regions characterized by common temporal behavior. This study demonstrates how muography, combined with PCA-based multivariate analysis, can be used to investigate the spatial organization and temporal variability of overburden mass at underground sites.

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Muography as a Non-Invasive Tool for Preserving Paleolithic Heritage: Hydroclimatic Dynamics and Karst Exploration in the Cosquer Cave

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Paleolithic decorated caves constitute an irreplaceable cultural heritage whose preservation critically depends on internal hydroclimatic stability. In coastal environments, sea-level rise and marine forcing introduce additional threats. The Cosquer Cave [1], a semi-submerged Upper Paleolithic site embedded in a low-permeability limestone massif in southeastern France and listed as a UNESCO World Heritage site, represents a unique case in which the sea plays a dual role: both a destructive agent and a temporary preservative mechanism.

Seasonal marine-induced pressurization of the submerged karst network generates air overpressure within the cave, temporarily lowering the internal water level and exposing the lowest decorated panels for several weeks. However, the mechanisms governing these pressurization events—including potential variations in permeability driven by groundwater dynamics—remain insufficiently understood [2].

We propose muography as a non-invasive, high-resolution imaging technique to investigate the internal structure of the cave and its surrounding karst system. By coupling muographic density imaging with continuous in-situ hydroclimatic monitoring, we aim to (i) characterize structural pathways controlling air inflow and outflow, and (ii) detect hidden conduits and secondary galleries through density contrasts.

High-resolution laser scanning of the cave [3] and its surface environment enables optimization of detector positioning and will be incorporated into the density inversion framework. The detector must operate passively and autonomously during a one-month campaign and will be deployed through a narrow 137 m-long access tunnel, including a 40 m submerged section, under strict heritage preservation constraints. These constraints impose strong requirements on robustness, compactness, and transportability.

This pioneering approach will support the exploration of previously uncharted galleries and refine the conceptual model of the Cosquer Cave hydrosystem, providing a basis for predictive simulations under future sea-level rise scenarios. More broadly, this study highlights the potential of next-generation portable muography systems for safeguarding vulnerable coastal karst heritage by integrating geophysical imaging with cultural conservation strategies.

Keywords: Soil permeability; Muography; coastal karst; Paleolithic heritage; sea-level rise.

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ARTI-muon: fast muography simulations using generative models

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The feasibility of muography studies depends on accurate estimates of the atmospheric muon flux at the site of interest, as well as on its interaction with the target structure and the detection system. However, many existing frameworks rely on simplified parameterizations restricted to specific angular and energy ranges, which do not include geographic and geomagnetic effects. This limitation hinders realistic exposure-time estimates for detecting density anomalies in geological targets.
To address this problem, we present *ARTI-muon*, a modular framework for end-to-end muography simulations. In our approach, the surface-level muon flux is obtained from ARTI-based simulations, which incorporate geographic and geomagnetic effects in the secondary-muon flux. In addition, we implement a conditional normalizing flow model to reduce the computational cost associated with repeated flux simulations. Trained on a dataset of ARTI simulations, this generative surrogate reproduces the angular and energy spectra of muons, including at sites not used during training, with a reduced Poisson deviance $D\_\nu < 0.2$ relative to the reference. It also reduces computation time from hours (5–9 h per run, equivalent to one hour of ARTI-simulated flux) to approximately 2 minutes per scenario.
Unlike conventional parametric approaches, our framework integrates, within a single pipeline, a site-dependent stochastic flux, transport through the object of study (Python stage based CSDA, and a backward/adjoint propagation), and the detector response (detailed MEIGA/Geant4 simulation). This approach achieves substantially lower computational cost through the use of generative AI models. Finally, we illustrate the applicability of the framework with case studies at Cerro Machín (Colombia) and Mt. Etna (Italy). The methodology generalizes to any location defined by its latitude/longitude, target geometry, and detector configuration.

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Explorations of Mt. Qixing using Muography

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Since 2020, National Central University and Academia Sinica have spearheaded the inaugural muography program in Taiwan. The detector utilizes a SiPM-coupled plastic scintillator design with a pixelated readout system, optimized for precise particle tracking. The collaboration has completed two initial R&D phases to optimize detector performance and data analysis frameworks. These efforts have culminated in the current large-scale geophysical survey of Mt. Qixing, the prominent peak of the Tatun Volcanic Group.

As one of the highest peaks in the Tatun Volcanic Group, the internal density structure of Mt. Qixing remains a subject of great interest to the Earth Science community in Taiwan. Our objective is to generate the first 3D density reconstruction of the mountain using muography. The project utilizes three observatories strategically positioned around the peak. The first observatory, located on the southeast flank, began stable data acquisition in late 2025. We are currently deploying a second observatory opposite the first to provide the cross-sectional data necessary for a more precise multi-directional density measurement. This poster presents the setup and preliminary results for the first observatory. It also highlights the construction status of the second observatory and our future agenda.

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Reducing Imaging Times in Muon Tomography Using Deep Learning

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Across industry, muography is becoming an increasingly prevalent next-generation non-destructive evaluation technique. A key limitation of muon tomography, however, remains the low natural muon flux, which leads to long acquisition times, noisy reconstructions and artefacts that complicate interpretation.

This work explores the application of deep learning to post-reconstruction muon tomography data to enhance image quality and feature recovery. Using simulated datasets, we demonstrate that U-Nets and conditional generative adversarial networks can be deployed for predictive upsampling and detailed semantic segmentation. Structural Similarity Index Measure (SSIM) and Peak Signal-to-Noise Ratio (PSNR) evaluations indicate that machine learning can reduce effective imaging times for reinforced concrete structures from weeks to days. Segmentation performance shows similar time-dependent improvements, while also mitigating z-plane smearing effects and improving overall interpretability.

Comparable learning-based approaches have been applied in other imaging domains to achieve substantial reductions in the number of events required to produce target results, suggesting broader applicability of these techniques. Overall, this work demonstrates how machine learning can both accelerate data acquisition requirements and enhance reconstruction quality, supporting the wider industrial adoption of muographic imaging.

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Muography on Mars and on the Moon

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Muon tomography is a promising method for future Mars and Moon missions, due to it's spectacular penetration depth, low energy consumption and the unique information it can provide. The study on the feasibility of muography on other planets and moons has to start with understanding the cosmic muon production on these planetary bodies. Cosmic muons on Earth are generated in the atmosphere above ~15 km altitude as a result of a cosmic radiation induced particle shower where pions and kaons decay into muons. Due to the vastly different environments on Mars and the Moon, muon tomography may have very different capabilities on these planetary bodies compared to Earth.

Our goal with this study is to assess the possibilities and challenges of conducting muon tomography measurements on Mars and the Moon using cosmic-ray muons produced in the planetary atmosphere and rock. We carried out the simulation of the cosmic muon production and transport on Earth, Mars and the Moon using the Geant4 simulation toolkit. We found that although Mars has a much thinner atmosphere with a distinct chemical composition, the cosmic muon flux is comparable, or even higher than what we find on Earth, however the charged particle background is much higher. The muon production on the Moon takes place in the Moon rock, which significantly reduces muon production efficiency, leading to an up to 3 orders of magnitude lower muon flux under a flat surface.

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Muography Simulations for Carbon Capture and Storage Monitoring

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Carbon Capture and Storage (CCS) is a critical technology for reducing global CO_2 emissions, and ensuring safe storage requires robust monitoring methods. While seismic techniques are widely used for subsurface investigations and excel at imaging reservoir lithology, they have limitations in directly quantifying density variations. Muography, a technique utilizing cosmic-ray muons, offers high penetration power and direct sensitivity to density changes, making it a promising complementary tool for continuous CCS monitoring.

Conducting muography simulations for CCS presents a significant computational challenge, as typical storage sites lie at depths of 800-3,000 meters, with CO_2 plumes extending hundreds of meters requiring Monte Carlo simulation of muon transport through massive rock volumes with prohibitively long computation times. To address this, we developed a two-stage workflow using MUSIC (MUon SImulation Code) and PHITS (Particle and Heavy Ion Transport code System). MUSIC transports muons through the hundreds-of-meters-thick overburden, and PHITS then propagates surviving muons through site-specific reservoir models and muography detectors.

We also developed an open-source Fortran/Python toolkit that generates surface muons using either the CosmoALEPH or power-law spectral parametrization, applies configurable multi-detector ray-tracing filters to pre-select geometrically relevant muons, and exports directly to PHITS and Geant4 source formats. An interactive Streamlit GUI orchestrates the complete CosmoALEPH → MUSIC → PHITS pipeline with 3D visualization and solid-angle estimation, making the simulation chain accessible to the muography community.

We evaluated this proof-of-concept approach through simulations of the kilometer-scale Sleipner CCS facility under idealized conditions, and the 50-meter-scale Svelvik CO_2 Field Lab with more realistic detailed modeling. Our simulations demonstrate muography's capability to detect CO_2 plumes and resolve density changes associated with varying CO_2 saturation levels, providing information not directly accessible through seismic techniques alone. By offering insights into the density distribution of CO_2 plumes, muography can complement seismic tomography, thereby enhancing the safety, reliability, and transparency of CCS operations.

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Probing the Solid Earth with Cosmic-Ray Muons: From Volcanoes to Crust-Mantle Transition Zones

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Cosmic-ray muons penetrate large rock volumes, provide measurable fluxes through hundreds of metres of material, and their attenuation encodes density and thickness information. Proof-of-concept studies have already demonstrated that muography can support geoscientific applications (e.g., [1]). Here, we highlight recent results from our geoscientific studies and demonstrate the versatility of muography in characterizing density and structural changes and dynamics in Earth's subsurface.

At the active Sakurajima volcano (Japan), we studied how magma moves beneath the craters by combining satellite measurements of ground movement with muography [2]. We observed that magma first moved sideways beneath the craters and later rose toward the surface, influencing which crater was active at different times. Our results indicate the presence of both a magma pathway at ~700 m depth, and a shallow magma storage zone at ~350 m depth that feeds all eruptions at Sakurajima. The combined use of ground deformation data and muography shows promise as a complementary approach for monitoring shallow volcanic processes and gaining insights into eruption behavior.

Volcanoes can remain unstable long after eruptions, and weakened slopes may collapse, causing dangerous landslides. At Mount Unzen (Japan), we used muography for structural characterization [3]. The results showed that lava lobes deposited on the volcanic edifice are less dense than the volcano's rock, confirming structural weakening of lava lobes after past eruptions. By comparing these measurements with rainfall data, we found no signs of rain-triggered instability during the study period. Long-term muography can help assess volcanic stability and landslide risk.

Studying ophiolites provides insights into the physics and geology of the currently inaccessible oceanic crust-mantle structure [4]. Muography of a crust-mantle transition zone at Wadi Fizh in the Samail ophiolite in Oman revealed a highly serpentinized Moho [5], in contrast with petrological profiles which previously revealed gradational transition from the mantle to the crust at Wadi Fizh. Moreover, a higher density zone was revealed beneath the ophiolite ridge, indicating the presence of fresh peridotites beneath the thin layer of gabbroic cover. Muography can provide complementary density information about the ophiolites and, by extension, about the architecture of the oceanic lithosphere.

All these examples show that muography provides a quantitative approach for observing material distribution and movement across diverse geological settings, and offers insights into both static structures and dynamic processes.

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Absorption muography for disused mining site stability

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Europe hosts thousands of decommissioned mines situated below inhabited zones with significant real estate prices. These inhabited sites, with histories of gallery collapse, are unsuitable for traditional active geophysical monitoring methods. A passive observation method with metre-scale precision is therefore required to support stakeholders' risk mitigation strategies. Muon absorption tomography is capable of passively imaging an endangered region at metre-scale precision, with no increased risk to site stability. Muodim and IRIS Instruments deployed two differing muon detector technologies with binocular vision, in a disused mine gallery, to image an unstable zone of characteristic size 50x50x30m. From 40+ days of data, both 2D results from each detector and combined 3D results show similar density distributions with mean rock densities of ~2.65g/cm3, coherent with geological observations. Crucially, 2D and 3D muography results also reveal strong evidence for a low density anomaly (-0.6g/cm3, ~7x7x9m in size) located between the surface and the closed gallery extremity. Evidence for a decompressed zone is consistent with the location of historical gallery roof collapse. To our knowledge, this is the first study to successfully combine both MicroMegas and Scintillator detectors in a 3D muography reconstruction. Muography results critically informed client decision-making to ensure safety of the area, protecting people and property. Such insights cannot be obtained using other existing technologies without endangering operators.

18

An algorithm to localize position indicators using atmospheric muons

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Muon scattering tomography enables non-destructive imaging of dense or shielded structures for which absorption-based techniques fail. Since the muon scattering angle correlates with the atomic number of the traversed material, high-Z inclusions can be identified within lower-density surroundings. A common objective is therefore to image regions of enhanced scattering by statistical analysis of reconstructed muon trajectories and their angular deviations. Among the available reconstruction methods, the Point of Closest Approach (PoCA) algorithm provides a computationally efficient approximation by reducing Multiple Coulomb Scattering to a single effective interaction point. This approach is particularly suitable for scenarios involving small, dense markers embedded in a larger, lower-density structure.
In this work, the PoCA is extended to localize compact position markers of known shape in large structures. As a representative application, a lead sphere placed inside a distillation column could be considered. Its reconstructed position can serve as an indicator for internal misalignment or mechanical faults. Reliable marker localization, however, requires a quantitative understanding of measurement time, achievable spatial accuracy and additional scattering contributions from container walls and surrounding materials. The presented work addresses the development of an algorithm that evaluates the spatial distribution of reconstructed scattering points of a lead sphere within a discretized volume of interest and estimates the marker center via maximum correlation with a spherical object mask. Performance is assessed using simulated muon data generated with G4beamline, from which requirements on acquisition time and localization precision are derived. Additionally, weakly and non-scattered muons are incorporated into the workflow using a three-dimensional digital differential analyzer (3D-DDA) scheme. The developed algorithm is finally applied to experimentally acquired detector data for validation using a setup of two drift-chamber-based hodoscopes. The proposed approach provides a method for assessing muon detector performance and determining the feasibility and expected accuracy of marker localization in specific industrial applications.

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19

Internal Structure Investigation of Temple 8 at the Copán Maya Site Using Cosmic-Ray Muon Imaging with Nuclear Emulsion

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The Copán archaeological site, located in western Honduras, is an ancient Maya city where numerous temples and stelae remain in well-preserved condition. Among them, Temple 8 has not yet been investigated internally, and the possibility of an undiscovered royal tomb has been suggested.

In this study, we conducted a cosmic-ray imaging observation using nuclear emulsion to non-destructively investigate the internal structure of Temple 8. Nuclear emulsion are three-dimensional tracking devices based on silver halide photographic technology. They offer high spatial and angular resolution, and are compact, lightweight, and require no power supply, making them particularly suitable for archaeological observations.

However, observations at Temple 8 present several challenges. The accumulation of noise tracks caused by environmental radiation limits the possible exposure period. In addition, from the standpoint of heritage conservation, the detector size and installation locations are strictly constrained. To address these issues, we optimized the detector structure and improved the imaging methodology, establishing a comprehensive observation framework covering detector production, installation, retrieval, and data analysis.

In this presentation, we report the development process and the results of the observation.

20

From raw data to muon tracks: the MURAVES Data Processing Framework

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A transmission muon radiography of the Mt. Vesuvius volcano (Naples, Italy) is carried out by the MURAVES (Muon Radiography of Vesuvius) experiment. The measurement relies on the reconstruction of trajectories of cosmic-ray muons passing through the volcano to investigate the internal structure of its summit cone.

This contribution focuses on the data processing framework, describing both the reconstruction pipeline itself and the surrounding software infrastructure designed to ensure reliability, reproducibility, and user independence.

The pipeline encompasses all stages of the processing chain, from raw detector output to reconstructed muon tracks, with particular emphasis on the adopted tracking strategy. The entire workflow is orchestrated by a Python-based workflow management system, Snakemake, that handles task dependencies and ensures a structured and automated execution of all processing steps. Combined with a containerized environment, Snakemake guarantees user-independent operation and fully reproducible results. Finally, the versioning of the framework allows full traceability of modifications: each output is uniquely associated with a specific version of the workflow.

This work establishes a transparent and reproducible data-processing framework that ensures the reliability and long-term consistency of the MURAVES measurements, supporting both current analyses and future developments.

21

Classifying low-Z materials with muon scattering tomography for border security

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With the rise of online shopping and e-commerce platforms, the volume of packages passing through EU shipping centres has more than doubled, requiring new techniques and technologies to help prevent smuggling. CosmoPort is a Horizon-EU funded project aimed to deploy muon scattering tomography in EU postal centres, targeting illicit goods such as drugs, tobacco, and firearms. Using a prototype scanner system developed by GScan OÜ, a material classification exercise was conducted to assess the feasibility of discriminating different low-Z materials, based on machine learning. Using training data consisting of 30 minute measurements of 6cm side-length cubes of various low-Z materials, a classification accuracy of greater than 98% was achieved with this prototype system. This presentation will discuss the results of this exercise, the application of machine learning techniques to the low-Z problem, and ongoing developments in reliable material identification.

22

First results of modular drift chamber design based myon hodoscopes

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We present first imaging results of our in-house developed muon hodoscopes that are based on modular drift chambers being operated with ArCO2 gas mixture. The basic design is provided by two oppositely arranged printed circuited boards (PCBs) forming an optimized homogeneous drift field volume [1] with a drift length and width of 250 mm, respectively. The chamber height of 10 mm, i.e. the distance between both PCBs, is realized by printed polyamide frames that additionally provide an integrated ionization gas inlet and outlet. Because of its quadratic shape multiple drift chambers can be stacked together to enable three-dimensional muon path investigations.

Therefore, six drift chambers for x- and y-direction each are used to assemble a single muon hodoscope. All twelve drift chambers are successively arranged in a continuously rotated sequence to each other to achieve an interlaced stack of chambers with drift directions +x, +y, -x and -y. Together with a scintillation detector of similar active area at the top or bottom of such stacks is what we call a hodoscope. In that way, a hodoscope height of about 300 mm is achieved as well as highest measurement accuracy achievable. Furthermore, the alternately arranged opposite drift directions avoid systematic error in muon path determination if a more or less undisturbed, i.e. straight, muon passage is assumed. Another advantage of that stack design is the applied daisy-chain connection of the operating voltages for the drifting fields and anode wires along both interlaced drift chamber stacks. Finally, a base plate provides connections for drift chamber signal collection.

With two identical hodoscopes single lead objects and more complex objects, such as STYRODUR® and reinforcing steel embedded in concrete, have been investigated to evaluate the application of these muon hodoscopes for non-destructive investigations, e.g. at bridges and dams.

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23

Applicability of Ethernet-Based Synchronization Mechanisms to Muography Detection Systems

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Muography is emerging not only as a powerful non-invasive imaging technique, but also as a useful tool for Positioning-Navigation-Timing (PNT) systems and cryptography [1]. In this context, the timestamping capability of the muographic detectors is becoming increasingly important, requiring precise time synchronization across distributed detector modules, often deployed over large physical areas and harsh environments. Ethernet-based synchronization technologies —specifically the Precision Time Protocol (PTP) [2] and White Rabbit [3]—offer scalable, cost-effective, and high-precision timing solutions that can meet these stringent requirements while leveraging standard networking infrastructure.

PTP (IEEE 1588) enables sub-microsecond synchronization over conventional Ethernet networks and is widely adopted in telecommunications and industrial automation [4]. White Rabbit, an extension of PTP originally developed at CERN for distributed detector systems, combines sub-nanosecond accuracy with deterministic data transfer and syntonization, making it particularly suited for high-resolution time-of-flight measurements and coincidence detection in particle physics experiments.

This contribution evaluates the applicability of these technologies to industrial muography systems. We analyze synchronization requirements derived from spatial resolution, detector geometry, and event-rate constraints, and compare achievable timing performance, scalability, robustness, and cost. We further discuss integration architectures for distributed scintillator or gaseous detector arrays, including hybrid data acquisition networks that merge timing and data traffic.

The transfer of Ethernet-based synchronization solutions from high-energy physics—in particular, White Rabbit—can significantly improve the usefulness, reliability, modularity, and deployment flexibility of muography instruments. These technologies represent a path toward standardized and interoperable synchronization infrastructures for the next generation of muographic applications.

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24

ACROMASS: a portable magnetic spectrometer with particle identification capability for in-situ calibration of atmospheric muon flux models in muography

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The contribution of simulations in muographic measurements is crucial for the correct interpretation of data and for the estimation of the average density of the target along the detector lines of sight. One of the dominant sources of uncertainty in the density reconstruction arises from the model used to parameterize the differential flux of atmospheric muons at ground level in the simulation framework. This systematic effect can reach values as large as 10%. Such models are often based on experimental datasets collected by different detectors, characterized by distinct systematic uncertainties, covering different energy ranges and acquired at geographical locations that do not necessarily match those where the muographic measurements are performed.

In this context, the ACROMASS experiment, developed by INFN Florence and University of Florence, represents an upgrade of the ADAMO experiment. ADAMO was a magnetic spectrometer that collected data in 2004 at the latitude of Florence, but it did not allow particle identification (PID). Its dataset has been used as a reference for some of the muon generators employed in muography, such as EcoMug implemented in GEANT4. ACROMASS is designed as a portable, low-power magnetic spectrometer equipped with a set of sub-detectors enabling particle identification in the energy range 100 MeV–250 GeV. The detector consists of three subsystems: a Time-of-Flight (TOF) system, a magnetic spectrometer, and an electromagnetic calorimeter. Its lightweight and transportable design allows measurements to be performed also at high altitude.
The experiment will contribute to a more accurate calibration of the models used in muographic simulations, potentially reducing the systematic uncertainty on differential muon fluxes below 5%, even at low energies (<1 GeV), where electron and positron contamination is significant. Moreover, ACROMASS will enable online measurements of the muon flux simultaneously with ongoing muographic data taking and at the same geographical location, thereby reducing uncertainties related to atmospheric and solar variations, which can exceed 20%.

In this work, the ACROMASS detector will be presented together with some preliminary results obtained from two test beams performed at CERN in Geneva.

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Extensive muographic survey of Esztramos Hill

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The Esztramos Hill, located in the northeast of Hungary, is a small hill that is a member of the Aggtelek Karst, and is mostly made up of dolomite and limestone. On the boundary of these two rock formations a deposite of iron ore formed that reached up to the current surface. From the early 19th up until the late 20th century this ore deposit was subject to mining operations on several levels of the hill, until the deposite was almost entirely depleted. At the late stages of mining a limestone quarry was opened on top of the hill, that left a large part of its surface flat and exposed. The hill now hosts a large cave-mine complex with interconnecting tunnels of the abandoned mine and multiple cave systems [1].

Our research group at the HUN-REN Wigner RCP has been conducting muographic measurements at the lowest level of this complex for years. There are three main drifts there that have each hosted multiple measurement positions so far. We currently have 3 MWPC [2] type muograph detectors operating inside the hill. Based on our measurements so far, we have been able to create a 3-D reconstruction of the position and extent of partially collapsed, inaccessible parts of the iron ore mine, and also detected a nearby void that could be caused by a previously unknown cave [3]. While exploring the known cave systems of Esztramos Hill, our muographs detected large density anomalies in the close proximity of the Rákóczi cave system, the main cave of which is part of the UNESCO World Heritage list [4]. In this presentation we will summarise the results of this extensive survey, including 2-D muograms and 3-D muographic inversion results.

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26

Tracking upgrades and results of cavity imaging in more than 200 m depth

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In a recent work, feasibility with the MURAY detector were studied for subsurface density imaging and structural characterization, in a salt mine for potential green hydrogen storage. The referenced study reports the design, deployment, expected results, and first data of the 1 m2 muon-tracking system in a challenging environment. The results confirm that such detectors can provide reliable transmission muography measurements over extended operation periods, establishing a robust baseline for further studies.

To enhance performance, a tracking upgrade implementing a '5-point'track configuration has been developed, in which the 3D track is reconstructed using only five coordinates (three in one projection and two in the orthogonal projection) out of a possible six (three X and three Y layers). This track acceptance increases the total muon detection efficiency while providing a new tool for efficiency checks. The 5/6-point track method was tested on the MURAY detector, but it can be applied to any detector system with at least three detection planes, each providing two independent coordinate projections. Overall, together with hardware and software improvements, the upgraded MURAY system delivers improved angular resolution, more efficient reconstruction, and stable high SNR in low-flux environments.

Field results from the Italkali salt mine in Realmonte (Sicily) demonstrate a new record in muographic cavity-imaging validation at depths exceeding 200 m within a salt mine. Data collected from the first underground position over 130 days of live time at an average rate of 0.1 Hz show stable detector performance throughout the campaign. The measurements resolve density-length variations at the 2–3% level with high statistical significance and provide geologically useful density information for the surveyed region. These results validate the upgraded detector's capability for deep underground muography and confirm its potential for high-resolution subsurface imaging in complex geological environments.

27

Recent analyses of muon tomography in the nuclear field

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The need for more stable, low-carbon energy sources is driving the construction of new nuclear reactors around the world. This also increases the production of nuclear waste, which must be stored and monitored for safety reasons.
At CEA-IRFU, Micromegas detectors, designed for high-energy physics, are used to study the application of muon tomography in the nuclear field. Studies have focused on multiple aspects of the nuclear industry, ranging from the examination of entire power plants to waste management. Different reconstruction techniques are used. Transmission muography has been used to reconstruct the G2/G3 nuclear reactors being dismantled at CEA-Marcoule, as well as to monitor water level variations in the steam generators of an active pressurized water reactor. This allows for the inspection of the plant in an accident situation without prior knowledge of these levels. Scattering muography is used to inspect different types of nuclear waste containers at their storage sites. Recently, machine learning architectures and statistical filters have been applied, which have helped improve the reconstructed images.

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LiquidO Opaque-Scintillator Detectors for High-Resolution Muon Imaging

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LiquidO is a radiation-detection technology that moves beyond transparent scintillators. Instead of allowing light to propagate freely through the detector volume, it uses an optically opaque scintillator that strongly scatters scintillation photons [1]. This scattering confines light close to the particle track and preserves local spatial information. A lattice of wavelength-shifting fibres collects this optical signal, enabling intrinsically high-resolution tracking without mechanical segmentation.

Recent prototypes demonstrate this advantage experimentally [2], [3]. A 3 cm opaque-scintillator cube with fibres at 3.2 mm pitch achieved 450 μm position resolution in one dimension using cosmic-ray muons [3]. This represents roughly a factor-of-two improvement over conventional transparent scintillator detectors with similar readout granularity, and performance comparable to triangular scintillator bar systems.

These results were obtained with non-optimised scintillator composition, fibre layout, and detector geometry. Simulation-validated studies indicate that, by tuning optical properties and fibre pitch, LiquidO detectors could achieve a factor of five to ten improvement in spatial resolution. This gain can be used either to increase imaging performance at fixed channel count and cost, or to achieve the same resolution with fewer channels and lower cost.

LiquidO therefore has strong potential for muon imaging applications. We have built a first planar LiquidO detector with orthogonal fibre planes for muon-tomography studies. The detector is currently taking cosmic-ray data and demonstrates clear track reconstruction capability. Further optimisation and larger-scale prototypes are in development.

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29

Deep Q-Network for Adaptive Reconstruction in Muon Scattering Tomography

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Muon scattering tomography (MST) reconstruction is particularly challenging when multiple high-Z objects are closely spaced, material distributions are heterogeneous, or targets are embedded in heavy shielding under low-contrast conditions. To address these difficulties, we introduce a physics-constrained deep reinforcement learning reconstruction method that integrates a Deep Q-Network (DQN) into the PoCA pipeline for adaptive parameter tuning. In the proposed DQN approach, the current voxelized reconstruction serves as the state representation, and a 3D convolutional network is employed to extract spatial features for parameter estimation and action selection. A bounded discrete action space is defined to adjust key PoCA-related controls within geometrically feasible ranges, while the reward is formulated based on the relative improvement in image quality compared to the initial reconstruction, to stabilize temporal-difference learning.

The DQN-based reconstruction is evaluated on four representative scenarios, covering multi-target identification, heterogeneous materials, heavy-shielding under low contrast-to-noise ratio (CNR) conditions, and the localization of deeply embedded high-Z targets. Quantitative evaluation shows that, averaged across the four scenarios, the proposed method improves intersection over union (IoU), structural similarity index measure (SSIM), and peak signal-to-noise ratio (PSNR) by 225%, 98%, and 12%, respectively, relative to traditional PoCA. Compared with MLSD, the DQN-based method shows competitive overall performance with metric- and scenario-dependent variations, and demonstrates its most evident advantages in the complex shielding and low-contrast scenarios. These results demonstrate that high-dimensional state encoding with DQN provides an effective and practical framework for adaptive MST reconstruction, particularly in structurally complex and noise-sensitive environments.

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Simulation and Experimental Study of an Imaging System Based on Cosmic-Ray Muon Imaging Technology

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Cosmic-ray muon imaging technology, as a non-destructive detection method, offers significant advantages including high penetration capability, the absence of artificial radiation sources, and environmental friendliness. These features make it particularly suitable for mineral resource exploration and investigations in complex geological terrains. Moreover, it can serve as a complementary technique to conventional geophysical prospecting methods.
The key to muon imaging lies in the precise reconstruction of muon trajectories, which requires a high-performance detection system. In this study, two mineral exploration systems based on cosmic-ray muon imaging technology were developed, targeting surface (adit-based) and borehole exploration scenarios, respectively.
For surface exploration, a large-area muon imaging system based on triangular plastic scintillators coupled with photoelectric conversion devices was designed. The system provides an effective sensitive area of 500 mm × 500 mm and achieves millimeter-level spatial resolution. It is suitable for high-precision imaging of overlying strata and demonstrates high detection efficiency and spatial resolution.
For borehole exploration, a borehole-type muon imaging system based on plastic scintillating fibers coupled with photoelectric conversion devices is proposed and has been investigated through simulation studies. The borehole system supports multi-well joint detection and enables joint inversion of muon data with subsurface density models derived from conventional geophysical methods (such as seismic and gravity surveys), thereby improving the accuracy and reliability of mineral resource exploration.

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The ScIDEP Muon Radiography Project at the Egyptian Pyramid of Khafre

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Dora Geeraerts on behalf of the ScIDEP collaboration

Despite centuries of study, the Egyptian pyramids at Giza continue to raise fundamental questions regarding their internal architecture and methods of construction. While the Great Pyramid of Khufu exhibits a complex system of chambers and corridors, the Pyramid of Khafre, the second largest pyramid at the Giza Plateau, appears to have a relatively simpler interior layout, raising the question of the possible presence of undiscovered voids.

The ScIDEP (Scintillator Imaging Detector for the Egyptian Pyramids) Collaboration is developing scintillator-based muon telescopes to measure the internal density distribution of the Pyramid of Khafre at Giza using the technique of transmission muon radiography. Two complementary detector concepts are currently under construction: (i) large-area PVT scintillator plates with fiber readout, and (ii) modular plastic scintillator bars. The collaboration aims to place one detector inside the pyramid, in the King's burial chamber centrally located at the base of the monument, and a second detector outside the pyramid. This configuration from multiple viewpoints enables a three-dimensional reconstruction of potentially unknown internal structures.

A comprehensive simulation framework based on Geant4 has been established to support the development and optimization of the ScIDEP muon telescopes and to model the expected muon flux through the pyramid. The framework includes a three-dimensional model of the Pyramid of Khafre, incorporating its known internal geometry, as well as a full detector description with realistic scintillator properties and optical photon transport. This contribution presents an overview of the ScIDEP project, detailing the detector concepts under development, the Geant4-based simulation framework, and first results on track reconstruction and muographic imaging performance.

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Meaurements of GeV-muon beams created by laser-wakefield-accelerated electrons at the ELI-NP 10 PW beamline

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Artificial muon sources have come closer to reality with the acceleration of electrons using high power laser systems (HPLS). Gamma-induced muons, with forward momenta, can be obtained up to high energies. Indirect measurements of muons, relying on detecting the delayed electrons resulting from muons decays, have confirmed in 2025 the presence of muons in the beams resulting from the interaction of laser-accelerated electrons with solid targets. We present direct measurements of GeV muons and transmission measurements performed at ELI-NP, using the 10 PW beam.

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Full-Scale Geant4 Simulation of Cosmic-Ray Muography Through Multi-Kilometer-Scale Overburden

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We develop an end-to-end Geant4 simulation framework for cosmic-ray muography of multi-kilometer-scale targets. To efficiently sample rare transmitted events, we use a staged workflow: (1) atmospheric muons are transported through topography-derived overburden and recorded on a virtual scoring plane to boost statistics within the instrument field-of-view; (2) the surviving phase space is re-simulated with a detailed detector model including Geant4 optical photon transport and SiPM response; (3) a Python-based electronics model converts Geant4/SiPM outputs into realistic digitized waveforms, trigger primitives, and reconstruction-level observables. The pipeline yields instrument-specific response functions for transmitted flux and angular distributions, supports high-statistics production on HPC resources, and enables quantitative detector design, validation, and systematic uncertainty studies.

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Design, Construction, and Calibration of the MuTe 2.1 Muon Telescope

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This work presents the design, construction, and field calibration of MuTe 2.1, a portable hodoscope developed at the Universidad Industrial de Santander (Bucaramanga, Colombia) for muography of the Cerro Machín volcano (Tolima, Colombia). The instrument is intended to complement traditional geophysical surveys by providing density-sensitive imaging of the volcano's internal structure.
The detector consists of two parallel scintillator panels, each composed of a 15×15 array of plastic bars with 4 cm pitch, resulting in an active area of 60×60 cm per panel. Each bar is coupled to a wavelength-shifting (WLS) fiber (Saint-Gobain) and a Hamamatsu S13360 SiPM. Readout is performed via a FERS A5202 module (CAEN) connected to a local PC through Ethernet. Data is transmitted to the cloud via a Starlink link, enabling real-time monitoring and remote access during extended field campaigns.
Calibration of the detector was carried out in three stages. First, the open-sky muon flux was measured using two coincidence configurations: adjacent panels (2-fold) and stacked panels (4-fold), yielding approximately 170 and 12 part$\cdot$m$^{-2}\cdot$s^{-1}, respectively. These measurements were compared with ARTI (CORSIKA) simulations, showing a discrepancy of about 18%. Second, the detector response to matter absorption was characterized by interposing lead slabs of increasing thickness (0.5 to 3 cm) with the panels oriented parallel to the atmosphere. The observed attenuation (~30%) is consistent with simulations performed with MEIGA (Geant4). Third, a test muography was conducted on the mountain range adjacent to the laboratory. The reconstructed topographic profile validates the performance of the hodoscope under real field conditions and confirms the reliability of the simulation and analysis chain.

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From Tunnel Overburden Reconstruction to Tidal Measurements via atmospheric muons

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Muography with scintillator-based detectors enables the investigation of mountain topography above tunnels and underground structures. The Hankuk Atmospheric-muon Wide Landscaping (HAWL) is the first real-time portable muon tomography project. It successfully charted the mountainous region of eastern Korea by measuring cosmic ray muons with a detector in motion. HAWL achieved a tunnel-length accuracy of 6.0% over an overburden range of 8–400 meter-water-equivalent (m.w.e.). The HAWL upgrade (HAWLU) features a more compact design and enables angular resolution. This capability is based on a redesigned sensor mounting scheme that determines hit positions within each panel using charge and timing information, combined with two-panel coincidence measurements. Using this upgraded system, we successfully reconstructed undersea tunnel topography and, for the first time, measured tidal variations with water-level resolution on the order of 1 m.

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Muography at 1 km depth - Results

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The Occidental College/KoBold Metals collaboration is exploring a detector to extend muography underground to depths of 1 km. Deployed at scale such a detector would utilize 1000s of square meters of surface detectors to detect incoming air showers and inexpensive, non-directional borehole detectors in coincidence. The measurement of muon direction and depth provide the basic parameters needed for muography. As a proof of principle, we have deployed an array of 10 surface scintillators in conjunction with 4 borehole scintillators at Occidental College. Results from this test array will be presented including angular resolution measurements and comparisons with air shower simulations.

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Development of a Modular Muography Detector with FPGA-Based Data Acquisition for Geological Imaging in Taiwan

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National Central University and Academia Sinica have been developing a muography detector for geological exploration in Taiwan. The detector consists of four layers of plastic scintillators read out by silicon photomultiplier (SiPM) arrays, with a lead absorber to suppress electron background. A tree-structured, FPGA-based data acquisition (DAQ) system enables streaming readout and synchronized timing using a common reference clock, while front-end comparators provide signal discrimination. The detector was deployed in Daxi, where it measured the muon flux through Xizhou Mountain with stable operation over one year. A new measurement campaign targeting Qixing Mountain in the Datun Volcano Group is currently underway. This poster presents the development and performance of the muography detector and its FPGA-based DAQ system.

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Experiences with tomographic inversion of subsurface muographic measurements

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It is well known that the muontomographic inverse problem is considerably underdetermined for several reasons, and therefore various types of regularization methods are required for its solution, which significantly influence the estimation bias and the covariance matrix of the estimated parameters. Following an overview of applicable regularization methods, the presentation examines several important properties of the Bayesian-type method linked to a priori information for the inversion of subsurface muographic measurements. It deals in detail with the relationship between the prior model and spatial resolution, the tuning of the prior density distribution to the near and far zones of the detector and analyzes the spatial distribution of bias and the regularization effect appearing in the variance of the results. The presentation also will discuss the symmetries characteristic of muographic mapping, which necessitate regularization.
The results of the analysis are presented by examining tomographic reconstruction based on field measurement data collected by Wigner RCP.

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A Sealed, Light-weight gRPC-Based Muon Telescope for Muography Applications

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Portable muon detection systems are increasingly in demand for muography applications in environments requiring flexible installation and transportability. We present the ongoing development and implementation of a portable muon tracking system based on glass Resistive Plate Chambers (gRPCs). The work addresses the fabrication and assembly of compact, position-sensitive RPC detectors, along with their performance when operated with a standard gas mixture and coupled to external front-end electronics and a scalable multi-channel data-acquisition system. The system design prioritizes modular construction, mechanical robustness, operational safety, autonomous functionality, and cost-effectiveness.
Measurements with atmospheric muons demonstrated stable detector performance and reliable tracking capability, confirming the suitability of this architecture for muographic measurements. We will conclude with an outlook on further developments of the detection system.

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Muon spectrum generation with generative AI

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Performing a realistic simulation of atmospheric muon flux requires well-established tools like CORSIKA, since they model in detail all components of the shower and the particle transport processes in the atmosphere. However, this accuracy comes with a high computational cost. For example, simulating one hour of flux can take several hours of computing time, which limits its use in feasibility studies for muography. In this type of study, it is often necessary to simulate weeks of flux and explore multiple candidate locations with different geomagnetic conditions and altitudes.
To address this limitation, we developed an algorithm based on artificial intelligence that, trained with CORSIKA simulations (through ARTI), is able to reproduce the energy spectrum and angular distribution of the muon flux at any latitude and longitude. The model was implemented using conditional normalizing flows and learns the flux dependence from a reduced set of site descriptors: altitude and the local geomagnetic field components (Bx, Bz).
Training was performed with simulations at 45 locations worldwide, covering altitudes from 0 to 5230 m a.s.l. (35 for training, 5 for validation, and 5 for testing). Tests on sites not included in the training show that the model preserves the reference spectral profiles, reducing computation time from several hours (≈5–9 h per ARTI simulation) to about two minutes with our model.
Finally, an interactive web application was developed, where users can enter their latitude, longitude, and geomagnetic field components, and instantly obtain the estimated muon flux for that specific location.

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MULE: A Portable Muon Detection System for Real-Time Subsurface Density Monitoring

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Subsurface density monitoring is essential for geohazard mitigation, yet it remains challenging, for instance in deep-seated landslides and around metropolitan infrastructures where conventional methods are not often neither cost effective nor practical for continuous observation. We present MULE (MUon Lightweight Explorer), a portable plastic-scintillator-based muon detection system suitable for continuous monitoring of subsurface density anomalies such as cavities, saturated zones, and structural variations. The system has been tested in multiple field experiments: along the Tokyo Metropolitan subway, and at a large rainfall-induced landslide site in volcanic tuff formations. Preliminary results show a correlation between muon flux and overburden thickness, and possibly sensitivity to saturation level variations associated with environmental changes. These results highlight MULE's potential for continuous real-time density monitoring across a range of applications, from geohazard early warning systems to tunnel excavation and operation, and potentially CO_2 plume monitoring, and mineral exploration.

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Status and Upgrades of the MuGrid-v2 Detector: Toward Economical, Large-Scale Muography

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The widespread adoption of muography in civil engineering, volcanology and diverse multidisciplinary domains is currently hindered by the high production costs and complex assembly associated with traditional scintillator-strip detectors. To address this challenge, we present **MuGrid-v2**, a novel detector architecture that replaces discrete scintillator bars with a monolithic plastic scintillator coupled to a 3D-printed optical grid.

Compared to grooving or drilling on the scintillator, this design not only eliminates invasive machining processes but also leverages enhanced reflection to boost signal significance, enabling a more precise reconstruction of the hit position.

A prototype with three layers of 30×30 cm^2 scintillators has been built for initial, achieving a spatial resolution of 4.6 mm. We then conducted field tests including a muographic imaging of a mountain, successfully revealed its three-dimensional structure, showing excellent agreement with topographic data.

We recently developed an upgraded 60×60 cm^2 detector module, optimizing the reflective grid material to significantly increase photon collection efficiency. The upscaled version also demonstrates a superior effective detection area ratio compared to smaller prototypes. We are currently optimizing the hardware and the algorithm, hoping to achieve a spatial resolution better than 3mm.

By balancing low-cost manufacturing with high-precision performance, MuGrid-v2 offers a scalable solution that we hope will promote the large-scale application of muography technology in various scenarios.

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Geometric Errors and Performance Limits in Muography Detectors

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This work investigates the performance limits of muography detectors of the MATE type by analyzing the propagation of geometric and instrumental errors and their impact on density reconstruction. A theoretical uncertainty-propagation framework is combined with Monte Carlo simulations that incorporate the angular muon flux, attenuation in homogeneous material, and counting statistics. Three main sources of error are examined: angular misalignment, uncertainty in the inter-plane distance, and effective pixel size. Results show that distance errors introduce a systematic positive bias, whereas angular and discretization effects produce negative biases amplified at large zenith angles. The study provides experimental tolerance estimates and calibration guidelines to improve the accuracy of muographic measurements in geophysical applications.

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Anomaly Detection in Operational Muon Cargo Inspection with Real Scan Data

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This work reports the first operational deployment of a neural network-based anomaly detection system for maritime container inspection using muon scattering tomography. While maritime container inspection is essential for infrastructure security, it remains highly complex due to the wide range of structural cargo configurations in which anomalies are likely to occur. In addition, the physical principles governing muon scattering impose fundamental constraints on the data which, combined with the scarcity of experimental measurements, significantly limit the availability of representative anomalous samples. Under these conditions, anomaly detection models must operate within a physically consistent framework to compensate for the lack of real detector measurement data, enabling the system to distinguish between genuine anomalies and extreme but physically plausible cargo configurations.

To overcome the combined challenges of structural cargo variability, data constraints, and limited experimental measurements, a synthetic dataset of physically realistic scenarios was constructed in cooperation with customs authorities. This dataset accurately replicates operational conditions and complies with transportation regulations. In addition, dedicated measurement campaigns were conducted under operational conditions to complement and experimentally validate the synthetic dataset using real detector measurements. The proposed anomaly detection system integrates unsupervised and semi-supervised learning approaches to identify structural inconsistencies in cargo by modeling the distribution of benign transport data and establishing a statistically robust baseline of normality. Furthermore, we demonstrate that combining experimental measurement data with models pre-trained on simulated data substantially enhances generalization through sim-to-real transfer. This approach enables unsupervised anomaly detection without requiring prior specification of contraband materials.

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Modeling Martian Muon Flux and Subsurface Attenuation: Assessing the Feasibility of Muography in Lava Tubes

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Muon radiography represents a promising non-invasive technique to image the interior of large-scale geological structures on other planetary bodies such as Mars. This method provides insights into the thickness and density of geological formations, crucial for the detection of potentially habitable subsurface environments and for future mission planning. However, on Mars, the absence of a global intrinsic magnetic field and the presence of a thin CO_2-dominated atmosphere significantly modify the development of secondary particle cascades compared to Earth, potentially affecting the muon spectrum reaching the surface. Characterizing the muon flux is therefore essential to evaluate the feasibility of muographic imaging on Mars.

Recent observations have highlighted the presence of voluminous underground caves and potential lava tubes on Mars, with sizes typically reaching 50 meters and depths often exceeding 100 meters. These structures are of strong interest as natural shelters for future human exploration and represent possible targets for planetary muography.

In this work, we implemented detailed Monte Carlo simulations using CORSIKA 8 and FLUKA to model the atmospheric shower development and the subsequent transport of muons through the Martian subsurface, adopting a detailed and realistic atmospheric model. To ensure the reliability of the computational setup, preliminary results of simulated surface particle spectra were compared with in-situ measurements from the Mars Science Laboratory Radiation Assessment Detector (RAD) and with simulations performed using NASA's OLTARIS tool, showing consistent trends in particle distributions at the Martian surface.

We extracted the muon flux and characterized its energy and angular distributions under different shielding configurations, from surface conditions to subterranean caves, considering different subsurface compositions and solar activity conditions. By evaluating muon flux attenuation as a function of rock thickness and composition, we provide quantitative constraints on the physical feasibility and intrinsic limitations of muographic exploration of the Martian subsurface.

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Impact of geometrical acceptance constraints in muon scattering tomography on the MLEM reconstruction of spent nuclear fuel casks.

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The MUTOMCA (MUon TOMography for CAsks) project is an international research collaboration that investigates muon tomography as a potential candidate for the re-verification of strongly shielding spent nuclear fuel casks to strengthen international nuclear safeguards. A field trial was performed within the scope of this project, where atmospheric muons crossing these casks were measured using an experimental setup of two detectors on opposing sides, rotated over three measurement positions. Good results have been obtained with an absorption-based imaging technique, demonstrating the capability of muon tomography to distinguish fuel assemblies from dummy elements using experimental data. However, a significant difference was observed in the imaging performance of the maximum likelihood / expectation maximization (MLEM) reconstruction algorithm when using muon scattering data from these experiments compared to simulations. This talk analyzes how experimental constraints, most notably the limited geometrical acceptance of muon scattering events resulting from the detector setup, distort the distribution of scattering density as assigned by MLEM and reduce the algorithm's accuracy in reconstructing the interior of a spent nuclear fuel cask.

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DSTAR: a Modular 4π Muon Detector for Field Measurements and Evaluation of Ambient Conditions in Low-Background Experiments

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Low-background experiments are strongly affected by the cosmic-ray muon background, which is commonly characterized in terms of meters of water equivalent (m.w.e.). However, direct measurements of the effective overburden in natural environments, in particular in water, remain limited and are often restricted in angular coverage.

We present the DSTAR, a compact modular 4π muon detector, composed of paired scintillator–SiPM modules with dedicated DAQ and slow control and arranged in reconfigurable three-dimensional geometries. In its full configuration, the detector forms a near-spherical modular geometry providing a full solid-angle (4π) coverage. The detector architecture is easily scalable. The DSTAR is portable, enabling rapid deployment and long-term autonomous field operation in different natural and experimental environments.

A 14-module prototype has been operating at the Kalinin Nuclear Power Plant since October 2025, providing a continuous muon background monitoring for background rejection in a neutrino experiment and demonstrating a stable performance. On the basis of the results obtained by the prototype, the system has been scaled up to a 64-module configuration. The full-scale detector is prepared for underwater deployment in Lake Onega for direct measurements of the effective water equivalent at the depths up to 30 m. The modular design provides a flexible platform for evaluating ambient conditions in future low-background experiments and, in the longer term, for near-surface muon radiography and tomography.

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Muon scattering tomography with laser-plasma-accelerator-driven muon source

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Laser plasma accelerators (LPAs) can generate GeV scale electron beams in ultra-compact footprints, making them ideal drivers for various secondary sources. Among these is artificial muon generation, with various groups measuring LPA-driven muons recently. Muons are unstable, heavy elementary particles, that interact mostly by scattering off nuclei as they propagate through matter. This means that they can penetrate large and/or dense objects, with the scattering angle of the emerging muon carrying information about the elemental composition of traversed material. Properties of muon beams driven by an optimised LPA will be presented, along with first simulations of muon scattering tomography and object reconstruction using LPA-driven muons.

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Simulations of muons generated from laser-wakefield-accelerated electrons with a 10 PW laser

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Laser-generated muons have been indirectly measured in 2025 and additional experimental campaigns have confirmed them directly, at ELI-NP, at the 10 PW laser. In order to fully describe the muon beams obtained from the interaction of high-energy electron (accelerated via laser-wakefield interaction) with solid targets, along with the background of other types of particles, we have developed full GEANT4 simulations that take into account all the complete experimental set-up.
The staring point of the simulations is the experimentally-measured electron spectra, and the results support measurements performed at the ELI-NP 10 PW laser beam.

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Muography at 1 km depth - Hardware

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The Occidental College/KoBold Metals collaboration is exploring a detector to extend muography underground to depths of 1 km. Deployed at scale such a detector would utilize 1000s of square meters of surface detectors to detect incoming air showers and inexpensive, non-directional borehole detectors in coincidence. The measurement of muon direction and depth provide the basic parameters needed for muography. As a proof of principle, we have deployed an array of 10 surface scintillators in conjunction with 4 borehole scintillators at Occidental College. All surface detectors use a unique GPS system to measure time with an accuracy of a few ns across the array. Each unit communicates wirelessly for deployment at scale.

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Analysis of Case-dependent Detector Placement Around a Thick-walled Nuclear Waste Cask

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Resolving the internal geometry of a thick-walled spent nuclear fuel cask in detail is a demanding task in the field of muography. In thick-walled, heterogeneous systems, the multiple-scattering nature of cosmic muons complicates both trajectory reconstruction and the exact localization of where the dominant scattering occurred as the measured net deflection represents an integral over many material transitions and scattering events. This becomes particularly relevant when the object of interest shifts from coarse anomalies, e.g. fuel assemblies, to finer cask features as individual fuel rods, polyethylene rods or features located in the cask center. Analyzing the trajectories within the cask in high detail provides a first valuable information map, showing that detector positioning can improve the material information measured particles are providing. The measured muon flux an be narrowed to particles with specific information on material scattering or comparatively isolated trajectories with few material transitions.

This study uses theoretical interaction statistics within a CASTOR® V/19 to derive strategies for positioning detectors that are tailored to specific applications in interim storage facilities. A series of representative measurement geometries are evaluated: varying the arrangement, vertical height, active area of the detectors, and the number of detectors.
For each configuration performance-related factors are evaluated, e.g., the expected exposure time needed for the muon statistics, usable muon flux under acceptance constraints, feasibility of use in high-security environments, and implications for suitable reconstruction algorithms.
Several use cases relevant to interim storage are addressed. From a safeguards perspective, the re-verification of cask-contents to provide a continuity of knowledge, such as empty fuel assembly slots or discriminating fuel assemblies form non-fuel bearing dummy elements to provide is looked into. Other aspects include the analysis of deviations in the polyethylene moderator rods and changes in the local positioning of the fuel rods. In addition, scenarios such as fuel leakage leading to an accumulation of fuel on the cask bottom are being investigated. These scenarios lead to scattering anomalies, but require detector geometries that preferably measure only muons in the lower part of the cask to avoid a high level of integral scattering information one muon is carrying.
The results show that the placement of detectors can be optimized if the setup is adapted to the structure of interest: Smaller detectors with an additional upper layer may be sufficient for localized investigations in the lower region (e.g., a leaking fuel cone), while configurations near the upper edge efficiently investigate deviations of the moderator rods. Overall, the work provides a requirements-oriented framework that links detector positioning with specific measurement scenarios, covering exposure times, and reconstruction approaches for muography within the context of interim storage of nuclear waste.

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Borehole Muon Radiography of Subsurface Density Variations

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Most applications of muon radiography (muography) are focused on a static determination of the bulk density of above ground structures or of the subsurface as is. In this paper, we present recent results from a demonstration of muography's potential for determining contrasts in bulk density over time. Similarly to the so-called contrast agent CT in the medical field, contrast muography offers promise in addressing
significant inefficiencies in mineral processing.

The measurements were performed in a dedicated underground demonstration facility designed to generate well defined and repeatable density variations under controlled conditions. The facility allows for the use of borehole muon detectors installed in horizontal or vertical pipes at a depth of ≈ 2.5m.

A range of well defined density contrasts can be produced using reconfigurable tote bins at the surface of the facility. This allows to both precisely control the amount of water added to system, and to create well defined density phantoms and test objects. Note that the facility also allows for the validation of different measurement normalization schemes (at depth, at surfaces) and is being equipped with a standalone weather station.

Initial measurements indicated a stable and repeatable detector response over extended observation periods, maintaining excellent sensitivity to small variations in incident muon flux and bulk density perturbations. The system currently achieves meter-scale spatial resolution and long-term stability exceeding 95% under controlled conditions. Comparative measurements between dry and water-injected configurations yield spatially resolved density maps that localize imposed anomalies within the test volume. Monte Carlo simulations were used to model muon transport and detector response in the above experimental configurations, showing consistent agreement with measurements.

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Simulation study on high-resolution muon tomography of a spent nuclear fuel storage cask

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A significant fraction of the spent nuclear fuel used in nuclear power and research plants around the world is stored in dry storage casks. Since these casks are equipped with heavy shielding, monitoring of the condition of the spent nuclear fuel is often based on indirect methods, such as temperature or radiation checks. Due to their high penetration power and natural occurrence, the use of natural cosmic-ray muons presents a suitable way to directly image the fuel inside such storage casks. As a result, applying muon tomography to the monitoring of nuclear fuel casks has become an active field of research over the recent years. While these studies have shown promising results, the complex and heavily shielded cask geometry has only allowed up to now the reconstruction of only entire or partial fuel. The necessary goal of reconstructing single fuel rods has not been achieved so far.

This work presents the first clear demonstration of the feasibility for single fuel rod resolution within a nuclear storage cask. The study is based on a simplified, but realistic cask model of the CASTOR V/19 storage cask, the most common nuclear storage cask in Germany. The cask is imported to the GEANT4 simulation toolkit using the B2G4 workflow for three different scenarios: an empty cask without any fuel rod, a cask randomly filled with fuel rods at 90% capacity, and a cask filled with fuel rods at 100% capacity. The presented work utilizes a gradient descent-based implementation of the MLEM algorithm allowing a sparse and scalable, but high-resolution reconstruction of the different cask scenarios. In order to achieve single rod resolution, the resulting tomographic maps are denoised in the final step of the analysis by a residual U-Net deep learning architecture with an incorporated attention mechanism. When overlaid with a ground truth model denoting fuel rod positions a clear correspondence is shown, indicating that single fuel rods can be successfully identified.

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Geant4-based simulations for muon imaging of volcanoes

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This study presents a numerical modeling framework for planning future muography experiments aimed at imaging the internal structures of large-scale geological objects through simulations of atmospheric muon flux propagation. Muography utilizes attenuation of high-energy cosmic-ray muons in dense geological media, enabling non-invasive imaging of volcanic conduits and crater regions.

Previous muography experiments in volcanoes, pyramids, and underground facilities have demonstrated the potential of this technique for 3D density imaging. However, such experiments typically require long observation periods to achieve sufficient spatial resolution, which is often impractical under demanding field conditions. In our study, we demonstrate how numerical modelling of atmospheric muon propagation through 3D objects can be used to optimize detector setup and exposure time in muography experiments.

Simulations were conducted using the Geant4 toolkit (Agostinelli, 2003), providing detailed physics models of particle–matter interactions. The approach is demonstrated with the example of the Iwodake volcano, located on Satsuma-Iojima Island, Japan, which has been the subject of prior muographic surveys (Tanaka, 2009). A three-dimensional digital elevation model of Iwodake volcano was constructed from Shuttle Radar Topography Mission (Farr, 2007). To investigate dynamic volcanic processes, multiple density configurations were considered, representing different stages of magma convection and degassing. Muon propagation was modeled using a modified parameterization of the Gaisser formula for sea-level muon spectra (Guan, 2015), with muons generated from a virtual hemisphere surrounding the volcano. Computational efficiency was enhanced through energy thresholds and a backtracing algorithm to focus on trajectories intersecting detector planes. The detection system was represented by virtual observation planes at realistic field locations. We demonstate how the optimal position of detectors and exposure time can be evaluated using analysis of synthetic muographic images.

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Interactive diorama as a tool for Muography outreach

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Muography is a powerful imaging technique, but its physical principles can be difficult to communicate to non-specialist audiences. To support outreach activities, I developed a small interactive diorama illustrating different structures, such as a pyramid and underground environments, together with their corresponding muographic responses.
The installation was presented at the Science is Wonderful! science fair organised by the European Commission and at my university's Researchers'Night. The diorama combines physical models with simplified modelling of muon transmission, allowing visitors to visually connect density variations with changes in detected muon flux.
The aim of this work was to provide an intuitive and tangible explanation of muography, especially for school students and families. The hands-on format encouraged discussion and helped translate an abstract detection principle into a concrete experience.
In this contribution, I present the design of the diorama, the modelling approach used to illustrate the muography response, and reflections on its effectiveness as an outreach tool.

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Physics-informed μTRec algorithm for accelerated muon scattering tomography

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Muon tomography is commonly divided into absorption and scattering modalities. Absorption approaches are well suited for very large structures, while muon scattering tomography (MST) targets medium scale, heavily shielded objects such as dry storage casks and cargo containers. MST leverages multiple Coulomb scattering (MCS), where the distribution of angular deflections and lateral displacements depends strongly on material composition, enabling inference of changes in effective density and atomic number. A central limitation is the low cosmic muon flux, which often requires hours to days of data collection, especially when using simplified trajectory models such as straight-line path (SLP) or point of closest approach (PoCA) that effectively collapse MCS into a single interaction. This work presents μTRec, a physics-informed reconstruction algorithm that models the cumulative nature of MCS through a Bayesian framework. Using a Gaussian approximation to the bivariate scattering process (angle and displacement with covariance) and a constant average energy loss model, μTRec reconstructs a stepwise curved muon trajectory constrained by measured upstream and downstream tracks. In GEANT4 based studies of dry storage casks, μTRec achieves missing fuel assembly detection with approximately 20× fewer muons than PoCA for comparable signal-to-noise and contrast-to-noise ratios, substantially reducing required acquisition time and enabling near-real time imaging. We also present the first MST study for sealed microreactors, which are intended for remote deployment and long lifetimes (about 5 to 10 years) with limited physical access. Non-intrusive monitoring is therefore essential for safe operation, safeguards assurance, and maintaining public trust. Including muon momentum measurements improves μTRec detectability for missing fuel scenarios by about a factor of two. Moreover, Momentum-informed μTRec resolves key microreactor components and increases detectability by about 350%, with higher confidence than momentum-integrated PoCA. Finally, we demonstrate a Python based analysis pipeline for cargo security, applying machine learning based (unsupervised and one class) anomaly detection to identify concealed uranium from muon scattering derived features.

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Methodical and experimental muon imaging for monitoring of industrial facilities

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Muon imaging is a highly promising and rapidly evolving technique for non-invasive monitoring or investigation of various structures across a wide range of applications. This is particularly advantageous for objects that cannot be examined using traditional methods such as X-ray radiography or CT due to their high density and/or large geometries.
A frequently discussed area of application is the monitoring of transport and storage casks to determine the condition of the radioactive inventory. In addition to Monte Carlo simulations of such casks and the development of suitable image reconstruction algorithms, we are preparing a series of large-scale experiments. A robust and modular muon detection system, consisting of scintillation detectors and stacked drift chambers, has been developed for use in combination with novel image reconstruction algorithms. To precisely measure the cask geometry and test these reconstruction algorithms, a large-scale phantom was constructed, replicating a cross-section of a CASTOR V/19 cask. The vertically mounted steel disc, simulating a horizontally positioned cask, matches the material composition of the actual cask wall and ensures realistic muon scattering behavior. Steel rods, held by rotatable perforated plates, represent the fuel rods and allow for the simulation of various cask orientations. The phantom's frame supports the integration of muon detectors above and below the disc, providing a realistic testing environment for muon scattering tomography. This experiment enables the acquisition of experimental benchmark data for muon imaging of transport and storage cask geometries. Once the detection system and image reconstruction algorithms are proven to deliver accurate images, the next step will involve examining an actual cask in an interim storage facility.
Based on the current state of the art, there is growing interest in utilizing muon imaging for other applications. The detection system and reconstruction algorithms can also be applied to the monitoring of industrial infrastructure. Currently, small samples of reinforced concrete are being examined with our muon detectors to gain initial insights into the condition of objects such as bridges and to identify areas with reduced density or corrosion. Furthermore, the algorithms are being applied to simulations of industrial furnace geometries to evaluate the wear of lining materials. The accuracy and required measurement time to detect these effects are also being investigated.

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Global Cosmic Ray Monitoring with the Belgrade Muon Station and the gLOWCOST Network

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The Belgrade Muon Station has conducted continuous cosmic ray monitoring since the early 2000s, operating synchronized ground level and shallow underground detectors to study rigidity dependent cosmic ray variations. Enhanced stability and sensitivity have been achieved through ongoing instrumental upgrades and the development of two atmospheric correction methods based on principal component analysis and machine learning. These approaches significantly improve the precision of primary cosmic ray flux measurements and support studies of Forbush decreases, transient events, and quasi periodic modulations. The laboratory's research further includes collaborations on cosmogenic radionuclides and investigations of high energy solar events and their impacts on the lower ionosphere, including Sudden Ionospheric Disturbances. Future work involves participation in gLOWCOST, a global network of cost effective muon detectors enabling real time, synchronized measurements of cosmic ray flux. This emerging network enhances space weather monitoring capabilities, supports atmospheric tomography, and fosters international STEM collaboration. Preliminary global observations from Solar Cycle 25 are presented.

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Density Evaluation Strategies for the Mt. Vesuvius Great Cone

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The MURAVES (MUon RAdiography of VESuvius) experiment aims to investigate the internal structure of the "Great Cone", the summit cone of Mt. Vesuvius, an active volcano near Naples, Italy. The experiment uses the muography technique with scintillator-based tracking stations installed on the volcano's flank. Each layer of the tracking stations comprises two orthogonal planes segmented into scintillator bars read out by SiPMs, enabling directional counting and muon tracking and long-term stability monitoring. This contribution presents updated results using additional data collected since the last publications, optimised processing and improved χ2-based track-quality selection. The simulation incorporates a detailed DEM-based model of the surrounding topography to compute direction-dependent rock thickness, and a dedicated muon transport simulation based on the Mulder framework. Mulder provides a Backward Monte Carlo approach, allowing simulations starting from the detector location with a prescribed energy spectrum and particle transportation through the topography to predict the expected flux at the instrument location.
To compare data and simulation while minimizing normalization systematics, we define a per-angular-bin data-to-simulation double ratio D(ϕ,θ), defined as the time-normalized measured Vesuvius-to-freesky rate ratio divided by the corresponding simulated transmission. This observable provides a direct consistency metric and serves as an input to density evaluation across the "Great Cone". The outcome confirms the robustness of the double ratio approach and provides a robust basis for density evaluation of the "Great Cone"in Mt. Vesuvius.

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G-Multiplexing via SiPM Ganging

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Genetic multiplexing (S.Procureur et al.) is a cost-effective readout technique for large-area particle detectors. While it was specifically developed for Micro-Pattern Gaseous Detectors (MPGDs) such as Micromegas, it can be implemented also with SiPM photo-sensors coupled to the scintillation elements. We describe our hodoscope prototype, which uses 84 scintillator bars coupled to 168 SiPM sensors, being read out by 4x14 = 56 CAEN electronic channels. The reduction of the electronic channels is possible by the multiplexing technique implemented via 3-SiPM sensor ganging into one readout channel.

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Overview of Laser-Driven Multi-GeV Muon Sources and the ELI Beamlines plan

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Recent improvements in laser technology have allowed on one hand to reach unprecedented levels of energy and intensity and on the other hand to develop new target systems to produce ever more energetic electron beams. These developments have made it possible to accelerate electrons to sub-10 GeV levels in the space of 10s cm. The electron beam, interacting with a high-Z target can produce muons either via pair production with the Bethe-Heitler mechanism, or via the decay of mesons generated in photo- and electron-nuclear interactions. The production of muons using lasers has been recently investigated and demonstrated by several teams worldwide.
This contribution will review the current status of laser-driven muon beams and the most notable experimental results. As well, it will detail the future plans for the development of a muon beam at the ELI Beamlines facility.

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Characterization of a Compact 16×16 Interleaved Scintillating Bar Detector

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This study presents the physical characterization and the development of a 3D reconstruction framework for a high-resolution muon tracking detector, originally designed for the NA64 experiment at CERN. The instrument consists of two detection planes, each featuring a grid of 16 horizontal (X) and 16 vertical (Y) overlapping plastic scintillating bars. The bars are arranged in an interleaved architecture with a symmetric readout of 8 channels per side, a configuration optimized for high-rate particle environments now being adapted for cosmic muon radiography.

To transition this technology from fixed-target particle physics to geophysical exploration, we implemented a modular processing pipeline. The detector's response is modeled by calculating the pixelated angular acceptance ($\mathcal{T}$) and the solid angle ($\delta\Omega$) based on the specific 16×16 bar geometry and the inter-planar separation. This geometric model is integrated with digital elevation data to perform ray tracing through a voxelized volume, utilizing a digital differential analyzer (DDA) approach to determine the intersection lengths ($F_{i,k}$) within the grid.

The 3D density reconstruction is formulated as a linearized inverse problem based on the density-length relationship ($\gamma = F\rho$). Due to the underdetermined and ill-conditioned nature of the muographic survey, the solution is stabilized using a Bayesian Maximum A Posteriori (MAP) estimation. This allows for the incorporation of geologically relevant prior information ($\rho^{(0)}$) and a weight matrix (W_γ) derived from the Poissonian statistics of the observed muon counts. We present simulation results evaluating the sensitivity of the $16X \times 16Y$ hodoscope to density anomalies such as mineral veins and cavities. By leveraging the high-precision tracking capabilities inherited from its original design for CERN experiments, the system demonstrates the ability to resolve subsurface structures with high spatial resolution and quantified uncertainty.

A defining characteristic of this instrument is its extreme compactness, designed for high-resolution imaging in highly confined spaces. The detection planes consist of scintillating bars with individual dimensions of 70 mm in length, 3 mm in width, and a thickness of 1 mm. By implementing a 1 mm overlap between adjacent bars, the configuration of $16X$ and $16Y$ elements results in a precise active area of approximately 33×33 mm^2. This miniaturized footprint, combined with the high-density readout, allows for the deployment of the hodoscope in narrow boreholes and small-scale mining galleries (typical of small and medium-sized mining operations) where conventional muographic equipment cannot be installed.

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Comparison of muon trajectory reconstruction methods with detailed track simulations for track reconstruction optimization

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Muon scatter imaging is based on detectors giving information on the incoming and outgoing muon positions and angles, and extracted total scattering angle, with no direct information on the muon track between the detectors. That is, we are trying to recover rich information from a low information environment. There are many methods of reconstructing each muon's path, including straight line, point of closest approach, splining, and even iterative methods.

In our current work we examine the fidelity of reconstruction methods using Geant4 Monte Carlo simulations as a reasonable representation of reality, or the rich information to be reconstructed. In the simulations we have the entire trajectory for each muon and we compare the residuals - the difference - between common track reconstruction results and the detailed path simulations. A priori knowledge is used to guide reconstructions, such as using known geometries and running straight line paths through air portions of a region imaged, such as the air outside of a spent nuclear fuel cask. Other considerations include energy loss effects, as the muons tend to scatter to larger angles as they lose energy (e.g., [1,2]). Path curvature change may be considered by combining different track reconstruction methods such as straight line and spline with a moving weighting. While experimentally we don't know the muon energy, we do know the general behavior that high total scattering angles are associated with lower energies, which can guide us in parsing the data into subsets for analysis.

Residuals between full path simulations and reconstructions based on the entrance and exit positions and angles are compared for different reconstruction methods to find an optimal path reconstruction. Image reconstructions of Geant4 simulated data with the MC-10 spent nuclear fuel cask at Idaho National Laboratory were performed to compare the imaging outcomes of the different reconstruction methods including previous image reconstruction [3].

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Muon scattering tomography studies of a sealed container and commissioning of a Micromegas tracking system

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Muon tomography research at Canadian Nuclear Laboratories continues to expand through both applied investigations and detector development activities. As part of legacy waste characterization at the Perch Lake site, a sealed 80-kg steel pail containing a dense internal object was examined using the Muon Portable Imager for Counter-terrorism (MuPIC). Conventional imaging methods, including gamma-ray measurements and x-ray radiography, were unable to penetrate the object, motivating the use of muon scattering tomography. MuPIC was deployed to a waste-characterization facility to collect data on the target, enabling reconstruction of the internal structure and revealing a high-density cylindrical flask with an inner cavity. Estimates based on scattering density measurements indicate material properties consistent with lead, and no evidence of high-Z inclusions was observed within the void region, reducing concern regarding potential hazardous radiological contents. In parallel, commissioning and benchmarking studies were conducted for a Micromegas-based muon tracking system integrated into the MuPIC tower. A structured lead-brick target was scanned simultaneously with both detectors, providing the first direct comparison of two different tracking technologies operating on the same data set. Using a common Point-of-Closest-Approach reconstruction, Micromegas demonstrated improved image contrast and reduced reconstruction noise relative to MuPIC, attributable to its finer position resolution. These results support further development of Micromegas-enabled scattering density estimation and expanded benchmarking activities with CRIPT and future reconstruction algorithms.

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The NAUM Project

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The NAUM (Non-invasive Archaeometry Using Muons) project is a collaboration between US and Mexican institutions exploring El Castillo pyramid in the archaeological zone of Chichen Itza, Mexico, using a scintillator-based muon tracker. The development of non-intrusive remote sensing techniques has been one of the major interdisciplinary successes of archaeometry. Ground-penetrating radar and electrical resistivity tomography are examples mainly used for subsurface exploration. We are employing an alternative technique that uses the transmission of atmospheric muons through large archaeological structures. Since February of this year, the detector has been measuring the flow and direction of atmospheric muons beneath the pyramid. In this talk, we will outline the project's scope, the detector, results from prototype tests, and the project's status. This work is partly supported by the National Science Foundation under Grant Nos. NSF-PHY-2011339 and NSF-PHY-2011442.

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Application of Muography in Geological Monitoring During Shield Tunneling: Long-Term Field Validation in Complex Urban Environments

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Urban shield tunneling faces severe challenges from deep-seated hidden geological hazards. Constrained by limited penetration depth and complex urban electromagnetic interference, traditional geophysical methods struggle to achieve dynamic monitoring of deep hazards during excavation. This paper proposes a 3D dynamic absorbtion -based muography technology tailored for shield tunneling environments. To overcome the effects of continuous dynamic displacement and complex urban background interference, a data fusion strategy based on a "quasi-static approximation" and a refined "strata-surface building" quantitative correction model were developed. Furthermore, a highly integrated, automated detection hardware and software system was engineered to withstand the extreme conditions inside the tunnel boring machine (TBM).
A long-term field dynamic experiment was conducted on Shenzhen Metro Line 25, achieving continuous monitoring over 492 TBM rings (736.8 m in total). Field results demonstrate that: (1) The system achieved real-time dynamic perception of the strata ahead of and above the TBM. It successfully detected and 3D-reconstructed a utility intersection cavity (approx. 27.6 m^3) located 3.5 m above the tunnel, with spatial positioning highly consistent with ground-truth verification via field manhole inspection. (2) By correlating with known utility distributions, the engineering applicability boundaries of the system at typical depths were delineated, verifying its meter-level spatial resolution. (3) Hypothesis testing based on empirical data resampling confirmed the system's ultimate detection sensitivity for micro-cavities as small as 1 m^3 within the strata. This study not only validates the engineering feasibility of dynamic muon imaging in urban shield tunneling but also clarifies its applicability boundaries and resolution characteristics, providing reliable technical support for quantitative risk management in complex underground engineering.

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Muography for Structural Health Monitoring of Hydraulic Dams: A Field Experiment on a Reservoir Auxiliary Dam

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To address the challenge of internal structural monitoring and anomaly detection in large hydraulic structures such as earth-rock dams, this study investigates a non-destructive detection approach based on cosmic-ray muons. A field experiment was conducted at the auxiliary dam of the Mangshan Reservoir in Hunan Province, China, using a muon detection system based on plastic scintillator panels. Continuous measurements were carried out to record the muon flux passing through the dam body and the surrounding mountain, and three-dimensional density reconstruction was performed based on the acquired data. The results demonstrate that Muography can effectively reveal the density distribution within the dam body and the adjacent rock mass. Several density anomaly regions were successfully identified, and their spatial distribution shows good agreement with known engineering structures and geological conditions. The study indicates that Muography can detect and spatially locate internal density anomalies within an earth-rock dam without interfering with its normal operation. This work provides a practical example of applying cosmic-ray Muography to hydraulic engineering structures and highlights its potential as a complementary technique for dam safety monitoring.

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Muography for Large Archaeological Heritage Sites: A Case Study of the Yungang Grottoes

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Large archaeological heritage sites are important carriers of human cultural heritage, and the structural integrity of these sites is crucial for their long-term preservation. However, prolonged exposure to natural processes and human activities often leads to structural deterioration within such sites. Among various environmental factors, rainfall-induced erosion and water infiltration play a key role in affecting structural stability. Due to the large scale, immovability, and structural complexity of archaeological heritage sites, conventional inspection techniques are often difficult to apply for effective non-destructive investigation. Muography, a non-destructive imaging technique based on cosmic-ray muons, provides a promising solution for probing the internal structure of large-scale objects.

In this study, muon imaging was applied to investigate the overlying strata above Caves 7–10 of the Yungang Grottoes, one of the four major grotto complexes in China and a UNESCO World Heritage site. Using muon tomography, the density distribution of the geological layers above the caves was reconstructed, and a detailed structural reconstruction of Cave 8 was achieved. The results reveal several low-density anomalies above the grottoes, including a low-density structure associated with the historical Yungang city wall and restoration-related remains located above Caves 7–8.

In addition, long-term observations were conducted during the rainy season to explore the feasibility of dynamic monitoring of water infiltration using muon imaging. The results show no evidence of significant infiltration channels above the caves, confirming the effectiveness of previous seepage control measures. By combining experimental data with simulations, the sensitivity of the imaging system under different infiltration scenarios was systematically investigated.

The results demonstrate that muography is an effective non-destructive technique for investigating the internal structure of large-scale cultural heritage sites and has strong potential for long-term monitoring of hydrological processes. This study provides a new technical approach for internal structural investigation and seepage monitoring in large archaeological heritage sites, offering important support for the scientific conservation and risk assessment of cultural heritage.

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Monte Carlo study of muon scattering tomography using RPC-based detectors

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Cosmic-ray muons provide a powerful probe for non-invasive imaging of dense structures. Among the available techniques, muon scattering tomography (MST) exploits the multiple Coulomb scattering of muons in matter to infer the internal composition of an object. The magnitude of the scattering depends on the atomic number of the traversed material, making MST particularly suitable for material identification and security applications. In this work, a Monte Carlo simulation framework based on the Geant4 toolkit has been developed to investigate the response of a muon scattering tomography system based on resistive plate chamber (RPC) trackers. This detector technology offers excellent time resolution and allows the signal readout electrodes to be optimized for specific applications without substantial modifications to the detector structure. Atmospheric muons are generated using the EcoMug library, which provides realistic energy and angular distributions. These muons are then propagated through different materials, such as aluminum, iron, and lead, to study their interaction signatures. The simulation includes several target configurations designed to test the response of the system to different internal structures: (a) a homogeneous single-material layer, (b) a layer containing an air cavity at its center, (c) a layer with an embedded inclusion of a different material, and (d) multiple material blocks placed at different positions inside the container. Muon trajectories are reconstructed before and after crossing the target volume, and the resulting track deviations are analyzed using observables such as the scattering angle and the muon flux. The muon flux is directly related to the achievable image quality and in practical applications such as cargo inspection, it also determines the required exposure time of the container. The interaction points inside the target are estimated using the Point of Closest Approach (PoCA) algorithm, which approximates the most probable location of the scattering event by calculating the minimum distance between the incoming and outgoing muon tracks. This approach enables the reconstruction of the spatial distribution of scattering events within the inspected volume. The results provide insight into the correlation between scattering observables and material properties, highlighting the potential of MST techniques for material discrimination. The developed framework can be extended to more complex geometries and applications, including cargo inspection systems and the study of large-scale structures in geophysical and civil engineering contexts.

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B2X - Seamless integration of complex 3D scenes with Monte Carlo frameworks

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Particle transport and radiation physics simulations rely on accurate representations of detector systems, experimental environments and material compositions. In many established Monte Carlo frameworks, the creation of detailed geometries remains a labor-intensive process that requires manual coding of hierarchical volumes, surfaces, and materials. As simulation studies increasingly involve complex experimental configurations, this geometry definition process becomes a significant bottleneck. Moreover, lacking interoperability of geometry workflows often requires the same scene to be recreated independently for multiple simulation packages, introducing duplication of effort and potential inconsistencies.

To address some of these challenges, Blender-to-Geant4 (B2G4) was developed and published. It defined a modular workflow that uses the open-source 3D modeling software Blender to design simulation geometries. While B2G4 proved valuable for large-scale 3D datasets creation in the context of muon tomography, it is only available for Geant4. This work introduces Blender-to-X (B2X), generalizing B2G4 across multiple physics simulation frameworks. This is done through a custom Blender addon that allows users to easily parameterize and configure 3D scenes and models for export. These scenes are then automatically parsed into input configurations for several particle transport codes, including Geant4, MCNP, and CORSIKA 8. To support potential extensions to other codes, an open-source interface is defined.

B2X focuses on simplifying simulation workflows by enabling researchers to design, modify, and reuse complex geometries within a unified visual environment. In contrast to structured geometry formats such as Geometry Description Markup Language or mesh-based CAD import approaches such as DAGMC, B2X emphasizes interactive scene construction, support for randomization and large-scale datasets. Example workflows are demonstrated using different test setups in Geant4, MCNP and CORSIKA 8 with a focus on muon-based imaging.

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Efficient Muon Tomography Image Reconstruction Using Gradient Descent Optimization

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Image reconstruction in muon scattering tomography is a complex task, and finding suitable reconstruction algorithms for a given application often requires compromises: Simple approaches, such as the Point of Closest Approach (PoCA) or Angle Statistics Reconstruction (ASR) algorithm, require little computational effort but are inherently limited in achievable image quality due to their underlying simplifications. In contrast, statistical approaches can provide significantly improved results; however, their implementation is numerically complex and requires substantial computing resources.

In this work, we present a statistical maximum-likelihood reconstruction framework that enables both accurate and computationally efficient muon image reconstruction. The method is based on a per-voxel likelihood formulation of the muon scattering information, quantifying the agreement between a candidate density map and the detector data. The likelihood is maximized directly using gradient descent optimization, treating the voxel densities as free parameters and therefore yielding an optimal density map.

The gradient descent optimization is performed via automatic differentiation, a method that allows for efficient gradient calculations that are free of uncertainties. To ensure scalability to large datasets and compatibility with limited computational resources, the implementation leverages parallelization, GPU acceleration, and batched processing.

This contribution introduces the theoretical foundations and practical implementation of the proposed gradient descent reconstruction algorithm. Based on example scenes with varying complexities, the performance of the algorithm is compared to traditional algorithms with respect to reconstruction quality, runtime, and memory consumption.

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Instrumentation for muon measurements

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In recent years, our focus has been on developing new detection techniques that come with a segmentation of the detectors to measure individual muons. This aspect provides more detailed information about the direction and also about their number, offering better performance, greater efficiency compared to integration on large surfaces where optical signals are lost in the plastic scintillator.

In addition to the aspect related to the shape of the detector, we have implemented solutions for reading the scintillators that are compact, efficient and have low power consumption.
Thus, the detectors can provide the muon flux but also the direction of arrival due to the relatively high granularity for each detection plane.

Most detectors are based on SiPM and have relatively compact individual electronics, each channel having a preamplifier and a discriminator. Overall, we managed to have a detector that has a relatively large number of channels and consumes little, thus being able to be used in in situ measurements where energy resources are relatively low, being able to be used even on a battery and why not on a photovoltaic system.

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Muography advancements in industrial extremes

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Muography is an excellent imaging method targeting geological objects from volcanoes to underground treasures. Growing industrial interest and application cases faced us novel challenges, solutions enhanced the muograph portfolio and later scientific applicability.
The presentation will focus on novel hardware validation and case studies in active industrial environments.

Mining recultivation and hazard awareness requires muographic imaging from flooded tunnels, underwater pits, or wells. We have developed a wire-chamber based muograph with sealed encasing optimised for underwater operations. Performance and validation tests in Budapest has been followed by robot-driven underwater operation in Portugal.

While geological objects are mostly stable, industrial sites shall deal with swift changing surface and internal structures. Muographic imaging thus demands inspection of continuous time evolution, and could lead to controlled monitoring as well. Case studies of 4D muography in the active mining site in Bulgaria, and the daily changes of 40m buffer of a solar power plant in Morocco will be presented.

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Precision parameter analysis based on a series of measurements conducted at the Jánossy Underground Laboratory

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During the last decades, muography proved to be an excellent method for the non-destructive examination of the internal structure of man-made objects. Muography indirectly provides information about the internal density conditions of the target object. Possible anomalies can be located in two ways: either by triangulation using 2D muograms, or through inversion of the 2D muograms. Inversion yields is a 3D density distribution, however, artifacts may appear due to the geometry of the imaging. In our presentation, we demonstrate that precision parameter estimation is also possible based on muograms, meaning that the parameters describing the target object, such as diameter, direction etc. can be determined with high precision.

The HUN-REN Wigner Research Center for Physics operates an underground laboratory, the Jánossy Underground Laboratory (JURLab). It has a well-defined geometry, and measurements can be performed in multiple tunnels at three levels: -10 m, -20 m, and -30 m. These features make it an excellent location for detector testing. Here, we conducted a measurement series lasting more than two years using multiple detectors across all tunnels.

Our goal was to create a data system that could serve as a basis for testing data processing steps and for testing inversion method in various ways. Furthermore, with the help of well-defined tunnels and surface buildings, it became possible to examine the sensitivity of the method and to conduct precision parameter analyses.

The presentation will discuss the steps of data processing, the sensitivity analysis of the parameters, the determination of parameters for diameter and direction in the case of well-defined tunnels, and the determination of wall thickness in the case of surface structures.

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SiRO, a scintillator-based hodoscope for muography applications

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SiRO—SiPM ReadOut muon detector, is a detection system based on plastic scintillator bars designed for muography applications. Using six 1 m2 layers of active medium, grouped two by two into three rectangular matrices of pixels (24x24), each separated by a variable distance, the spatial coordinates of the muon's impact point on every matrice are obtained and used for trajectory reconstruction.

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Development of Cosmic-Ray Muon Imaging for Levee Safety Assessment Using Nuclear Emulsions

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We have previously revealed the internal structures of nuclear reactors and pyramids using cosmic-ray muon imaging with nuclear emulsions. In this study, we aim to apply this technique to levees and to establish a new method for levee safety assessment by visualizing the internal material distribution. In this presentation, we report the current status of the analysis of observational data collected over a two-year period starting in 2021, and discuss the issues associated with the current detector configuration as well as a new observation scheme proposed on the basis of these findings.

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Development of a Nuclear Emulsion Focusing on Gelatin for Long-Term Cosmic-Ray Muon Imaging

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Cosmic-ray muon imaging with nuclear emulsions is an effective method for investigating the interior of large-scale structures, with expected applications for various targets such as volcanoes and industrial plants.
However, in high-temperature environments—such as during summer—the recorded particle tracks significantly disappear due to latent image fading, which restricts long-term observations. Therefore, it is necessary to suppress this fading for the practical use of nuclear emulsions under high-temperature conditions.
One of the primary causes of latent image fading is the oxidation and decomposition of the latent image (silver clusters) by hole-derived Br2 generated during its formation. In this study, focusing on the halogen bonding between Br2 and methionine, we devised a method to trap and deactivate Br2 using methionine within the gelatin. We applied fish gelatin , which contains 2.5 times more methionine than bovine bone gelatin , to nuclear emulsions and evaluated its effectiveness.
In this talk, we will present the experimental results and discuss the feasibility of cosmic-ray imaging with Nuclear Emulsions under high temperatures.

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Muon Studies of Urban Tunnel Overburden in Shanghai: Sediment Monitoring, Tidal Response, and Ongoing 3D Muon Radiography

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Cosmic-ray muography has emerged as a powerful non-invasive technique for probing the internal structure and overburden conditions of large-scale infrastructures in complex urban environments. In this work, we report recent progress on studies of two representative underground tunnel systems in Shanghai, China.
First, a portable dual-layer muon flux detector based on plastic scintillators was deployed in the Shanghai Outer Ring Tunnel, an immersed tunnel beneath the Huangpu River, to investigate sediment accumulation above the tunnel crown and to validate the influence of tidal variations on muon flux. By combining in situ measurements with Geant4 simulations that include sediment, water, and concrete layers, we established a quantitative correlation between muon attenuation and overburden thickness. The measured muon flux exhibits a strong anti-correlation with nearby tide-gauge water-level data, demonstrating the sensitivity of muography to both sediment distribution and tidal fluctuations in submerged infrastructure environments.
Second, we are carrying out an ongoing muon radiography campaign in the Caobao Road Tunnel using two transmission-imaging detectors to probe the overburden region above the tunnel. This study aims to reconstruct the three-dimensional density distribution of the overlying soil and structural environment from transmission measurements. Preliminary progress indicates the feasibility of resolving large-scale underground heterogeneities in a dense urban setting and highlights the potential of multi-detector observation for 3D muon radiography of urban infrastructure.
Together, these studies demonstrate the applicability of cosmic-ray muons to long-term monitoring and three-dimensional imaging of urban underground infrastructure. The results support the growing role of muon radiography in civil engineering, geotechnical assessment, and resilience-oriented infrastructure management.

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Cosmic-Ray Muon Imaging with Nuclear Emulsions

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Research and development of cosmic-ray muon imaging using nuclear emulsion detectors is being carried out at Nagoya University. Nuclear emulsions are three-dimensional charged-particle tracking detectors based on silver halide photographic technology. Although they are lightweight, compact, and require no power supply, they provide submicron spatial resolution and milliradian angular resolution. After exposure, the developed emulsion films are read out by a high-speed automated track-scanning system and analyzed in detail. We are currently working on the development of higher-sensitivity nuclear emulsions as well as a next-generation readout system. Taking advantage of these unique features, we are pursuing nondestructive imaging of a wide variety of targets, including archaeological remains, civil infrastructure, subsurface structures, and the internal structure of trees. In this presentation, we report on the current status of these developments.

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Ready to deploy high performance muography instruments

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Building on its strong relationship with French academic sector, Iris Instruments is proud to show its ready to deploy instruments for muography. Two versions are available : a micromegas based and a scintillator based. The first one is the direct industrialization of the successful instrument deployed by CEA during the ScanPyramids mission with an even better gas managing system allowing the instrument to consume less than 1.5L/h of a premixed gas mixture. The second one is a next generation instrument based on the instruments deployed by CNRS/IP2I for more than 10 years in the Soufriere de Guadeloupe. These two technologies offer complementary advantages : the very fine precision of the micromegas technology or the large collection surface of the scintillator. This allow our instruments to cover a large range of use cases while both are field ready with a power consumption below 50W on a 12V battery compatible supply and with a remote lightweight web monitoring fully usable on slow connections (GSM). Theses two different instruments have been fully tested in geosciences environments (decommissioned mines and quarry) and are suited to various harsh environments both in and outdoors.

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Rotational Muon Detector: Development and Proof-of-Concept for Muography Applications

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This work presents the design and successful proof-of-concept of a novel muography detector based on continuous rotational acquisition. The primary objective is to demonstrate that a compact prototype (0.5m×0.5m×0.3m) can significantly enhance angular resolution and acquisition efficiency compared to conventional, static telescopes. The detector architecture leverages plastic scintillators coupled with a readout system based on Silicon Photomultipliers (SiPMs), integrated with an AS5600 magnetic encoder to ensure precise angular synchronization of detection events.
To validate the experimental findings, computational simulations were performed using Monte Carlo methods, showing high agreement with the captured zenith muon flux. Furthermore, Bayesian inference methods were implemented for uncertainty estimation, providing a robust statistical framework to characterize the system's precision. These experimental measurements confirm the feasibility of a portable, rotational design for applications in geophysics, structural engineering, and archaeology. Ultimately, this proof-of-concept opens new perspectives for developing a more efficient and versatile generation of muon detectors.

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Development of a three dimensional wireless muometric navigation system

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Muometric positioning is a novel positioning technique with envisioned applications in indoor, underground and underwater navigation. The technique exploits the highly penetrative cosmic-ray muons, that can penetrate kilometers of rock or water and have low angular scattering even on large distances.

A muometric positioning system includes a receiver detector with unknown position and reference detectors with known positions. The goal is to find the position of the receiver detector measuring muons crossing both a reference and the receiver detector. Various possible realizations of such muometric positioning system have been proposed and investigated in recent years, from the first prototype based on the measurement of the time of flight of muons with wire based communication between the detectors, to the most recently developed wireless system built from MWPCs and utilizing the direction vector of cosmic muons, capable of reaching centimeter level positioning accuracy in 2 dimensions.

This system was further developed and now consists of two reference detectors with angular resolution of ~ 30 mrad, capable of 3 dimensional positioning. We present the first demonstration of 3 dimensional positioning with this system using a Kalman filter based algorithm to position and follow the movement of the receiver detector. With the proposed hardware and algorithm ~ 20 cm positioning accuracy was reached with a distance of ~ 7 m between the receiver and reference detectors.

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Identification of cosmic muons and determination of their momentum distribution using a semiconductor detector

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Measuring the flux of cosmic ray particles involves multiple scientific disciplines and carries significant technical applications. In our case, the primary motivation for determining the muon spectrum was the scarcity of literature data available in the momentum range below 1 GeV/c. Furthermore, we aimed to investigate whether such measurements could be performed using a device originally designed for a different purpose but suitable for the identification of muons. Additionally, cosmic rays constitute a constant external background in gamma spectroscopy; therefore, we wanted to quantify this unshieldable background contribution during the activity measurement of gamma-emitting samples.

One of my project's aims was to measure the energy deposition spectrum of
cosmic rays on every floor of the Northern Building at the Lágymányos campus. This provides insight into the variations in particle flux and the production of secondary particles as they travel through matter. My other goal was to provide a quantitative description of the background radiation's contribution to gamma spectroscopy.

During my research, I performed multi-day measurements across the floors
of the university building, which provided a better understanding of the spectral shape and the facilitated the determination of the contributions from both muons and secondary particles. Furthermore, I developed a simulation environment using the Geant4 software environment and compared the simulated energy deposition spectra with the experimental results.

Moreover, the detector and measurement method employed provided insights
into the shape of the cosmic muon momentum distribution at low momenta,
specifically in the 0-1 GeV/c range.

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TOMAR: High Resolution RPC-based Muon Tomography

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Muon tomography (MT) is non-invasive technique for imaging the internal density of large structures, with applications ranging from civil infrastructure monitoring and mining exploration to port security. This presentation introduces TOMAR, a project aimed at democratizing access to muography through the development of a portable, autonomous muon tomograph based on Resistive Plate Chamber (RPC) technology.

The TOMAR demonstrator incorporates a novel readout system capable of simultaneously extracting particle position, with a resolution better than 1 mm, and time-of-flight, with a resolution better than 100 ps, using a small number of channels that do not depend, to first approximation, on the detector area. The inherent low cost of the RPC technology combined with the new readout allows for high-granularity 4D imaging at low cost The proposed system features a four-plane configuration with an active area (per plane) of 36x36 cm² Design and initial test on the system will be reported in this commination.

By combining high-performance imaging with economic viability, TOMAR aims to bridge the gap between particle physics research and real-world industrial applications.

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From HEP experiments to industrial developments: a roadmap for muography

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The most common description found in the literature is that muography is an innovative method of imaging structures, comparable in principle to clinical X-ray radiography. But it is in fact a complete technology and research field in its own right, the development of which has accelerated significantly over the last three decades. And this acceleration covers all relevant aspects in such an interdisciplinary field, from sensors developments and integration to particles tracking techniques and algorithms optimization in the inverse problem resolution. Unlike all academic researches, muography has also opened new horizons in the non destructive testing paradigm for industrial applications. This is growing up rapidly in civil engineering, mining prospection, nuclear industry, metallurgy etc by offering not only structural imaging solutions but also monitoring capabilities.

In this talk I will review early (recent) developments in geosciences with a dedicated focus on volcanology and related progress in risk assessment and mitigation that muography promises. Then I will follow the technology transfer and valorization processes that led to the birth of a dedicated company proposing muography-based services, MUODIM, to a variety of clients in the private sector. Technical but also economical challenges will be discussed and addressed on a few examples.

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Muometric Positioning, Navigation and Timing

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Since ancient times, solar energy has been recognized as a source of energy for growing crops, but in recent years, the technology for harnessing solar energy to generate electricity has also developed. The total amount of cosmic muon energy available on Earth is much smaller than the total amount of solar energy available on Earth; however, if energy is gauged at the unit of one particle, the muon has much higher energy than the solar photon. Due to this feature, it is possible to utilize muons as signals for spaciotempoeal positioning. The advantages of this technique are: 1. unlike conventional positioning signals (RF, sound, and visible light), muon signals are unimpeded by almost all obstacles, and therefore can be used in environments where other signals fail, enabling navigation in some areas where other existing navigation technologies are not applicable, and 2. being a naturally occurring phenomenon, muon signals do not have to be artificially generated. In this talk, it will be presented that indoor and outdoor positions will be seamlessly define universally based on the Earth's center of gravity and/or Universal Coordinated Time by integrating muometric navigation with GPS/GNSS and indoor/underground geometry Improvements to the accuracy of digital twin models and smart society applications are anticipated in which this new technology could be used.

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A Scintillation-Based Cosmic Muon Detector for High School Particle Physics Education

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We present the development and implementation of a scintillation-based muon detector as part of a high school educational project aimed at introducing fundamental concepts of particle physics through experimental practice. The project builds on students' prior knowledge of atomic and nuclear physics and extends it to elementary particle physics, including leptons, quarks, and fundamental interactions. The detector was constructed using a modular approach based on a starter kit provided by the University of Debrecen. Students were involved in all stages of the process, including assembly of the scintillation units, detector configuration, and optimization of the geometry. The flexible design allows for systematic studies of detector performance. Data acquisition and analysis were carried out using simple software tools, providing students with insight into experimental methods and basic programming techniques. The resulting setup is a fully operational muon detector that remains available for further educational and experimental use.

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Simulation study of muon scattering tomography for low-contrast medical imaging

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Muon scattering tomography (MST) leverages the multiple Coulomb scattering of cosmic-ray muons to reconstruct the internal structure of dense objects. While extensively studied in security and geophysics, its application to medical imaging remains an open question. We report on a simulation-based study evaluating the feasibility of MST for imaging biological tissues, with a focus on spine monitoring. Using GEANT4, we implement voxelized anatomical phantoms based on ICRP reference models and introduce controlled deformations to simulate scoliosis curvature. We quantify the detectability of bone structures ($\rho \approx 1.85$ g/cm^3) against surrounding soft tissues ($\rho \approx 0.95$–1.05 g/cm^3) and assess reconstruction performance in terms of spatial resolution and contrast-to-noise ratio. We investigate the impact of acquisition time and compare scenarios based on natural cosmic muon flux. The results provide insight into the physical limits of MST in low-contrast biological environments and help define the parameter space in which clinically relevant measurements, such as Cobb angle estimation, may be achievable.

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Measurements of cosmic-ray muon flux with a mobile detector at the Belgrade muon station

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Cosmic-ray muon intensity has been continuously measured at the Belgrade muon station since 2002, at both ground level and shallow underground. A new, mobile detector set-up dedicated for cosmic ray measurements has recently started operating. It consists of three parallel plastic scintillator plates (50cm x 50cm x 2cm), placed at 30 cm apart, with a thin lead plate above each scintillator. The detector set-up can operate in single and coincidence mode, utilising off-line analyses of stored event information for all three scintilators. The detector response and calibration for both single and coincidence mode were obtained using a Geant4 based simulation. From experimental and simulation data muon flux has been determined. Time series of the cosmic-ray muon flux were also carried out.

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Cosmic-ray Muon Scattering for Nuclear Material Measurement

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At Fukushima Daiichi, the removal of nuclear debris is underway, and when loading debris in a container, it is important to measure the amount of the nuclear fuel contained in the debris to reduce the storage cost by classifying the waste by the amount of contained fuel. The highly radioactive debris makes the conventional passive and active measurements using gamma rays and neutrons difficult. Muon scattering imaging is a possible method to measure the amount of uranium in the debris. A prototype muon-scattering system capable of operating under elevated radiation environments was developed at Toshiba.

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Implementation of Muon-Induced Secondary Particle Detection for Enhanced Imaging

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While cosmic-ray muography has become a proven tool for inspecting large-scale geological and industrial structures, such as nuclear reactor fuel, imaging small objects with low atomic numbers and low densities remains a significant challenge. Our research group has demonstrated a novel imaging method that addresses this limitation by detecting secondary radiation produced within the target material. By leveraging the production rate of these secondaries—detected in coincidence with muons using plastic scintillator detectors and a muon tracker—we have successfully produced the first cosmic-ray muon images of organic structures, specifically bone and soft tissue.
To refine this technique, we utilized Geant4 Monte-Carlo simulations to model muon interactions across various detector configurations and target materials, optimizing the experimental setups for image clarity. This paper presents a comparative analysis of two specific experimental setups: MUCA (Novi Sad) and COMIS (Budapest).
• MUCA (Muon Camera): Utilizes four 50 cm x 50 cm x 5 cm plastic scintillation detectors and a muon tracker consisting of five 25 cm x 25 cm Close Cathode Chamber (CCC) boards positioned above the target.
• COMIS (Cosmic Muon Induced Secondaries): Employs a tracker of five 50 cm x 50 cm CCC boards (2 mm resolution) below the target, supplemented by four 50 cm x 50 cm x 5 cm scintillators surrounding the object and four 25 cm x 25 cm x 5 cm scintillators beneath the target volume.
The primary objective of this research is to advance the imaging and composition analysis of low-Z, low-density materials using exclusively naturally occurring cosmic radiation. We provide a detailed comparison of the experimental results obtained from both setups, highlighting the efficacy of secondary particle detection in expanding the functional range of muography. By establishing a framework for imaging organic matter, this work paves the way for non-destructive material analysis.

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Advancing Muography for Mining Applications in the Horizon Europe Projects AGEMERA and Mine.io

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Muon imaging, or muography, is emerging as a valuable non-invasive method for mineral exploration and mining, particularly where density contrasts can complement conventional geophysics. In the Horizon Europe project AGEMERA (2022–2025) (doi:10.3030/101058178), muography was developed as one of the project's three core innovative geophysical methods for critical raw material exploration, alongside passive seismic and drone geophysics. Its role was to enable density characterisation of rock volumes to support 2D and 3D imaging in mining and brownfield settings, and contribute to integrated interpretations alongside other geophysical and geological datasets. AGEMERA also framed muography as part of a broader responsible-exploration workflow aimed at improving geological understanding while reducing reliance on invasive drilling.

In the ongoing Horizon Europe project Mine.io (2023–2026) (doi:10.3030/101091885), this work has been extended toward digitally integrated mineral exploration. Muography has been advanced through mining-oriented imaging and monitoring instrumentation and through an underwater concept that combines a muon detector, waterproof casing, and autonomous robotic deployment, validated in flooded open-pit conditions in Portugal as a step toward applications in water-filled mine environments. Within Mine.io, muography is thus being positioned not only as an imaging method but also as part of a broader digital exploration workflow linked with robotics, positioning, and integrated data environments.

Together, AGEMERA and Mine.io show how muography is moving from promising field-demonstration technology toward scalable, application-oriented exploration and mining solutions.

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Towards the Integration of Muography into EPOS: A New Observational Data Type for Geosciences

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The European Plate Observing System (EPOS) is a European research infrastructure designed to integrate geophysical observations, data services, and scientific communities into a unified framework for solid Earth science. Through its Thematic Core Services (TCS), EPOS provides access to interoperable datasets across domains such as seismology, geodesy, volcanology, and geological data. The purpose of EPOS is to enable multidisciplinary research by harmonising data access, improving interoperability, and supporting the integration of diverse observational Earth data types within a common platform.

Muon imaging, or muography, has been deployed across a wide range of geoscientific fields, including volcanology, glaciology, mineral exploration, and environmental studies. Its ability to provide direct information on subsurface density structures makes it a valuable complementary technique to existing geophysical methods. Despite these advances, muography and related muon-based technologies remain relatively underrecognised within the broader geoscientific community. This creates both a challenge and an opportunity to better connect muography with established Earth observation frameworks such as EPOS and its TCSs.

Within the Horizon Europe EPOS ON project (doi:10.3030/101131592), initial steps are being taken to engage the muography community and explore pathways for sharing observational data with the EPOS platform. A key challenge identified is the lack of standardised data formats and metadata for muography. In the Horizon Europe-funded EPOS ON project, integration work—led by the University of Oulu and supported by the HUN-REN Wigner Research Centre for Physics, which is not a project partner—has begun through volcanological use cases in collaboration with the EPOS TCS for Volcanology. These developments highlight a pathway for muography to evolve from a specialised technique into a recognised observational data type within the geoscientific community.

EPOS provides a pathway for muography to evolve into a recognised observational data type within the geoscientific community.

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Muon Solutions Oy: Practical Muography Applications Across Mining, Environment, and Infrastructure

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Muon Solutions Oy develops muography solutions for mining, mineral exploration, and other demanding settings where non-invasive density imaging and monitoring can improve subsurface interpretation and support operational decision-making. At the exhibition, we will present our recent work, with particular emphasis on mining and mineral exploration, including applications related to critical raw materials (CRMs) and rare-earth elements (REEs). We will also present broader directions in environmental monitoring and structural assessment.

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Gaseous tracking detectors based on lightweight MWPC-s

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Gaseous tracking detectors are known for high efficiency, high resolution
and field-proven reliability in muography applications. Over the last years, considerable developments were dedicated to reduce complexity and power consumption of the readout systems, and importantly to reduce the gas consuption.

The exhibition features various types of MWPC-like detectors developed at the HUN-REN Wigner RCP, ranging from small units for cave exploration up to components of large systems like the Sakurajima Muography Observatory. For underwater application a 13cm x 38cm area tracker has been developed which runs in a sealed mode, and was continuously operational without gas supply for over a year.

With a typical power consumption of 6-9W, detectors can be operated with humanly managable size batteries for periods of multiple weeks, allowing applications in remote locations.

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Arts and science: the SCENA project

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The SCENA project (Scientific Cosmic Experiments with Narrative Arts) aims to validate a static monitoring system for heritage buildings through the construction and field deployment of two dedicated muon telescopes. The system builds on a previously published feasibility study [1]. By correlating muon trajectories measured by two vertically separated telescopes rigidly fixed to a building, the setup enables the detection of relative shifts and rotations, even through internal obstacles such as floors or vaults. Detector optimization and real-time reconstruction algorithms are supported by Monte Carlo simulations based on GEANT4 and the EcoMug muon generator. A distinctive feature of SCENA is the creation of an "artistic clone"of the detector, that is a full-scale interface that converts muon-arrival data into light and sound using dedicated sonification methods. This multidisciplinary component supports public engagement and Citizen Science initiatives, highlighting the potential of particle physics as a shared language for cultural heritage protection and scientific outreach.

[1] G. Bonomi et al. "Cosmic ray tracking to monitor the stability of historical buildings: a feasibility study", Meas. Sci. Technol. 30 (2019) 045901 [doi: 10.1088/1361-6501/ab00d7]

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GEANT4 Simulations of Muon Scattering Tomography

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Muon tomography exploits the natural flux of cosmic-ray muons to probe the internal structure of large or dense objects using scattering and absorption signatures. GEANT4 provides a powerful Monte Carlo framework for modeling the passage of muons and secondary particles through matter, making it an essential tool for designing and optimizing muon imaging systems. Here I present a general approach to developing GEANT4 simulations of muon scattering tomography, outlining the key components of such models: the muon source, the detector geometry and response, the target object, and the relevant physical processes governing muon interactions. Particular attention is given to modeling realistic cosmic-ray muon sources, including angular and energy distributions consistent with measured atmospheric spectra. Several historical and recent simulation studies are discussed to illustrate typical setups and representative results. Finally, I highlight how detailed GEANT4 simulations can provide synthetic training data for machine learning models, facilitating rapid image reconstruction and material identification in muon tomography applications.

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CMOS Cosmic Ray Detector (CCRD): A desktop muon detection software for citizen science

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The CMOS Cosmic Ray Detector (CCRD) is a lightweight, cross-platform desktop application enabling real-time detection of cosmic-ray–induced events using consumer-grade CMOS camera sensors, without dedicated hardware. The system employs dynamic noise calibration and eigenvalue-based analysis of pixel-coordinate covariance matrices to identify linear particle tracks and suppress background noise. Real-time performance is achieved with millisecond-scale frame processing, and stable operation is demonstrated across Windows, macOS, and Linux platforms. Under standard conditions, an atmospheric muon detection rate of approximately 7 events per hour is observed. The results demonstrate the feasibility of using consumer imaging sensors for particle detection and establish a foundation for distributed, citizen-science cosmic-ray monitoring networks.

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SilentBorder2: Advancing Non-Invasive Cargo Inspection with Next-Generation Muon Imaging

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SilentBorder2 is a newly confirmed Horizon Europe project that builds upon the results of the SilentBorder project and will redefine non-invasive cargo inspection by exploiting both natural and artificial muon sources for imaging applications across diverse cargo types and configurations. Traditional muon scattering tomography systems rely solely on the natural flux of cosmic muons, enabling safe, ionising radiation-free 3D imaging but remaining limited by low muon statistics and consequently long scan times.

SilentBorder2 addresses these limitations by introducing a compact, high-flux artificial muon source to significantly accelerate image acquisition while enhancing spatial resolution to sub-millimeter precision. In parallel, the project tackles the central challenge of generalisation by developing methods capable of interpreting complex, mixed, and previously unseen cargo scenarios.

To achieve this, SilentBorder2 will combine physics-informed machine learning, advanced reconstruction algorithms, and multimodal data from muon, gamma, and neutron detectors. This approach will ensure robust material classification and anomaly detection under realistic customs conditions, extending the capabilities of existing X-ray-based inspection systems.

Developed in close collaboration with European customs and border authorities, SilentBorder2 ensures experimental validation in representative operational environments, as well as compliance with EU safety and radiation protection standards. By advancing both muon-based imaging methodologies and data interpretation frameworks, SilentBorder2 aims to deliver faster, more accurate, and operationally robust cargo inspection. This talk will introduce the SilentBorder2 project and outline the key scientific and technical activities planned over its three-year duration.