Thoughts about an Ideal Validation Environment for Muography Applications

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Abstract

Muography has many possibilities ranging from imaging volcanoes to observing civil infrastructures, industrial targets, or even small-scale objects. G. F. Knoll has laid out the fundamentals of radiation detection and measurement of muon flux. However, what is still lacking is the testing and verification environments for muon detectors used in muography. This work will present a few thoughts on such a possible muography test and method validation site in terms of micro and macroscale validation environments and introduce one candidate location, Callio Lab, Finland.

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1. INTRODUCTION

Muography is a rising method for investigating subsurface structures, similar to X-rays but up to a kilometr scale. Instead of X-rays, muography relies on the natural flux of highly penetrating cosmic-ray-induced muons that are constantly generated in the interactions between primary cosmic rays and nuclei of common elements in the Earth's atmosphere. The highest energy muons can penetrate up to several kilometers underneath the Earth's surface [1].

The muons ionize the matter they are passing, and thus, they are detectable by technologies used for detecting ionizing radiation. The detector technologies can be put in four simplified categories: emulsion film-, gas-, scintillation-, and semiconductor-based. Each of these technologies has its pros and cons. However, they all share a common feature: they can detect ionizing radiation, whether from radioactive decay-based gamma-rays, alphas, and betas or cosmic-ray-induced high-energy electrons and muons. The separation between muons and the background sources can be done by tracking whether using photographic emulsions, several layers of detectors (3+), or time of flight (TOF) analyzes [2, 3]. In the case of photographic emulsions, the tracking is done by visually analyzing the actual tracks produced by the incising particles within the emulsion. In TOF analysis, the time difference between hits (interactions) in different layers must be within the time of flight for the muon to pass the two or several incident detector levels. A line can be drawn along the hit positions using three or more layers of position-sensitive detectors. If all or at least 3+ layers have hits along a straight path, the passing particle can be estimated to be a muon [4].

Different muography applications require different detector technologies and assemblies or even combinations of different technologies. For example, in the ScanPyramids project, emulsion films, gas-filled, and scintillator-based detectors were used [5]. Pyramids are in the scale of tens of meters, but actually, the muography targets can range from submeter in homeland security [6] to kilometer-scale in volcanology applications [7]. The needed measuring times also vary greatly; e.g., in homeland security, the measuring times are in minutes [8], from hours [9] to months [10] in volcanology, and from weeks to months [11, 12] in the mineral exploration or archaeological [5] applications. How the detector technologies are applied (surface, underground, or heliborne) depends on the aimed use. Most known applications of muography are linked to observing unknown (e.g., archaeological [5] or geological [13, 14] target) or temporally changing (e.g., volcano monitoring [15, 16]) targets. There are also many possible well-known but aging targets in the civil infrastructures [17, 18, 19].

To understand the inner density structures of the investigated targets, both the muon measurements and the Monte Carlo simulations can be applied [20]. The simulations provide valuable insights. If the target is well known, then the muon flux passing through can be modeled. When compared with the measured muon statistics, invaluable information about the target interior can be acquired. If there also exist additional data such as topographic maps, gravitational data, conductivity or magnetic field data, or seismic reflectivity data, these can be used as a reference for the muography analysis. Moreover, different data sets can be combined by applying rough integration or more sophisticated data fusion methods; see, e.g., [21, 22, 23].

2. THOUGHTS ABOUT MUOGRAPHY VALIDATION ENVIRONMENTS

All established geophysical technologies have the advantage that they are already widely used and therefore validated in numerous real-world case studies. For muography, the validation is in its infancy as more and more technologies, methodologies, and fields of application are being developed by various academic and commercial players; see [6, 24] for some selected developers.

To overcome the challenges of muography compared to other geophysical methods, entry-level test and validation environments are needed for the technology, data, and method validation. The test environments should meet two requirements: (1) for validation purposes, a site needs to be geologically (especially rheologically and structurally) well understood; it is also highly preferable to have other geophysical or structural data available for comparison and integration purposes; (2) for the technology testing and development, there is rarely time to wait for weeks or months for the results; thus, the validation environment should have access to facilities that are shielded from the cosmic-ray air-shower-induced electrons but still have a reasonable high flux of muons ($>1\mu s^{-1}m^{-2}$) [25].

The two requirements mentioned above describe just the parameters of the environment. The environments must be safe for operators in terms of chemical and physical safety and air quality for the actual testing. The test environments should be easily and safely accessible, preferably with a car or a truck to deploy even the bulkiest detectors assemblies. In addition to having the site characterization data and high enough muon flux, the validation analysis method needs high-density-contrast targets (see Table 1) compared to the surrounding environment. The targets should be well known for their internal density profile and outer dimensions. For example, air against any liquid or solid target would create high contrast object and hence an ideal target for validating and testing muography detectors and imaging software. It would also be beneficial if there were both static and dynamic targets.

TABLE 1: Densities of some common materials and their relative densities compared to air.

Matter	Density kg/m^3	Relative density to air	Reference
Air	1.293	1	[26]
Water (20°C)	998.20	772	[26]
Sand	1,200–1,600	928–1,237	[26]
Granite	2,700	2,088	[26]
Concrete	1,500–2,400	1,160–1,856	[26]

2.1. *Macroscale (Large-Scale) Muography Validation Environments*

The targets investigated or used as a validation environment have been considered in the literature. In some cases, the objects have been pyramids or volcanoes. On the industry and civil engineering side, the targets have been storage silos, furnaces, water towers, tunnels, or even bridges. Common for all the above-mentioned targets is that they are large-scale targets already used, especially for transmission for muography. Let us define these large-scale targets as macroscale validation environments [27, 28].

Macroscale environments are suitable for transmission muography where the opacity (path-density) of the targets can be observed with changes in the incoming muon flux, similarly to X-rays, with lighter (lower path-density) parts allowing more muons to pass through and similarly dense (higher path-density) parts less. At the macroscale, the validation environment should be as real as possible. Suppose the goal is to validate muography for geoscience applications. In that case, the validation environment should, for example, have access to a subsurface facility while also having a well-understood geological and infrastructural environment. An underground mine would make an excellent infrastructure to meet all these qualities. The underground galleries, workings, and the tunnel network itself would make excellent muon radiography and muon tomography targets in such a setting. In addition, this type of environment would guide the validation process for testing the detector systems and the data reconstruction capabilities of the software.

Underground mines can be found with flat, and slope overburdens. The benefit of flat overburden is that only the geological settings affect the muon flux when the measuring location changes. With slope-type overburden, the change of position also changes the overburden additional to the geological settings making the testing and validations a bit more challenging than with flat overburden environments. Additionally, it would be beneficial if there could be stockpiles of sand, gravel, etc., on the surface, and these would have variable sizes, or some of them could be reshaped or changed in terms of size and time. Such stockpiles could be used to validate both the spatial resolutions of the chosen detector assemblies and the threshold limits for observing the temporal changes (see, e.g., Figure 1). Of course, if the stockpiles are constantly changing due to the production of minerals, it is crucial to have drone-based lidar or photogrammetric surface topology measurements as references.

The benefit of changing the stockpiles, and thus the overburden, is that with a change of a single parameter of the measurement, the effects of the change are much better controlled than moving the detector system to a different location and depth. Even if targets in interest would be available, the access and the wanted depth might not be due to a lack of tunnels or safe access to the tunnels. For deeper (more than 200 m.w.e overburden) measurements, the muon flux is already at or less than $1\,Hz/m^2$ [4, 25].

2.2. *Microscale Muography Validation Environments*

What, then, if there is no access to large-scale infrastructure or the site's characteristics or transformability is not meeting one's requirements? Or if the developed muography technology aims for measuring small targets, e.g., homeland security targets? If the

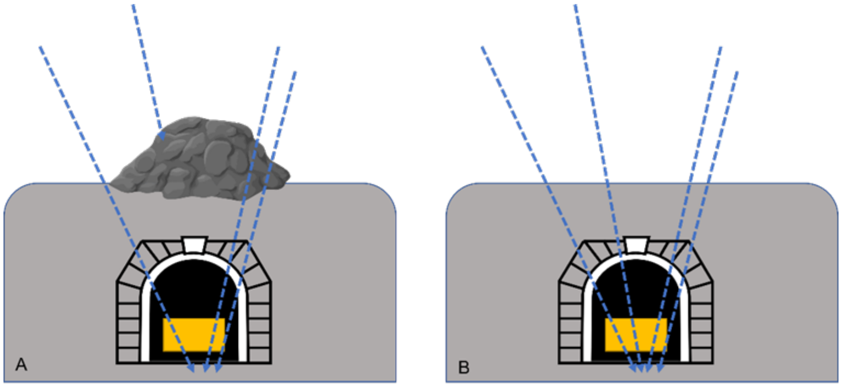

FIGURE 1: Within an underground test site, the thickness and density profile of the overburden can be changed by piling up gravel, ore, or other commodities or objects (compare (A) with (B)). Underground mines (mineral extraction) or quarries (construction rock extraction) can provide underground access and surface stockpiles for dynamic but well-documented overburden for transmission muography validation. The yellow box illustrates a muon telescope and the blue dotted lines muon paths.

site is not matching the needs, one option is to create an environment that meets the set requirements. In these cases, downscaled validation environments, microscale, could be the solution.

Microscale environments offer possibilities for both transmission and scattering muography. The latter is of particular interest in the field of monitoring nuclear materials (high Z-materials), whether hidden within cargo [28, 29] or stored in special facilities [30, 31]. The scattering muography benefits from the Coulomb scattering of muons in high-density materials such as uranium and lead. The deviation from the initial muon track allows backtracking where possible contrabands are hidden (see Figure 2 for an illustration). In macroscale targets, e.g., rock, the muon path scattering is around one degree for high-energy muons traversing through the medium. At low muon energies, the deviation is up to several degrees [32].

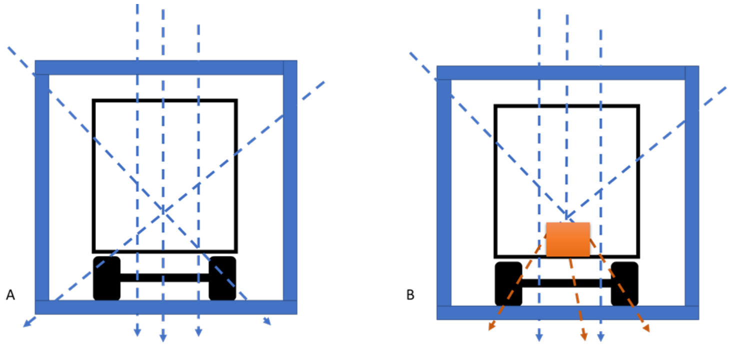

FIGURE 2: A simplified illustration of how the scattering muography can be utilized in a homeland security application. When a truck comes to a muon gate, the whole truck is being imaged. If there are no heavy elements within the cargo, the muon tracks follow straight lines (A). However, if there are, e.g., nuclear contrabands within the cargo, the muon tracks change from their initial directions ((B) scattered muons in orange). The scattering reveals the existence of high-density materials within the cargo. The dashed blue arrows illustrate the muons, the dashed orange arrows illustrate the scattered ones, and the orange box illustrates the nuclear contrabands. The blue square around the truck is the muon detector. Illustrations are adapted from [6, 29].

One option for creating artificial microscale muography validation targets is to use easily accessible industrial building blocks such as IBC containers (see Figures 3(A) and 3(B)) or sea containers. The benefit of IBCs is that they are easily accessible, durable, and lightweight can also host liquids. The most common unit has a volume of one cubic meter. Mining sites are often filled with gravel or beneficiated minerals. In practically all cases, the weight of the IBC stays within operational limits for any onsite loaders. Additionally, the container itself or a system created from a series of containers could contain integrated density anomalies (voids, denser structures) to enhance the validation tests related to contrast separation, angular resolution, inversion methods, and reconstruction of density profiles and tomographies. This could be called a microlevel validation environment.

As an example of using the containers, one could construct a pile of containers with the center-most container being filled with material of which average density differs from those of its neighbors (Figure 4(A)). Such a construction could be used, for example, to study the density contrast capabilities or tomographic possibilities of various detector systems. If one or more of the central-most containers were a controlled dynamic target (e.g., a water-filled pair of containers whose water levels could be changed with a pump), one would monitor the changes in the water dynamics. This type of setup could guide developing the detector analysis methods for larger real-world cases (Figure 4(B)). Similarly, one or more containers could be variably filled with liquids or bulk

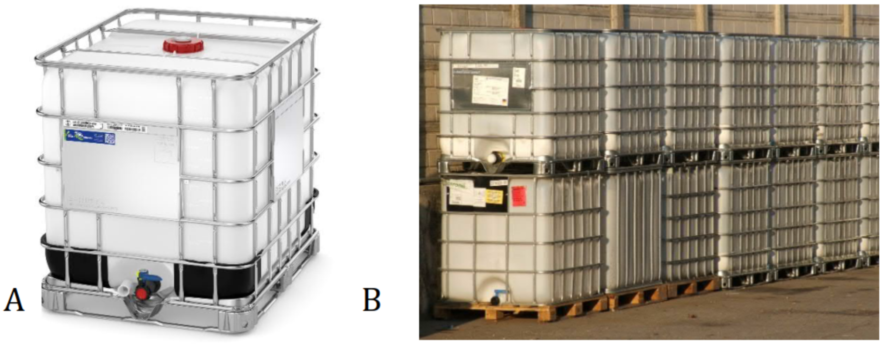

FIGURE 3: (A) IBC container is a one cubic meter standard logistics unit used to transport liquids and bulk goods. Marketing2Schütz, CC BY-SA 4.0, via Wikimedia Commons. (B) The containers can be operated with any forklift capable loaders, and they can be loaded on top of each other, enabling the creation of any kind of density configurations for muography testing and validation targets—image Luigi Chiesa, CC BY-SA 3.0, via Wikimedia Commons.

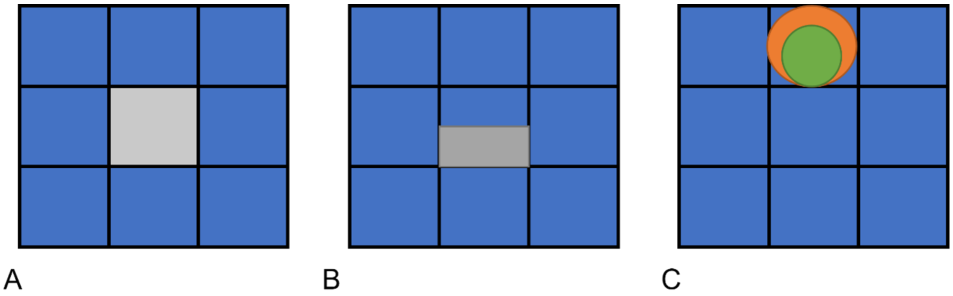

FIGURE 4: Schematic cross-section of an IBC container-based microscale test and validation setups for muography. (A) An unknown target located within a mass. This assembly would provide possibilities for muography and tomographic validation. (B) A dynamic target located within the volume. With the known influx or the change rate of the target, temporal muographic monitoring of targets could be validated. This could be very useful for developing time-lapse (time-sequential) muography. (C) Cavity formation within a volume by using an inflatable balloon. Such an assembly could be used for developing safeguard applications of muography.

goods, or a container could contain an inflatable balloon inside (Figure 4(C)). This could demonstrate the forming of cavities and provide muography developers with a hands-on tool to develop their analysis methods for analogous natural phenomena.

3. CALLIO LAB, BOTH A MICRO AND MACROSCALE VALIDATION ENVIRONMENT

The micro and macroscale environments described can be found or be found separately almost anywhere. However, to meet all the before-set requirements for the muography test and validation site, the number of available sites is reduced significantly. One such all-criteria matching site can be found in Pyhäjärvi, Finland. The Pyhäsalmi mine is a 1,444 m (∼4,100 m.w.e) deep base metal mine located close to the geographical center of Finland. The underground mining is ending in 2022, thus giving room for reuse activities throughout the mine infrastructure. The rebeneficiation of old tailing bonds is expected to continue to 2025/26. The construction of a pumped hydrostorage [33] is scheduled to begin right after the end of the underground mining. The construction will benefit from the existing tunnel access and networks, leaving the existing tunnel network and former primary levels open for reuse, such as a muography validation environment.

The Callio Lab [34, 35] is a science and R&D site located at the Pyhäsalmi mine, Finland. It is coordinated by the University of Oulu, Kerttu Saalasti Institute, and it offers an excellent opportunity to establish a micro and macroscale validation environment for the muography community. The underground mining is ending soon at this site, subsequently giving room for even 24/7 underground operations for other types of operators. However, the surface operation continues. The flat local overburden is ideal for both surface and underground validation tests for muography instruments. Geology and the mine infrastructure are well known and documented. From the infrastructure point of view, the underground has even a 1+ Gb internet connection, and with secure remote access, long-term remote tests are also possible.

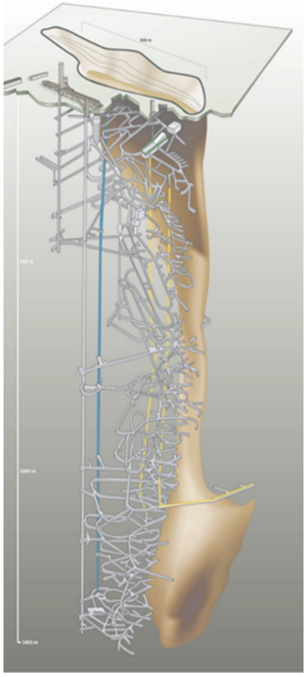

FIGURE 5: Axonometric view of the Pyhäsalmi mine. The tunnel network follows the ore body down to the depth of 1,444 m.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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