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# Muography:overview, applications and future developments

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Muons of cosmic origin can be used as probes to explore the interior of large structures, providing an alternative or complementary imaging technique applicable in many different fields: from applied geology to archaeology to countering nuclear smuggling and more. In recent years, a growing number of research groups have been exploring the limits and possibilities of such applications. These groups use knowledge developed in the field of elementary particle and cosmic ray physics research to build detectors and develop data analysis methods fit for this purpose.

Not all applications are at the same stage of maturity, but several start-ups and spin-offs have sprung up in recent years that are betting on the potential use of this technology outside academia. This is an example of how basic research not only contributes to the advancement of scientific knowledge, but is also a source of applications that can benefit civil and industrial society as a whole.

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# 1. Introduction

Muons are unstable particles with electric charge equal to that of the electron and mass about 200 times greater which interact with matter only through the electroweak force. These properties render them some of the most penetrating particles at the same energy level found in nature, excluding neutrinos, which, however, are challenging to detect due to their electrical neutrality.
Atmospheric muons originate from the decays of higher-mass particles, such as $\pi$ and $K$ mesons, which are produced profusely within the so-called cosmic showers, formed by the interaction of primary cosmic radiation (mainly protons and then, later, other heavier atomic nuclei), with nuclei in the atmosphere. The energy spectrum of primary cosmic radiation is continuous and reaches very high energies, on the order of hundreds of TeV and above. Part of this energy is inherited by muons, which, due to their sufficiently long mean proper lifetimes and relativistic time expansion, are able to reach the Earth's surface, with a flux that is around 100 Hz/m$^2$. When they reach the Earth's surface, they penetrate through the crust or pass through buildings or other structures. On the other hand, possessing electrical charge, muons can be easily detected with particle detectors. These properties make muons unique and allow us to use them as an imaging method applicable in various fields, as we will briefly explain in the next paragraphs.

# 2. Types, applications and technologies

In this section we will briefly describe the physical processes that underlie muon radiography and what are the main imaging techniques used. We will also discuss some fields of application. More details can be found in reviews and monographs dedicated to the topic [1, 2].
As they pass through matter, muons lose energy and are scattered from their direction. These effects are the basis of the two main investigation techniques: muon absorption radiography, also called muography, and muon scattering radiography, also called muon tomography, respectively. In addition to these two main techniques, muons can also be used for metrology measurements, to measure the relative position of parts of a structure, such as a building. Details can be found in chapter 5 of [1]. In the following we will limit ourselves to describing in some detail only the applications relating to the first two cases.

## 2.1 Muon radiography by absorption

Muons lose energy through electromagnetic interaction with atoms of the material they pass through. The average energy loss, per unit length, can be calculated very precisely and, for many materials, it depends mainly on the mass density $\rho$, much less on the composition of the material. In other words, the energy loss suffered in one meter of concrete (density 3 g/cm$^3$) is about the same as that the muon suffers in 3 meters of water. Once the density is fixed, it is possible to calculate the minimum energy $E_{min}$ that a muon needs to cross a certain length $x$ of material. All muons that have energy lower than $E_{min}$ will be stopped. Since the energy spectrum of muons is continuous, the measured flux will depend on $x$ and $\rho$. If you know $x$, you can derive $\rho$.
To be more precise, the amount that is typically measured is the transmission $T$ as a function of direction, defined as the rate of muons measured at the observation point divided by the rate of muons of free sky, which is obtained when no body is present between the sky and the detector. From

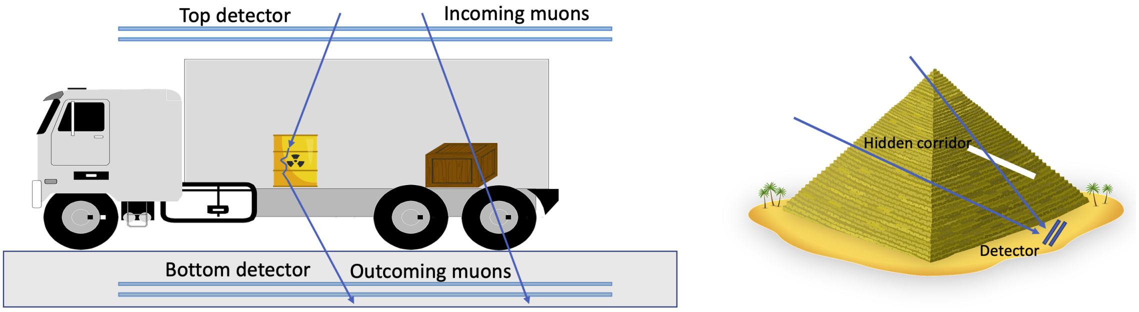

**Figure 1:** Left: pictorial description of muon radiography by multiple scattering. Two detectors, placed below and above the investigated volume, measure the entry and exit directions of muons. High-Z material (e.g. Uranium ) tends to deflect muons more than low-Z materials (e.g. wood). Right: pictorial description of muon radiography by absorption. The measured muon flux will be greater in the direction where a low-density region (e.g., a corridor) is located than in a higher-density region (solid stone).

the comparison of the measured transmission with the expected one, calculated from numerical models, the value of the average density along that direction is obtained. Significant deviations between the predicted and measured density values indicate the presence of anomalies, compared to the model, in the density distribution, such as, for example, those due to the presence of cavities, aquifers, mineral deposits, or others. Figure 1 (right) illustrates the case of cavity detection.
The information obtained from a single measurement point is a two-dimensional, angular image of the density distribution [3]. In some specific cases it is also possible, with a technique called back-projection [4], to obtain an estimate of the distance and size of the anomaly. With measurements from different points it is possible obtain 3D information, either through techniques based on triangulation or with more sophisticated algorithms [5–8].
The detector must be positioned at a lower position than the volume to be investigated. The two most used geometries are planar and cylindrical, the latter suitable for use in wells [9, 10]. Typical size of the detectors is of the order of 1 $m^2$. Several technologies have been adopted, among which the most common are those based on plastic scintillators or gas detectors. Some groups have successfully used nuclear emulsions, which are particularly useful in cramped environments with no electricity supply [2].

### 2.2 Muon radiography by scattering

Muons are deflected from their trajectory by the multiple electromagnetic interactions with atomic nuclei. The intensity of the deflection is very sensitive to the number of protons in the nucleus, the atomic number Z. This makes it possible to discriminate materials of different Z, particularly those with high-Z, such as fissile materials, from others.
Measuring the angle of deflection of the muons crossing a certain volume, it is possible to determine the presence and the position of high Z material. Many algorithms have been developed in recent

years to provide 3D information [11] and for this reason this technique is often named Muon Tomography.
This technique was originally proposed for the contrast of nuclear material smuggling in the USA [12], since it can be used also when the nuclear material is shielded by container, that can stop most of the natural radioactivity and escape the usual environmental radioactivity measurements. Many other applications are possible. Remaining in the nuclear material field, for the characterization of nuclear waste drums [13] and for the inspection of exhausted nuclear fuels storage facilities [14–17]. Other fields concern industrial application, as the inspection and control of blast furnaces and pipes. See figure 1 (left) for a pictorial representation of nuclear material detection.
From the experimental point of view this technique needs two tracking detectors to measure the incoming and outgoing muons direction. The two detectors must have good spatial resolution and cover as much as possible the inspected volume. Both these requests have a large impact on the cost. For large volumes (order 100 $m^3$ as in commercial storage containers) gas based detectors are preferred, because they are cheaper with respect to plastic scintillator based detectors.

| **Company name** | **Year of fundation** | **Country** | **Main activities** |
|---|---|---|---|
| Decision Sciences | 2001 | USA | Cargo scanning |
| Lingacom | 2012 | ISR | Cargo scanning, underground survey |
| Ideon Technologies | 2013 | CAN | Mining,national security |
| Muon System | 2015 | ESP | Industry, cargo scanning |
| Linkeos | 2016 | GBR | Nuclear barrels characterization |
| Muon Solutions | 2016 | FIN | Mining |
| GSCAN | 2018 | EST | Nuclear, security |
| Muon Vision | 2019 | USA, CHL | Mining |
| GEOPTICS | 2020 | GBR | Geology, industry, nuclear |
| GEOPTICS | 2020 | GBR | Geology, industry, nuclear |
| MUODIM | 2021 | FRA | Geology |
| MuonX | 2022 | ITA | Geology, industry, safety |

**Table 1:** List of active start-ups proposing muon radiography applications

## 3. Conclusions

Imaging by muons opens up exciting new perspectives in many different application fields. Some of these are interesting from a scientific point of view, but may not be competitive to use compared to technologies that already exist. In other areas, however, muography may be competitive or even provide solutions to problems that cannot be addressed by traditional techniques. Like any new technology, transfer from the research to the commercial world is not always easy, especially if it must compete with established technologies. In recent years, however, new start-ups have sprung up that are betting on the possibility of technology transfer in the industrial and commercial spheres. Table 1 lists the companies that, to the author's knowledge, are operational. It can be seen how the trend has greatly increased in recent years. It will be possible to estimate their true impact only in a few years, once we observe how the market responds to such technological offerings.

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