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# A novel muon detector for borehole density tomography

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ABSTRACT

Muons can be used to image the density of materials through which they pass, including geological structures. Subsurface applications of the technology include tracking fluid migration during injection or production, with increasing concern regarding such timely issues as induced seismicity or chemical leakage into aquifers. Current density monitoring options include gravimetric data collection and active or passive seismic surveys. One alternative, or complement, to these methods is the development of a muon detector that is sufficiently compact and robust for deployment in a borehole. Such a muon detector can enable imaging of density structure to monitor small changes in density – a proxy for fluid migration – at depths up to 1500 m. Such a detector has been developed, and Monte Carlo modeling methods applied to simulate the anticipated detector response. Testing and measurements using a prototype detector in the laboratory and shallow underground laboratory demonstrated robust response. A satisfactory comparison with a large drift tube-based muon detector is also presented.

## 1. Introduction

The determination of the density distribution of material in the Earth's subsurface, and the evolution of density as a function of time, has the potential to provide a sensitive, cost-effective, and precise monitoring technique to determine field-scale displacement of reservoir fluid induced by injection or production of liquids or gases. Geological carbon storage, natural gas storage, enhanced oil recovery, compressed air storage, aquifer storage and recovery, waste water storage and oil and gas production are examples of application areas. It is thus crucial to monitor in quasi-real time the behavior of these fluids, and several monitoring techniques can be used. Among them, those that track density changes in the subsurface are the most relevant. To date, the only way to collect direct and quantitative density distribution information is to measure changes in the Earth's gravitational field, known as time-lapse gravity measurements. Time-lapse gravity has been used for more than 50 years. Substantial developments over the last decade in gravimeter technology, as well as the advent of a precise Global Positioning System (GPS), have led to improvements in differential microgravity measurements; however, this technique is limited in that it only provides discrete values of the gravity field anomaly that represent the integral of the density distribution, and it is by nature an underdetermined problem.

Cosmic ray muon tomography (or muography) can provide a complete and precise image of the density distribution in the subsurface due to the dependence of the loss of flux on the varying density through which the muon passes. This approach has the potential to become a direct, real-time, and low-cost method for monitoring fluid displacement in subsurface reservoirs. Taking the example of geological carbon storage, such a method will allow monitoring the $CO_2$ concentration by watching for density changes over time as the $CO_2$ is injected and replaces brine. The muon detector for such an application needs to have sufficient angular resolution as well as high efficiency due to the low muon flux values at the depths at which $CO_2$ will be stored. The time scale for collecting a statistically significant number of muon events depends exponentially on depth, and linearly on the detector area. Signal to noise depends on the square root of the collection time. This means that a monitoring system for carbon sequestration requires

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a chain of many detectors (perhaps approximately 20) in a horizontal borehole beneath the site, and limits the use to depths less than approximately 1300 m. Data collection times will be days to weeks, but this is not a limitation since the changes in geology are on a longer time scale.

Within the New Subsurface Signals pillar of the U.S. DOE crosscut program SubTER, Pacific Northwest National Laboratory (PNNL), in collaboration with Lawrence Livermore National Laboratory, Los Alamos National Laboratory (LANL), Sandia National Laboratory, University of Utah, University of Hawaii and Paulsson Inc., has developed a borehole muon detector (BMD) to evaluate the density-dependent attenuation of the cosmic ray muon flux at depth. The BMD development has substantially reduced the size of muon detectors [1,2], providing confidence that borehole-deployable systems are technically and economically feasible. Following successful tests in surface laboratories, the BMD was deployed in the PNNL Shallow Underground Laboratory and in a tunnel at LANL where the data collected were compared to data collected by a large LANL muon detector instrument. After a brief introduction to the principles of muon tomography, the design of the BMD prototype, as well as the first results of the initial series of tests and benchmarking, is presented.

## 2. Muon tomography

Muons are generated in the upper atmosphere from cosmic ray interactions, and penetrate into the Earth at multiple angles, being attenuated by the different stratigraphic units depending on their densities. By measuring the muon flux at different depths in vertical, inclined, or horizontal wells, the attenuation of the muon signal due to the different stratigraphic units, or the fluids contained within these units, can be determined. These measurements can be performed continuously to identify and interpret variations in density and fluid content as a function of time, and be processed and interpreted jointly with other geophysical data (passive and active seismic because seismic waves are also sensitive to density, gravity, etc.), thereby improving spatial resolution and reducing uncertainty.

Muon radiography has been used to successfully image the displacement of magma in active volcanoes [3–5] with unprecedented detail using large detectors deployed at the surface. It was shown that the Tanaka detector, with a resolution of 10 mrad, was capable of imaging a volcano 1 km away to within approximately 10 m. Muon density imaging also has demonstrated potential for non-proliferation efforts to detect hidden nuclear weapons or nuclear material in vehicles [6]. Using scattering angles, significant quantities of very high-density material were detected inside cargo within a few minutes. Muon density imaging can also be used as a means to non-invasively monitor dry storage casks for spent nuclear fuel [7]. It was shown that, using either a small detector from multiple angles or a large detector that surrounds the cask, the special nuclear material content of the cask could be validated with high accuracy within two days.

The goal of producing tomographic density maps of $CO_2$ reservoirs presents new considerations surrounding the depth of deployment and associated reduction in muon flux. Although the flux rapidly decreases with depth [8,9], simulations indicate that the muon technique will have sufficient sensitivity to effectively map density variations caused by fluid displacement at great depths. For example, the progressive replacement of brine by $CO_2$ in a 20% porous reservoir at 914 m (3000 ft) would be detectable over periods of weeks to months.

The primary technical challenge preventing deployment of muon detection technology in the subsurface is the lack of miniaturized muon-tracking detectors capable of fitting in standard boreholes that will resist the harsh underground conditions for long periods of time. The development of a miniaturized muon-tracking detector deployed in a borehole is guided by strict requirements of size, ability to withstand an underground environment, data transmission rate limitations, background effects, as well as performance requirements. A typical borehole has a deployment diameter no larger than 17.8 cm (7”); hence, the detector, with all associated equipment, needs to be placed completely inside a stainless steel housing that does not exceed 17.8 cm (or less) in diameter.

The data transmission will occur through a cable connecting the detector to the surface. The cable will transmit power to the detector and transfer data from the detector to the surface. In the future when multiple detectors are needed in a tether, this approach can sequence detectors together and recover all the data. The assembly must have the ability to withstand the harsh environments present in the borehole, including pressure, heat, water and corrosive chemicals.

Discrimination of background radiation impacts on the detector from gamma rays and beta particles will be important to reach the required statistical quality of the data. Using GEANT4 simulations [10], it was shown that the background gamma rays from typical natural sources present at depth would be completely mitigated by placing an energy threshold of approximately 150 keV on each muon event [11]. Beta and alpha particles were shown to be unable to penetrate the stainless steel housing or generate any coincidence events in the detector.

## 3. Prototype borehole muon detector

The design for the BMD to be used in deep boreholes to monitor muon flux and the angle of incidence, is based on scintillating rods with fiber readout, pixelated silicon photomultiplier (SiPM), and integrated threshold and coincidence electronics. The BMD design is intended for a horizontal borehole positioned below the geology to be monitored, with integrated electronics and data transmission to the surface for long term monitoring applications. A prototype BMD [11] was built with four layers of 1 cm square polystyrene scintillator rods coated with $TiO_2$ reflector (provided by Fermi National Laboratory), as shown in Fig. 1. The BMD has dimensions of 15 cm wide, 68 cm long, and 8 cm high, designed to fit into a 17.8 cm (7-in.) borehole. Each rod includes a 2-mm diameter wavelength shifting fiber from Saint Gobain (Hiram, OH) glued in the center of the rod, which leads to a SiPM to pick up the scintillation light generated as a result of a muon transit. Top to bottom, the layers are alternating rows in the x and y directions, providing an internal coordinate system (the layers of long rods are seen in Fig. 1). There are long rods (68 cm each) and short rods (15 cm each) in the BMD with the top pair and bottom pair of layers separated by 5.8 cm center-to-center. While the two long-rod layers were fully populated with 15 rods each, the two short-rod layers were only partially populated with 30 rods each (centered on the long rods), for a total of 90 rods. Background was rejected by requiring a four-fold coincidence between the layers (within a 140 ns coincidence window to produce a hardware trigger). The angle of the muon transit in the x and y directions can be computed by extrapolating between discrete rod hits by weighting the energy deposition in multiple rods. The angular resolution obtained with the BMD was approximately 3 degrees, which

**Fig. 1.** Prototype BMD assembly showing layers of polystyrene rods and SiPM photodetector assemblies.