First Radiographic Characterization of an Active Leaching Heap

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Abstract

This paper reports on the first in-situ, fully volumetric measurement of the bulk density in an active leaching heap. This was obtained via so-called muon density radiography, a well-established technique for the near real-time characterization and digital mapping of bulk density across large objects. Muon radiography and/or tomography has already been successfully utilized for the characterization of the interior of volcanoes, ancient pyramids, and cargo containers.

Muon density measurements are close analogues of the more widely used medical or industrial X-ray. The key difference is that in place of a conventional nuclear source or X-ray tube, muon radiography is entirely passive as it utilizes the naturally occurring flux of so-called cosmic ray particles (aka muons) originating in the earth's upper atmosphere. This benign background radiation source is not only free and intrinsically safe, but also well-characterized and continuously available everywhere on earth. Muon particles are also highly penetrating and maintain directionality even in the subsurface. This allows muon radiographers to analyze and map the interior of dense structures up to thicknesses of at least a few hundred metres. In the case of leaching heaps, 2-D (radiographic) or 3-D (tomographic) density profiles can be reconstructed with a high precision (~0.01g/cc relative, <0.1g/cc absolute) and good spatial resolution (a few m^2) within time intervals typically ranging from a few days to a few weeks. When these data are compared with the initial ("dry") conditions of the heap material, or as a function of time, apparent density changes can be readily interpreted, with minimal systematic uncertainty, as the true fluid content (in litres/m^3) present in the heap. Thus, muon radiography is a promising diagnostic tool for the characterization of leaching heaps and other partially saturated media.

Here we report on the performance of a novel muon radiography sensor that was installed and remotely operated under an active leaching heap in the spring of 2022. We then highlight the applicability of muon density measurements as a new diagnostic tool for managing leaching heaps.

Introduction

Density measurements are a primary method for the characterization of any physical object. So-called nucleonic density (i.e., nuclear bulk density) is widely recognized as being one of the most robust and quantitatively accurate density measurements available, with broad applications ranging from medical imaging to industrial non-destructive testing (X-ray, CT, line inspection, cargo screening, etc.). In oil and gas exploration, borehole nuclear density services are worth well in excess of several billions of dollars per year in annual sales, and have been utilized since the 1960s as the primary method for determining the porosity of reservoir rocks, and ultimately to book proven reserves. In this paper we present our first results on the characterization of an open-air, gold-bearing leaching heap in the field.

Nuclear density measurements are an obvious choice to characterize granular or unconsolidated materials, determine their compaction, and quantify the presence of fluids within their pore space. The most desirable features of the nuclear density measurement are that it is independent of i) chemical composition, ii) chemical form and iii) temperature of the object under study. All nuclear density methods measure the attenuation of a known flux of penetrating radiation. For reasons of practicality, most of the nuclear density applications use γ-rays from a radionuclide source, but the method works just as well with charged particle radiation, such as electrons, protons, and other sub-atomic particles.

So-called cosmic-ray muons (aka atmospheric muons) are one such type of radiation and are particularly well suited for nuclear density measurement at large scales. Atmospheric muons are subatomic particles generated in the upper layers of the atmosphere by interaction with a primary flux of nuclear radiation generated by distant supernova explosions (mostly protons and light nuclei). This effect has been known for more than 100 years (Kaiser, 2018), and the muon flux on the surface of the earth has been very well characterized (Beringer et al., 2012). Indeed, so-called muon radiography has been utilized for looking inside of ancient pyramids (Alvarez et al., 1970), volcanoes (Lesparre et al., 2012), inspecting nuclear fuel casks (Gilboy et al., 2007) and tunnels (Guardincerri et al., 2017) and in mine exploration (Schouten and Ledru, 2018). The author of this paper was the first to build and field test a modern borehole detector for muon density measurement for an oil and gas application operating on a wireline in an actual oil-well (Botto et al., 2014).

Utilizing atmospheric muons is intrinsically safe as no dangerous nuclear source is required. Atmospheric muons come in all directions, and over a wide range of ultra-relativistic energies. This allows them to penetrate deeply into sub-surface while maintaining directionality, which is a key requirement for generating accurate radiographic images. Indeed, atmospheric muons have been recorded in very deep mines and underground laboratories at effective depths of >3 km.

Methodology

The concept of muon radiography applied to a leaching heap is schematically illustrated in Figure 1.

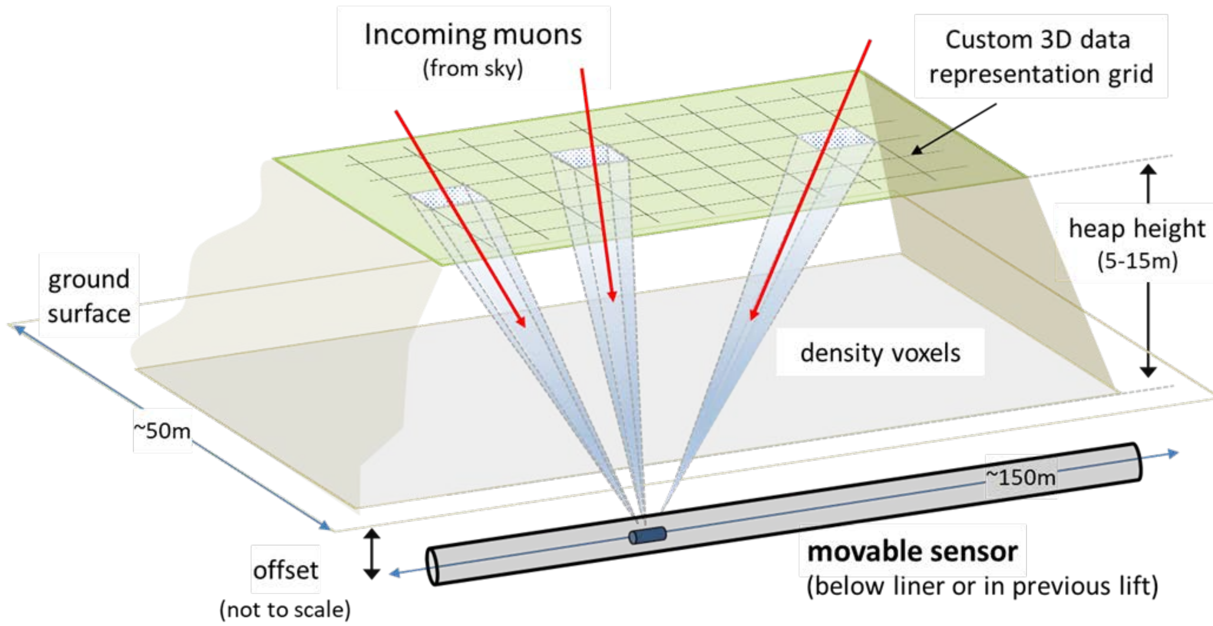

Figure 1: Muon radiography concept applied to a leaching heap. A detector buried under the heap reconstructs muon trajectories over a wide range of angles. These are grouped into inverted pyramidal voxels that are independently analyzed in terms of their average bulk density

The actual Muon Vision prototype sensor used in this work was contained in cylindrical housing with an overall tool length of 1.91 m and a 176 mm maximum diameter, and weighed a total of ~40 kg. Tool installation proceeded as follows: first, seven sections of standard smooth-wall HDPE pipe (280 mm PN16 PE100, high-density polyethylene), for an overall length of 84 m, were assembled on site. This was done in an empty, i.e. yet-to-be-filled, area of a standard leaching pad near Santiago, Chile (see Figure 2). The HDPE pipe was sealed on the far end with a custom blind section that also had an inner return pulley. The Muon Vision tool was then inserted into the HDPE pipe such that it could be moved up and down the pipe by leveraging a simple two-cable conveyance system and the return pulley at the far end. Note that the tool housing also featured two sets of spring-loaded external wheels to facilitate sensor movement and allow smooth travel over the ridge present in between joined pipe section.

The Muon Vision prototype tool has two feedthroughs to allow for data and power connections to the outside world. Tool operation (including data connection) requires ~5 W of power. For convenience, this was provided by a standard 220V AC line available on site that fed into a large electrical battery. Thanks to an on-board voltage regulator, input power supplied to the tool can be anywhere in the range of 12 to

30VDC, which is more than enough to compensate for voltage drops along the cables of different lengths. Future installations may use standalone power provided, e.g., by a solar panel.

Figure 2: Clockwise from top left:
i) the Muon Vision team on site, with the prototype sensor, prior to installation;
ii) the Muon Vision sensor inside the HDPE pipe during tests;
iii) the remote cabinet for managing power and data connection on site; and
iv) overview of the installation pipe, next to an already leached section of the heap, and prior to construction of the heap module measured

The data connection to and from the tool was realized via a standard optical fiber, which connected to a ruggedized field PC. The field PC also ran the data acquisition software and stored the data coming from the sensor. The field PC could be accessed over the internet utilizing a standard consumer-grade data plan. While muon radiography measurements are, by nature, continuous, data readout proceeded in buffered form and data taking was broken down in a series of successive runs, each with a fixed two hours' length. This approach helps minimizes any potential data loss. Data is transmitted in binary form, which further minimizes disk space requirement to a mere ~40 Mbytes/day. Binary files were then transferred remotely for offline processing of the data. Data and power connection were managed via a custom control cabinet that was also installed on site, as shown in Figure 2.

Results

As the construction of the leaching pad progressed, the sensor was initially parked at the entrance of its installation pipe, at an effective depth of just 0.4 m. During that time the tool could essentially only monitor the average surface rate of cosmic ray muons at the given location (32°27′S, 71°14′W). As soon as a leaching module was built on top of the installation pipe, the tool was advanced and the slant section of the heap scanned across different nominal heights, as shown in Figure 3.

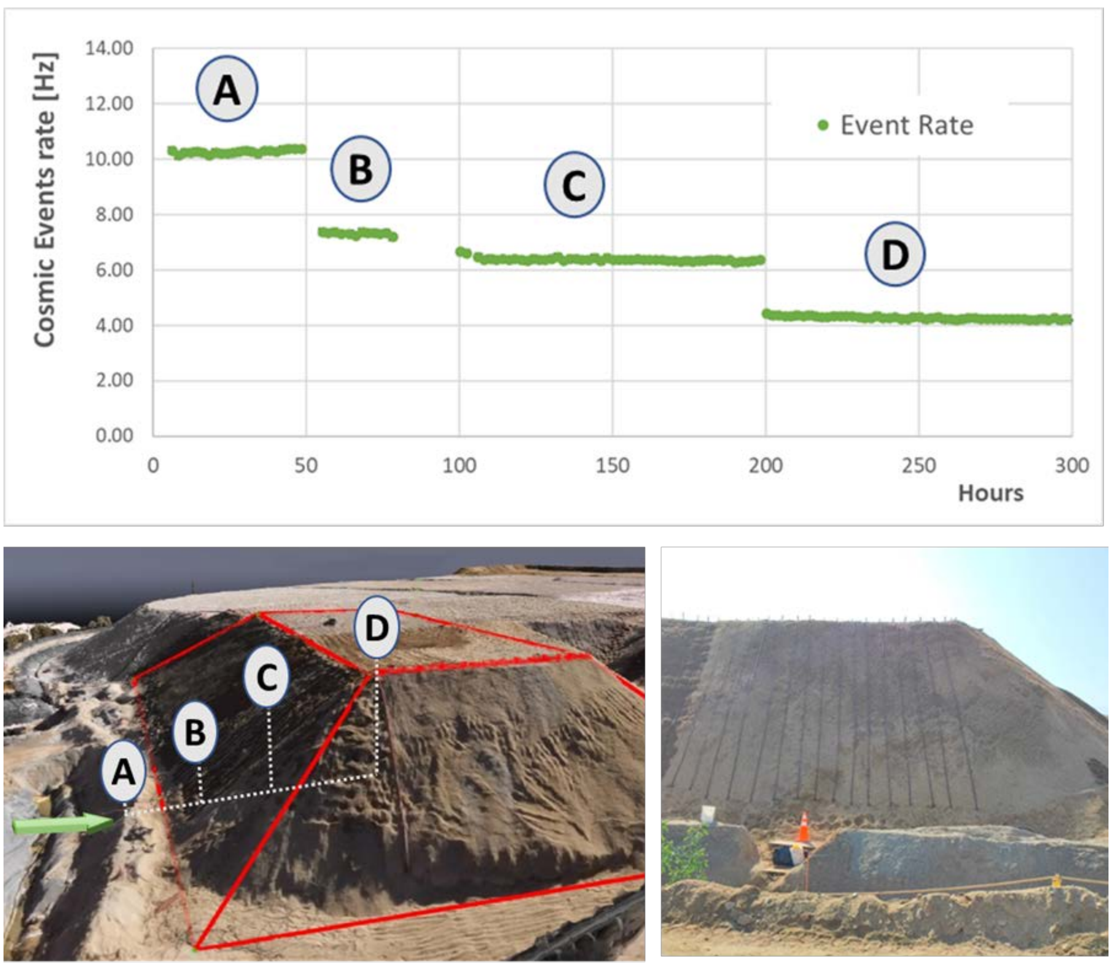

Figure 3: Top panel: measured muon count rate while scanning the slant section of the heap module. Bottom left: the green arrow indicates the entrance to the installation pipe and the red outline a simplified geometrical model that was later used in the data interpretation via Monte Carlo. Bottom right: side view of the heap and installation pipe (under the orange cone)

Cosmic ray muons are indeed individual physical particles arriving at any point on earth independently over a vast range of energies and azimuthal angles. Muons that have been generated at lower energies generally decay faster and may not even reach the surface of the earth. Higher energy muons on the other hand, will travel several kilometres through the earth's atmosphere and well into the subsurface. Generally, the muon flux is peaked along the vertical direction, which is also the direction of the shortest path to their source point that, conventionally, is taken to be 20 to 30 km above the earth's surface. Regardless of how and where muons are generated, and as with all other nuclear probes, their measured flux at the detector is related to the density of all materials between the source and the detector. The muon particle flux measured at a detector at a depth z and within a certain solid angle is formally given by:

$$I_\mu(z) = \iint_{E_0}^{\infty} \mathrm{I}_0\left(E_\mu,\ \theta_\mu\right) e^{-\alpha(E_\mu)\mathcal{O}}\, dE_\mu d\theta_\mu \qquad \text{(Equation 1)}$$

Where:

the integral runs over all possible muon arrival angles (θ_μ) and

energies (E_μ) above a minimum threshold ($E_\mu > E_0$).

Here $\mathrm{I}_0\left(E_\mu, \theta_\mu\right)$ is the intensity of the muon flux at surface and $\alpha\left(E_\mu\right)$ the muon absorption coefficient in matter, both of which very well-known from nuclear data tables, while $\mathcal{O}$ is the so-called integrated thickness or opacity, i.e., the line integral of the density of all materials traversed in the muon path to the detector:

$$\mathcal{O} = \int_{path} \rho(x, y, z)\, d\vec{l} \qquad \text{(Equation 2)}$$

In this sense a measurement under a leaching heap of the muon flux continuously samples the local density in the heap $\rho = \rho(x, y, z)$ over the full path-length L of each arriving muon with sub-atomic precision and simultaneously over all possible directions. The number of muons arriving at the detector (i.e., the count rate) is a strong function of the threshold energy E_0, which in turn is essentially a function of the depth of the sensor.

This general behaviour is clearly illustrated in Figure 3 (on previous page). The observed muon count rate closely tracks the heap profile. As the sensor is moved further in along the pipe, it finds more material above it, which means a higher threshold energy is required for muons to reach the detector. This results in an increased attenuation of the flux, and indeed the number of observed cosmic ray events drops from ~10 Hz at a nominal depth of 0.4 m (position A) all the way to ~4 Hz at a depth of 6.65 m (position D). Note that this data was taken as the heap was still being built and, in the plot, it has been staggered in time for clarity.

Right after our sensor reached position D, the operator started irrigating the heap material. This partially fills the porosity in the heap with the leaching fluid and thus changes the overall density of the heap. This is neatly contained in the basic volumetric equation for the bulk density of any porous material, which is commonly written as:

$$\rho_{bulk} = (1 - \Phi)\rho_{matrix} + \Phi\, S\, \rho_{fluid} \qquad \text{(Equation 3)}$$

where ρ_{matrix} is the matrix density of a rock formation with porosity Φ.

In a leaching heap, which is made of unconsolidated material, ρ_{matrix} is the (average) density of the crushed rock grains. When fluid, at a saturation S relative to the pore space, is added to the system then one can also write:

$$\rho_{bulk} = \rho_{dry} + \Phi S \rho_{fluid} \quad \text{(Equation 4)}$$

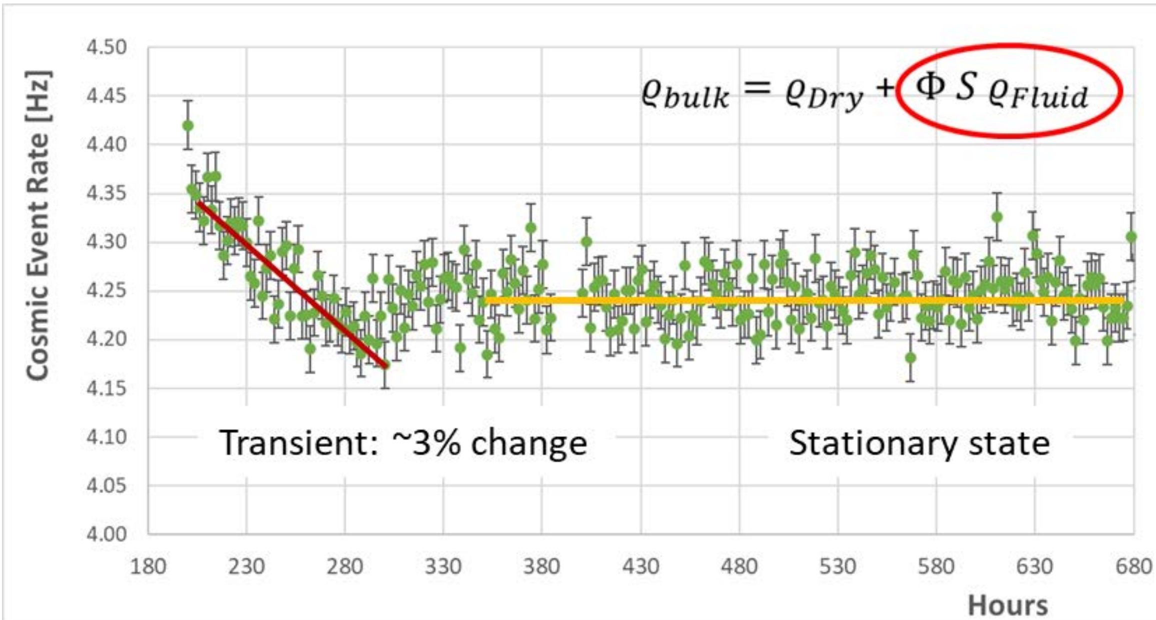

Figure 4: Observed rate of cosmic-ray muons with detector at position D. Irrigation starts at t = 180

Thus, given the material's dry density, its porosity and the fluid density (all of which are generally known or could be determined in-situ), a measurement of ρ_{bulk} provides a unique, nearly model independent determination of the total amount of fluid in the heap, i.e., the saturation S in Equation (3). A higher density, for a fixed heap height, also means a higher energy threshold for cosmic ray muons to reach the detector, and thus a reduction in the observed count rate. This is clearly illustrated in Figure 4, showing the data taken at position D.

Right after reaching the D position in Figure 3, which is also the moment heap irrigation was started, we observed a clear, highly statistically significant drop in the event rate from 4.35 to 4.2 Hz. This is shown in Figure 4. This ~3% change in the count rate implied that overall, the bulk density in the heap had changed by ~5%. This is well within expectations for a material with an initial density of ρ_{dry} =1.7 g/cc and a 36% porosity (ρ_{matrix} = 2.65g/cc, Φ = 0.36) saturated up to ~21% with a fluid. For simplicity we just assumed ρ_{fluid} = 1.0 g/cc. A higher fluid density would have simply resulted in a lower estimation of the saturation.

It is important to emphasize that neither the chemical composition of the heap nor the fluid matters here. Also, having started with (nominal) dry parameters, what we present is the total fluid content, with no consideration for the fact that the material was pre-wet in an agglomeration stage up to a nominal 11% saturation. If one starts from the density of the agglomerated material (i.e., $\rho_{dry} = \rho_{agglomerate}$), then our method would determine only the amount of fluid added in the heap leaching stage. Ultimately, proper values for ρ_{dry} and other key parameters can be determined empirically with a proper sampling campaign, as well as in-situ by characterizing the heap prior to irrigation.

Another important and also highly statistically significant observation that can be made from the data in Figure 4, is that after an initial ~100 hours of transient behaviour in the 6.65 m tall heap, the muon count rate reaches a stationary state, which was then maintained over several weeks. During this stationary state the density in the material does not change any more, and thus we conclude that the fluid content in the heap has also found its equilibrium value.

Note that the stationary state points to a fluid content that is just a bit lower than the maximum fluid content reached at the end of the transient phase, even though the flow rate was not changed by the operator. This indicates that, possibly, preferential flow channels were created in the initial transient phase, through which the fluid could quickly escape, and therefore that a fraction of the fluid never really contributes to the leaching process. We believe this should be accounted for in the overall balance and analysis of leaching performance. Also, we believe that our technology is uniquely posed to diagnose and potentially help remediate this effect by, for example, optimizing the stacking and agglomeration process in view of the actual hydraulic performance of the heap.

The data in Figures 3 and 4 also indicates that although the muon flux at surface is expected to have variations of 5 to 10% over long periods of time, it can be considered constant on time scales of a few weeks, which in most cases are sufficient for a heap radiography. Variations of the muon flux are mostly associated with small seasonal changes in the temperature and pressure density across the full 30 km length of the earth's atmospheric column (which slightly changes its overall density), as well as to changes in the earth's magnetosphere due to effects from the 11-year solar sunspot cycle. Both of these effects are dependent on the muon energy and impact a muon detector differently according to its depth which, as discussed, determines the muon energy threshold. However, we note that seasonal changes in the muon flux have different signs at different ends of the spectrum, and indeed expected to have a zero-crossing for depths between 5 to 50 m. This is well within the range of our application, which we think is particularly well suited for muon radiography investigations compared to surface or deeper measurements.

The data presented so far has essentially been count rate data in the aggregate, with no position information. One attractive feature of muon radiography is the potential to generate 2-D or 3-D density maps. With data from a single location, as in our case, one can only generate maps analogous to conventional 2-D radiographic X-ray images. This requires segmentation of the data along different muon directions. Since each pixel in the image will have fewer counts the total aggregate measurement, the statistical accuracy, and thus the resolving power for density differences, will be lower. Although the resulting image is 2-D, the heap is sampled along its full thickness, and as such even a 2-D projection contains bulk density data averaged in a 3-D pyramidal voxel, as shown in Figure 1. A true 3-D density map requires similar data segmentation but on multiple planes, e.g., parallel to the heap surface. Depending on the inversion algorithm this does not necessarily introduce additional statistical penalties. However, it is still true that for any true 3-D inversion, the volume under observation must be viewed from multiple view angles, and this is best done when multiple sensors are installed or moved to different locations (Guardincerri et al., 2017).

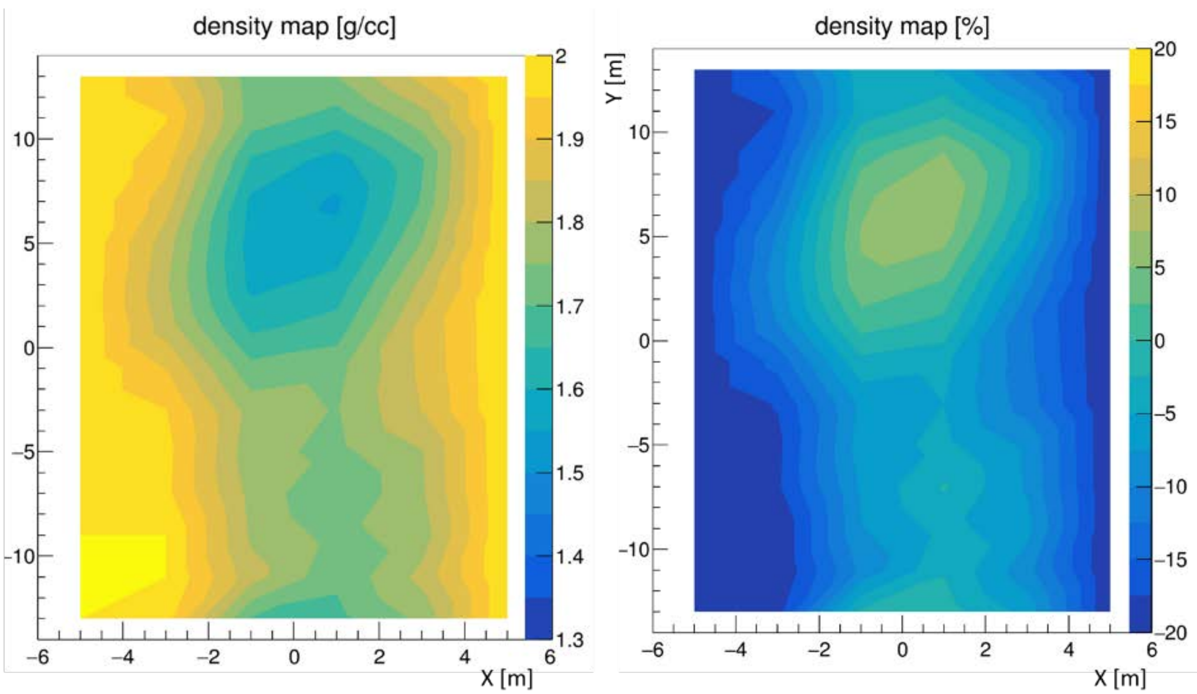

Figure 5: Absolute (left) and relative (right) density maps projected on the surface of the heap. See text for more explanation

Our first density map is shown in Figure 5. This is a 2-D map (in the sense given above) corresponding to data collected over a period of two weeks. To arrive at the density value, we compared the measured count rate with the expected count rate from simulations, assuming a nominal muon flux. The simulation was based on a well-known, highly sophisticated, and very high-fidelity open-source toolkit for particle transport from the CERN particle physics laboratory in Switzerland called Geant4 (Agostinelli et al., 2003). The same toolkit is also used to determine treatment dose in radiotherapy applications. Geant4 takes care of the generation and travel of muons from the sky source, through the heap and to the detector, for a nominal flux intensity. The simulation also included all the details of the detector and its response. For simplicity, we resorted to using a simple trapezoidal model of the heap (shown in Figure 6), which given the irregular shape of the heap, could not reproduce all the features in our data. This essentially limited our coverage, particularly in the region in front of the tool, where a big gap was present in the heap during data taking, which skewed the comparison with the data. All together our coverage was ± 60° in the longitudinal direction (i.e., along the installation pipe) and only ± 45° in the transverse direction (due to unexpected issues with the prototype after it was installed).

In Figure 5 we present both a relative (in %) and an absolute density map (in g/cc). The latter was obtained by applying a normalization factor that takes care of detector efficiencies and the actual value of the muon flux intensity in-situ. This normalization factor is indeed model dependent. In the future we plan to eliminate this dependency by bringing on site a second “witness” detector that will be placed outside of the heap and devoted to measuring the muon flux in-situ, rather than density changes in the heap. This additional measurement will provide the desired absolute normalization.

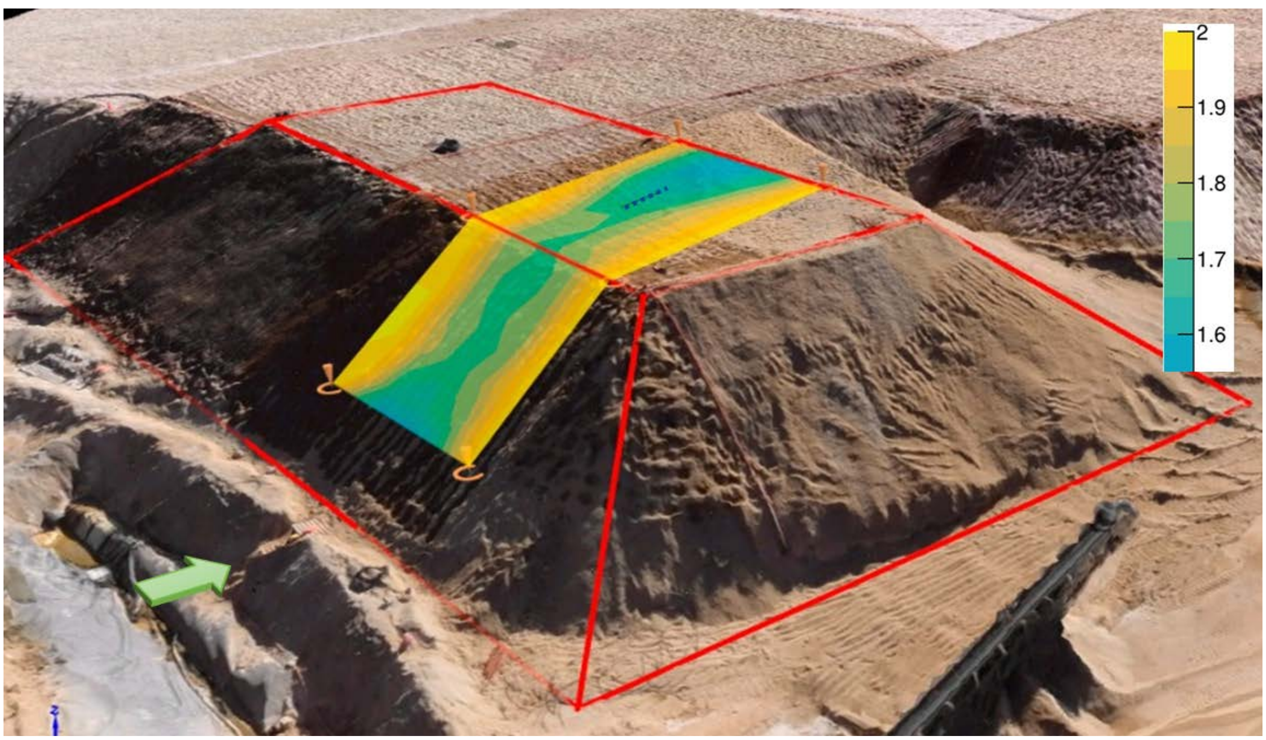

Figure 6: 3-D rendering of the heap based on measurements off a drone with our density map overlayed. The red lines are the outline of our geometrical model (a regular trapezoid) discussed in the text. The sensor position (under the heap) is indicated by the dashed line on top of the heap

In contrast, the relative density data in Figure 5 is free of this error and shows that the average bulk density in the heap was mostly within ± 5%. This is still a preliminary result as we are still in the process of calibrating the efficiency of the detector for angular reconstruction, and we also need to account for the effect due to different heap heights at different locations. Indeed, our test heap was built with an excavator and does not have a flat top. Varying heap heights or sloping heap surfaces can be measured accurately with a drone, as was done here, and results from such scans rather straightforwardly incorporated in our inversion model and analysis.

Future improvements will also include a better characterization of the orientation of the installation pipe (here assumed to be straight) and of the tool position inside the pipe (here nominally taken to be 15 m). Finally, the data in Figure 5 was smoothed with a kernel algorithm similar to those used in image rasterization. Notwithstanding the present limitation, our smoothed data are consistent with a small density anomaly at X=0, Y=+5 in Figure 5. While we believe this is likely to be a true effect, we cannot confirm it until we improve on our analysis.

Conclusions

We have presented preliminary results on the first radiographic analysis of an active leaching heap. This was done by analyzing cosmic ray muons tracks arriving at a small, remotely operated prototype sensor (0.2 m diameter) placed under the heap. The measured cosmic ray flux was well within expectations and clearly showed an accurate correlation with the amount of fluid added to the heap. Both absolute and relative density maps covering an area ~$10 \times 20 m^2$ above the detector were obtained. Our preliminary results open up the possibility of utilizing cosmic ray muons as an effective tool to quantitively determine fluid saturation, a key parameter for the performance and safety of all leaching heaps. There are potentially many benefits to be had with such an approach. These include:

- Increased metal recoveries and reduced lixiviant consumption, via a data-driven optimization of the placement of irrigation lines and tailored irrigation rates.
- Improved NPV determination, via the localization and quantification of by-passed ore, leading to improved financial visibility and informed decision making on potential reprocessing decisions.
- Reduced GHG and water footprint, per tonne of metal produced.
- Increased safety, by reducing the need for inspection personnel on the top of the heap and by reducing the uncertainty in the geotechnical stability model.
- Mine operational improvements via advanced analytics and feedback loops correlating operational parameters (e.g., agglomerator, ore composition) with actual percolation performance in the heap.
- Near real-time continuous monitoring and validation of operational setpoints, and the prompt identification of trends and non-standard conditions.
- Support for the implementation of realistic digital twins and 3-D heap models.

- Improved ore removal at the end of the cycle based on actual soil moisture content (e.g., avoids trapping of equipment or sticky ore that is difficult to remove from conveyor belts).

While this was, we believe, its first application to a leaching heap, muon radiography is nonetheless a well-established geophysical technique and a mature technology. In our view, what remains to be determined is not the validity of measurement per se, but rather how embedding muon density maps into operational leaching workflows will lead to achieving some or all of the above mentioned potential benefits. This knowledge will only come through new deployments and service offerings in collaboration with the leaching industry. Muon Vision is eagerly looking forward to its next opportunities.

Acknowledgements

Muon Vision would like to acknowledge support from NSF's SBIR Phase I program (award number 2026042) in the USA and CORFO (grant 19CVS-124170) in Chile. Muon Vision also gladly acknowledges help from Dr. DuPlessis for advice and proofreading, and continued support from the staff at the mine site.

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