

Experimental study of multiple-orientation muon tomography with image optimization in sparse data environments

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Due to the high penetrating power of cosmic-ray muons, they can be used to probe very thick and dense objects. As muons are charged particles, they can be tracked by ionization detectors, determining the position and direction of the muons. With detectors on either side of an object to measure particle direction change, scattering information within the object can be found. This can be used to produce a scattering-intensity image within the object related to density and atomic number. Such imaging is typically performed with a single detector-object orientation, taking advantage of the more intense downward flux of muons, producing planar imaging with some depth-of-field information in the third dimension. Several simulation studies were published with multiorientation tomography, which can form a three-dimensional representation faster than a single-orientation view. In this study, experimental muon-scatter-based tomography was performed using a concrete filled steel drum with several different metal wedges inside, with the drum between detector planes. Data were collected from different detector-object orientations by rotating the steel drum. The data collected from each orientation were combined using two different tomographic methods. A traditional inverse Radon transform approach used for computed tomography and a combination of multiple depth-of-field reconstructions were applied to the data. As cosmic-ray muon flux imaging is rate limited, the imaging techniques were compared for sparse data. Using the combined depth-of-field reconstruction technique, fewer detector-object orientations were needed to reconstruct images that could be used to differentiate the metal wedges.

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I. INTRODUCTION

Cosmic-ray muons provide a very highly penetrating source of radiation that can be used for imaging large and dense objects. Ionization detectors can be used to determine the position and direction of each charged muon particle. Small angle scattering, and occasionally attenuation, measurements give information on the materials and thicknesses that the muons interact with. Muons have been used for overburden imaging from boreholes [1,2], pyramid imaging [3,4], and even volcano imaging [5,6] by comparing flux rates at different angles due to attenuation.

With detectors placed on either side of an object, particle direction changes can be used to extract scattering information within an object. This can be used to produce a

scattering intensity image within the object, where intensity differences are caused by density and atomic number differences. Studies were published by Los Alamos National Laboratory's (LANL) Threat Reduction Team over the evaluation of cosmic-ray muons for this scatter imaging, enabling more sensitive imaging [7–9], beginning a flurry of activity in applications of the technology. Such imaging is typically performed with a single detector-object orientation, taking advantage of the higher downward flux of cosmic-ray muons created in the upper atmosphere. These have been used in three-dimensional imaging with some depth-of-field information in the vertical direction using the small range of incident zenith angles, producing single-orientation tomography. Muon-based single-orientation tomography has been applied to cargo inspection [10–12], high atomic number material detection [13], and even reactor imaging [14,15].

Proof-of-concept experiments on large objects were performed. The LANL Threat Reduction Team applied the scatter tomography technique to image inside a Westinghouse MC-10 spent nuclear fuel (SNF) storage cask in 2017 [16,17]. With the large cask size, 2.7-m outer diameter and 4.8-m height [16,18], the detector panels were on

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opposite sides of the cask with a large spacing between them. There was a 1.2-m vertical offset between the detectors, which were separated by a distance of 2.7 m. This allowed imaging from several different detector-object orientations with the same incident muon flux, multiorientation tomography. However, the large zenith angle limited the observed muon flux to nearly horizontal muons that passed through both detectors, resulting in very low statistics [17]. With only approximately 164 000 muons recorded over 200 h, only a one-dimensional reconstruction could be created. This one-dimensional reconstruction still proved useful in determining whether or not spent fuel bundles had been removed from the cask but limited the ability to determine the exact location of missing spent fuel bundles. With the ultimate goal to identify and verify the location of all spent fuel in a cask, it is pivotal to be able to perform this multidimensional imaging with sparse data to avoid severely long measurement times. This study was motivated by improving tomographic imaging techniques with such sparse data.

Several groups performed simulations on muon tomography of objects from multiple detector-object orientations, up to a full 360° around the object, including used fuel storage casks [19–21]. These produced very clear tomographic images, but they all used many different detector-object orientations with very high muon statistics, and perfect detectors.

Our goal in this experimental work was to use multiple muon-scatter datasets, from different detector-object orientations, to create tomographic images that enable faster, useable nuclear fuel cask measurements in the field. This is an experimental study of the muon tomography of objects from multiple detector-object orientations. Longer, higher statistics measurements are much easier to perform in a controlled environment, so laboratory-sited measurements were performed by the LANL authors, in 2017. A steel drum was filled with concrete, with metal wedges of different sizes and compositions placed inside, as described in Sec. III A. The steel drum was placed between the muon detector planes and imaged with different detector-object orientations by rotating the steel drum for different datasets. The recent image reconstruction of the steel drum and metal wedges forms the basis of the analysis performed by the UNM authors. These datasets were used to compare the performance of backprojection tomography and an alternative technique, combined depth-of-field imaging. Data quality was varied by reducing the number of orientations and the number of muons used to analyze the effects of data restrictions on each technique.

II. MUON INTERACTIONS

Muons are created in the upper atmosphere by high-energy charged particles interacting with air. The muon shower intensity approximately follows a cosine-squared

function with the zenith angle [22]. Muons at larger zenith angles also travel through greater lengths of air from the interaction point to the detector, preferentially reducing lower-energy muons and changing the spectrum as a function of angle [23].

When passing through matter, muons experience multiple Coulomb interactions, resulting in many scatters, and it is the total scattering angle between detectors that we use for analysis. For a single energy muon, total scatter closely follows a Gaussian distribution with a mean of zero radians. The width of the scatter distribution in radians is given by [7]

$$\sigma = \frac{13.6 \text{ MeV}}{pc} \frac{z}{\beta} \sqrt{\frac{X}{X_0} \left[1 + 0.088 \ln \left(\frac{Xz^2}{X_0\beta^2} \right) \right]}. \quad (1)$$

This width decreases at higher energies following the muon momentum (p). In this equation, z is the charge of the muon, $+1$ or -1 . Cosmic-ray muons have a velocity close to $v=c$, the speed of light, resulting in $\beta = v/c \sim 1$, so $|z|/\beta \sim 1$ for cosmic-ray muons. X is the mass thickness of the scattering material – the length $L \times$ the density ρ . The radiation length, X_0 , is material dependent. The constant terms, 13.6 MeV/c and 0.088, are correction factors provided to adjust the Gaussian approximation goodness of fit.

Tsai [24] gives a functional dependence of X_0 going as $A/(Z(Z+1))$, with minor modifications for screening, where A is the mass number and Z is the atomic number of the material. With X in terms of mass thickness $L\rho$, X/X_0 goes as $L\rho(Z(Z+1))/A$. It is noted that Z/A varies little over a wide range of elements [25], giving X/X_0 an $L\rho(Z+1)$ functionality.

The muons interact with all materials along their paths, so the measured scatter is an integral of the scattering along the entire path. In our data, the muons that pass through a metal wedge also pass through the surrounding concrete, so the scatters in a particular material cannot be individually isolated.

For distributions of energies, the scatter distribution width is a sum of the distributions from different energies, and the trend remains: scattering angles are higher for higher atomic numbers and denser materials. Since the test object was rotated in relation to the imaging system, rather than moving the detectors, the muon spectrum remained constant throughout the entire measurement campaign, and the specific energies did not have to be accounted for when comparing observed scattering.

III. MULTIVIEW MUON TOMOGRAPHY STUDY

A. Experiment

Muon-track data were collected by the LANL authors in 2017, while analysis was performed by the UNM authors beginning in 2022. These data were unpublished, and some

of the experimental details were not preserved. The delay between data collection and analysis also prevented feedback into the experiment for image improvement, such as recalibration of the detector gas tube response.

The experiment measured muon deflection through a single-walled steel drum filled with concrete using Quikrete concrete mix, with tungsten and brass wedges within the steel drum. LANL authors filled the steel drum and performed subsequent measurements. The steel drum had a 0.9-mm-thick steel wall, and the concrete filled volume was approximately 42 cm long and 34 cm in diameter, consistent with a 10-gallon steel drum. The metal wedges were triangular, each with uniform thickness. The brass wedge had a 9-cm base, a height of 7 cm, and a thickness of 5 cm. The tungsten wedge had a 15-cm base, a height of 10 cm, and a thickness of 4 cm. The brass and tungsten wedges were coplanar and centered 10 cm from one end. The wedge sizes and placements were determined by comparing experimental and simulated data reconstruction images and iterating the simulations until a good match was found. As voxel sizes are 1 cm, all wedge measurements and positions have a best uncertainty of ± 0.5 cm. A schematic of the steel-drum interior with the brass and tungsten wedges is presented in Fig. 1 (bottom). For comparison, the image made with the simulated data is presented later in Fig. 6 near the images from the measured data. Defining the x direction as the direction along the steel-drum symmetry axis, all wedges had their short edges in the x direction, with the wider sides seen in the tomographic views. As muon scatter is atomic number (Z) and density dependent, this range of high- Z wedges with varying densities was chosen to test the ability to differentiate these objects from the low- Z and low-density concrete surrounding the wedges. Both the Z and density are noted here for tungsten ($Z = 74$, $\rho = 19.3$ g/cm³), brass ($Z = 29$ and 30 , $\rho = 8.5$ g/cm³), Quikrete concrete (mix, with principal components $Z = 8$ and 14 , $\rho = 2.3$ g/cm³), and air ($Z = 7$ and 8 , $\rho = 0.96$ mg/cm³ at LANL).

The detector array used in this experiment, the Mini Muon Tracker (MMT), Fig. 1(top), is described in Refs. [16,17,19,27]. The MMT was designed by LANL and constructed in collaboration with Decision Sciences International Corporation. As the measurements were performed by the LANL collaborators several years before analysis by the UNM collaborators, we do not have information on the size of the steel-drum cradle and positioning, so we show the extracted steel-drum schematic separate from the detector.

The tracking system consists of two modules, each with 12 layers of sealed gas-ionization tubes. Tubes contain 47.5% Ar, 42.5% CF₄, 7.5% C₂H₆, and 2.5% He, all % by weight, at 1 atm. They measure 5 cm in diameter with a central anode wire held at +2550 V relative to the grounded Al tube wall. Muon interactions within each

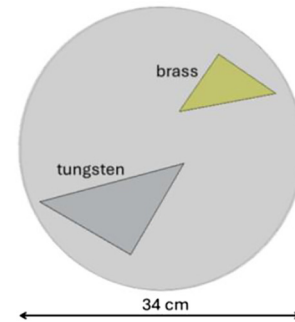


FIG. 1. (Top) MMT detectors used for measurements, from Ref. [26], (bottom) schematic of the steel-drum interior with tungsten and brass wedges surrounded by concrete.

tube will result in ionization of the gas and subsequent acceleration of the electrons to the anode wire, resulting in a voltage pulse. Each plane consists of parallel tubes, with the layers stacked in perpendicular orientations to gather both x and y information on muon tracks. Interactions in several detector layers were used to determine the trajectory of each muon. Each of the modules was 120 cm $\times$ 120 cm in area by 60 cm thick. Two detector modules were used to total 24 layers, with one placed above the other to use the high near-vertical muon fluence rates. A 60-cm spacing between the detector near faces was used, with the drum placed between the detectors. The detectors were configured to have an active imaging volume of $100 \times 100 \times 60$ cm³ [26].

The read-out electronics, designed by Decision Sciences, utilized voltage pulses from the tubes to determine muon position and reconstruct trajectories through each module. Pulse shapes in each tube were used in the reconstruction software to determine the muon-track position at the millimeter level. For muon signals firing in several tubes, in both modules, within the 100-ns coincidence window, the muon position and angle in the top and bottom modules were reconstructed and recorded, along with a time stamp. The on-board FPGAs, with Decision Sciences

proprietary programming, handled all pulse processing, and only the positions and angles in each array could be accessed by the user. The 13-column dataset comprised a time stamp; x , y , and z positions for each module; and the cosine of the angles from each axis for each module. The x and y axes were in the horizontal plane, with x along the drum symmetry axis, and the z axis was vertical.

The scattering angle, θ_s , extracted in this work was calculated using the overall change in the muon trajectory through the upper (1) and lower (2) detector arrays, $\vec{v}_1$ and $\vec{v}_2$, respectively, by

$$\cos \theta_s = \frac{\vec{v}_1 \cdot \vec{v}_2}{|\vec{v}_1| \cdot |\vec{v}_2|}. \quad (2)$$

The components of each vector along the x , y , and z axes are given by the cosine values in the dataset. With no deflection, the vectors would be parallel and give $\cos \theta_s = 1$, or $\theta_s = 0$. Small deflections in the muon trajectory would correspond to scattering angle values, θ_s , close to 0 mrad.

Each scatter angle was used along each corresponding muon track to populate the image space using two different imaging methods. Since scatters are typically small [muons through the strongest scatterer, tungsten, experienced a 55 milliradian (3°) average scatter] and we wanted to compare the imaging methods directly without complications from spline fitting or point of closest approach scatter position determination from incoming and outgoing vectors, a simple straight-line projection from the top detector was used for the muon track through the imaging space.

The steel drum was held in an aluminum cradle that allowed rotation and was manually rotated in 15° ($\pi/12$ radian) steps to better than 1° . A new dataset was recorded for each orientation. This process was repeated for a full 360° rotation, resulting in 24 total measurement datasets around the drum. The chosen 15° steps provide an abundance of detector-object views that allow for incremental reductions in the amount of data utilized for reconstructions. We refer to drum-detector orientations in degrees for conceptual clarity, but muon-scattering calculations were performed in radians.

The average recorded muon event rate was 33 muons/sec, and most orientations were measured for just under 1 day. This is lower than the rate of muons passing through the active region since the array was set to veto background gammas and neutrons for prior spent fuel cask measurements by requiring neighboring tubes to fire in coincidence. This is in addition to requiring tracks to be established in both the upper and lower modules within the 100-ns coincidence window by the tubes that did fire. The minimum number of recorded muon tracks was 2.4 million for one of the shorter runs over 20 h, and the maximum was 5 million tracks over 2 days at a single orientation to

allow for better single-orientation analysis, which was designated as the 0° orientation. For consistency and to not overemphasize any single orientation, the first 2.4 million recorded muon tracks in each dataset were used from each orientation when performing multiple-orientation imaging.

A key feature of this approach to imaging is that, since the steel drum was rotated but the detector did not move, every detector-object orientation has the same muon fluence rate and energy spectrum. This is actually similar to fuel cask data using detectors to the sides of the cask [16,28], where the different views are from different azimuthal angles though the zenith angle of acceptance did not change. It is noted again that the muon energy spectrum and intensity change with zenith angle, so this consistency in measurements allows different orientations to be compared directly. As such, a traditional tomographic approach can be studied, as in prior simulation studies [19,21]. Simulations in the presented work used a realistic energy spectrum and angular dependence for direct comparison.

Beyond that, in muon tomographic imaging using a single orientation, a depth-of-field image may be constructed with the three-dimensional information from a set of muon trajectories. The multiple-orientation approach with no preferred orientation allows an alternative method of combining depth-of-field information with equal weight from the different orientations, explained below. Both traditional multiple-orientation backprojection tomography and the combined depth-of-field imaging were examined.

B. Simulations

Muon-scattering simulations were performed using Geant4 [29,30] version 11.2. The EcoMug cosmic muon generator [31] was used to generate incident source muons using the natural cosmic-ray muon energy distribution and angular dependence. As the experimental measurements were performed in Los Alamos, New Mexico, latitude and altitude settings were chosen accordingly. The detectors were modeled as $1.2 \times 1.2 \text{ m}^2$ planes with 60-cm separation. The muon source was distributed uniformly over the top plane. The drum, concrete, air, and wedges were modeled as described in the experimental section using Geant4 material definitions. The simulated detectors had perfect efficiency and angular resolution. The goal of these simulations was not to match experimental results but rather to evaluate reconstruction performance under ideal conditions.

For muons passing through both detector planes, the positions and trajectories through each detector were recorded to match the 13-column position and angle data format of the Decision Sciences software output. Image-reconstruction analysis was performed exactly as with the experimental data.

To determine wedge sizes, simulations were repeated, and the wedge sizes were modified until image reconstructions from simulation matched experimental reconstructions. For comparison with experiment, 24 orientations were used at 15-degree steps, with the first 10 million tracked muons (tracked in both top and bottom detectors) used in image reconstructions.

IV. MULTIORIENTATION ANALYSIS METHODS

A. Sinogram and inverse Radon transform reconstruction

Following methods from medical imaging, the first technique utilized for tomographic reconstruction involved the population of a sinogram and subsequent backprojection via inverse Radon transform [32,33]. This follows the backprojection method applied in previous muon-tomography simulation studies [20].

The centerline of the drum was used for the image-reconstruction rotational axis. Using the muon trajectory and position recorded from the top detector, the distance of the closest approach to the centerline, r , was found, and the angle between the projected trajectory and the normal line that r lies on, θ , was extracted, Fig. 2. Both r and θ were used to determine the sinogram bin in which the muon-scattering angle was tallied. After all muons were projected and tallied, the average muon-scattering angle in each r , θ position of the sinogram was found. A unique sinogram was produced for each 1-cm step in x , along the drum symmetry axis, with θ in 1° steps. As mentioned, for a more direct comparison between image-reconstruction techniques, a straight-line trajectory from the top detector was used.

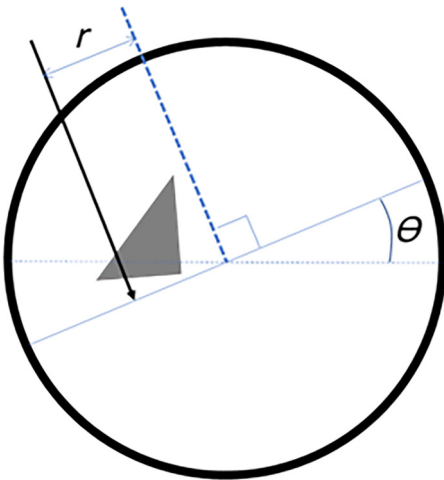


FIG. 2. Sinogram population diagram demonstrating the distance of the closest approach of muon to drum centerline, r , and angle of the line normal to the muon vector, θ , with a wedge and the drum boundary.

Populated sinograms were backprojected using the iradon function in MATLAB [34] to construct the image, populating 1 cm^3 voxels in the imaging space. Note that the default filter, the Ram-Lak filter, introduces a $2/\pi$ term. A $\pi/2$ correction is included elsewhere in the iradon function, expecting the Ram-Lak filter to be used. We used no filtering, so we removed this inappropriate correction for the backprojection analysis presented here.

B. Combined depth-of-field reconstruction

In x-ray-based tomography based on photon attenuation, the initial x rays travel in a straight line and the spatial intensity on the detector may be traced back to a single-source point through the object to determine the line along which attenuation occurred, with several orientations used to find the position of attenuation within the object. In muon-scatter imaging, even from a single detector-object orientation, there is a range of source points, and the trajectory of the muon is determined, which is a significant difference that aids image reconstruction.

As muon trajectories are followed in the image space, the paths with high scatter converge, which for muon imaging corresponds with the position of denser materials and/or higher atomic numbers. By tallying the scattering angle of each muon along its path through a voxelated imaging volume, a three-dimensional image of the scattering centers was produced. The resulting image, from a single detector-object orientation, provides depth information. A diagram of this tally structure is shown in Fig. 3. Black tracks represent muons that slightly scatter via interactions only with air. Orange tracks represent muons that only interact with the steel drum and concrete within, resulting in larger scattering angles than muons that only interact with air. Red tracks represent muons that experience relatively large scattering events during interactions with a high- Z and density wedge. These red tracks converge on the wedge. Due to the small angular spread in muon trajectories, there is depth information (z), along with the lateral information (x , y) of projection imaging. To keep data consistent between the imaging methods, a straight trajectory from the top detector was used for reconstruction.

In our implementation of depth-of-field image reconstruction, the three-dimensional imaging volume consisted of 1 cm^3 voxels. The scattering angle for each muon passing through a voxel was tallied for that voxel and weighted by the path length through the voxel. As scattering is an integral of muon interactions in the material over the full path of travel, muons with a longer path within a voxel will sample the material in the voxel more than muons that pass through a smaller section of the voxel. This enabled calculation of a path-length-weighted average-scattering angle in each voxel, in units of milliradians.

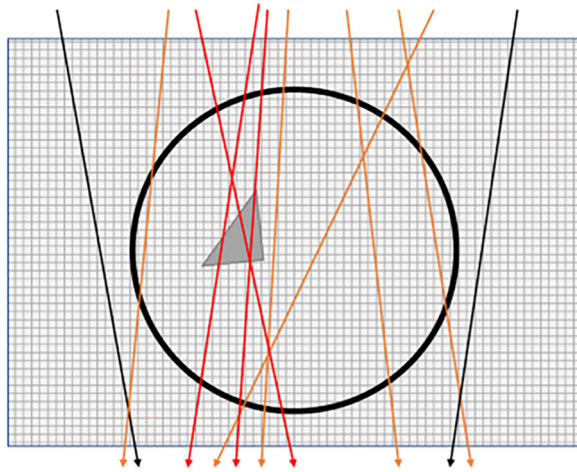


FIG. 3. Muon tracks projected from the top detector, with red having a high scattering angle, orange medium, and black low. The high scatter muon paths converge on a metal wedge, producing depth information from the muon paths. The scattering angle of each muon that passes through any voxel was recorded, and a path-length-weighted average was tallied for each voxel. We used straight tracks from the top detector to keep data consistent between imaging techniques.

The range of muon angles was limited to those that passed through both detectors, which ignored more horizontal muons and thus reduced image resolution along the depth (z) direction between detectors when using a single detector-object orientation. As the steel drum was rotated, the range of observed muon angles relative to the steel drum increased and improved position resolution along what was previously the z axis of the steel drum. As the detector-object orientation is relative, the steel-drum position was fixed in the imaging voxel space in the analysis, and the trajectories of the muons were rotated around the steel drum accordingly. This allowed for a single voxelated tally volume to be populated where the muon vectors were mapped onto the fixed imaging space voxel grid.

The depth-of-field images acquired at several different detector-object orientations were combined [35] and expected to converge to a three-dimensional image more quickly than traditional tomography, which is key with sparse data scenarios.

The essential differences between imaging using the backprojection and combined depth-of-field imaging techniques may be summarized. For backprojection, prior to the inverse Radon transform, the average scattering angle was found for each projection axis position r and axis angle θ , and then projected to map onto the volume voxels. For depth-of-field imaging, this was averaged per voxel directly in the imaging volume. In reconstructions, these differences manifested as differences in the observed image intensities and expected image streaking for backprojection with sparse data.

V. MULTIPLE-ORIENTATION IMAGING RESULTS AND DISCUSSION

A. Images

Three-dimensional images based on the combined depth-of-field technique using all 24 available detector-object orientations are shown in Fig. 4. Image intensity directly relates to the average scattering angle within each voxel. In Fig. 4(a), a minimum average scatter intensity threshold of 42 milliradians was selected by visual inspection to omit voxels outside of the steel drum that consist of air. In Fig. 4(b), a minimum threshold of 47.5 milliradians was selected by visual inspection to highlight the metal wedges. A slight deformation is seen in the side of the steel-drum image due to muon shadowing effects from the high- Z , high-density tungsten wedge. Expected average scattering values for different materials are discussed below.

Figure 5 shows a coronal slice, perpendicular to the steel-drum symmetry axis along a single value of x through the tungsten and brass wedges, which are coplanar. This

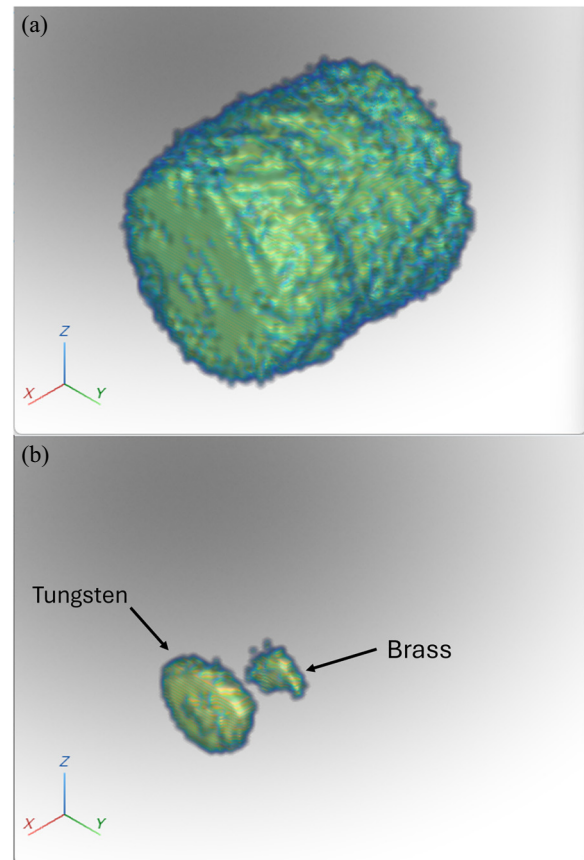


FIG. 4. (a) 3D reconstruction of the steel-drum exterior with a voxel threshold at 42 mrad and (b) of metal wedges with a voxel threshold at 47.5 mrad. The left wedge is tungsten, and the right wedge is brass.

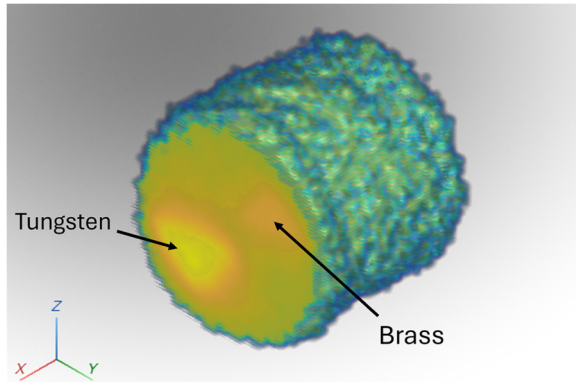


FIG. 5. 3D reconstruction of the steel drum with coronal slice along a single x through tungsten and brass wedges.

two-dimensional slice was used for the tungsten- and brass-imaging analysis in this work. There is also a lead wedge in the steel drum at a different x position. Discussion of this wedge is omitted for brevity but can be found in the thesis work of author J. Valencia [36]. As mentioned, the muon scatters along the entire path, so concrete scattering includes effects from air and the thin steel-drum wall, and the wedges include these along with the wedge materials.

Tomographic images that correspond to the coronal slice in Fig. 5 were created using combined depth-of-field and backprojection for image-quality comparisons, and the image from simulated data using combined depth of field is presented in Fig. 6. As a best-case simulation reconstruction scenario, 10 million muons were utilized for each simulated detector-object view. In the best-case experimental reconstruction scenario based on available

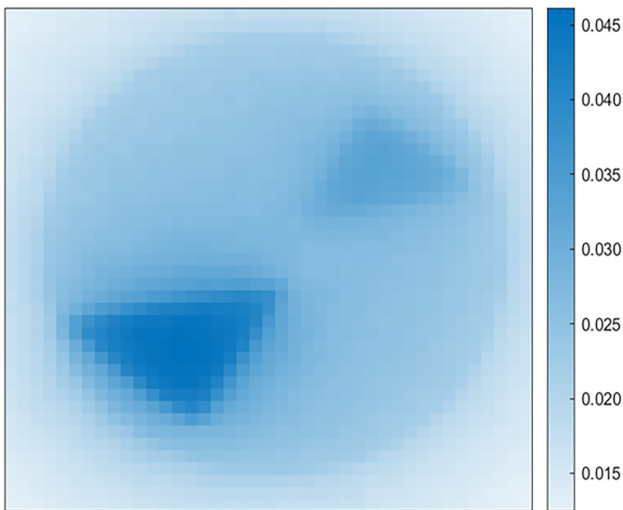


FIG. 6. Simulation with combined depth of field with 24 orientation views and 10 million simulated muons per orientation. Intensity is the average scatter angle (rad) in each voxel.

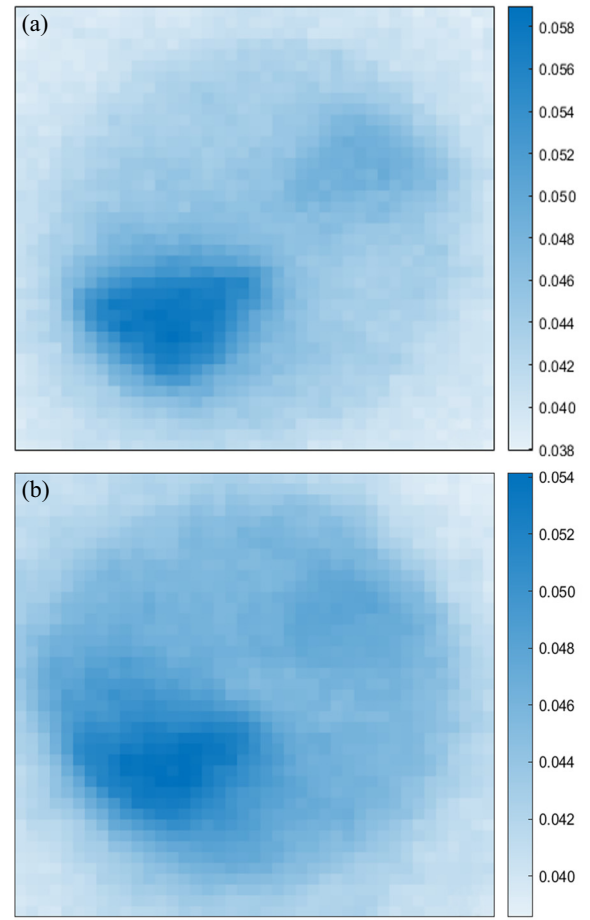


FIG. 7. Image reconstructions using combined depth of field (a) and backprojection (b) using 24 orientation views and 2.4 million muons per orientation. Intensity is the average scatter angle (rad) in each voxel.

data, 2.4 million muons were utilized for each experimental detector-object view, with 15° steps through 360° for 24 views, Fig. 7. In both tomographic images, the round concrete can be seen, the tungsten wedge is very clear in the bottom left, and the brass wedge can also be seen in the upper right. The outer bounds of the concrete can be discerned more clearly from the surrounding air for the backprojection image. However, the tungsten and brass wedges are more greatly contrasted from the surrounding concrete in the combined depth-of-field reconstruction. For examining metals, the combined depth-of-field results are more favorable. Image-quality metrics were found and are presented following the comparison images.

To study the reconstruction performance in less ideal scenarios with sparse data, additional reconstructions were performed on a small subset of the data.

The reconstructions in Fig. 8 were performed with two different steel-drum rotation datasets at 0° and 90° orientations and only 1 million muons per orientation, a total of 2 million muons vs 57.6 million for Fig. 7. In the

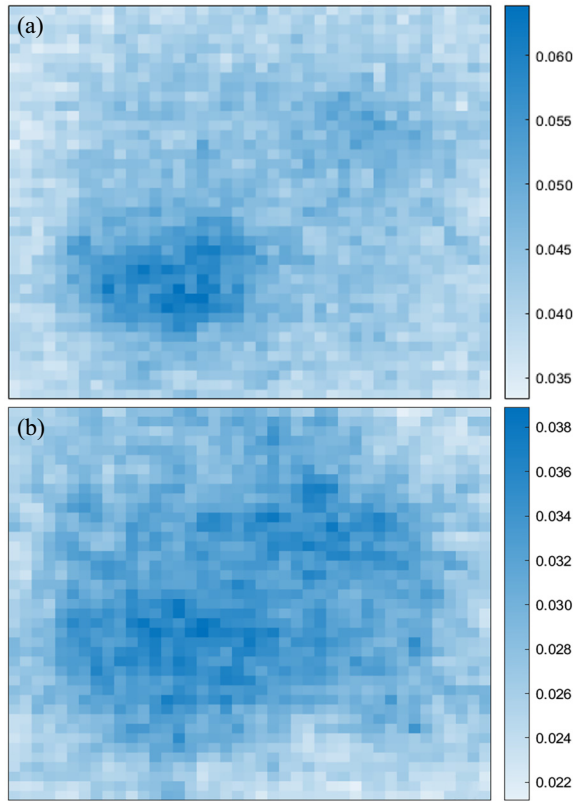


FIG. 8. Image reconstructions using combined depth of field (a) and backprojection (b) using two different detector-object orientations views and 1 million muons per orientation. Intensity is the average scatter angle (rad) in each voxel.

combined depth-of-field image, the limits of the tungsten wedge towards the bottom left are visible, and the brass wedge still appears. For the backprojection technique, the streaking broadens the wedges, making localization more difficult, and the poor contrast from the surrounding concrete makes the materials more difficult to distinguish.

In order to evaluate the quality of reconstructed images and compare the performance between similar techniques quantitatively, techniques common to computed tomography (CT) image analysis were applied: quantifying the contrast resolution and the spatial resolution. For contrast resolution, the contrast-to-noise ratio (CNR) was used, and for spatial resolution the image sharpness was examined using the edge-rise distance.

B. Contrast resolution

For a particular reconstruction image, the observed intensity distribution of each material was extracted by isolating the relevant region in the image. Using these distributions, the average material intensity value (μ) and the standard deviation (σ) were extracted for each material in

TABLE I. Average intensity and standard deviation values from experimental reconstructions created with all 24 unique detector-object orientations, 2.4 million muons per view, as in Fig. 7.

	Backprojection Intensity (mrad)	Depth of field Intensity (mrad)
Tungsten	51.9 ± 1.7	54.8 ± 2.5
Brass	47.3 ± 0.5	48.2 ± 0.6
Concrete	46.0 ± 1.8	44.5 ± 2.4
Air	39.4 ± 0.9	38.3 ± 0.7

an image. The CNR can be calculated using

$$\text{CNR} = \frac{(\mu_1 - \mu_2)}{\sigma_2}, \quad (3)$$

following the American College of Radiology QC guidelines for CT [37]. Here, μ_1 is the average intensity of the foreground material, for example, a wedge, and μ_2 and σ_2 are the average intensity value and standard deviation of the background material, for example, the surrounding concrete. For concrete CNR evaluations, concrete was the foreground material and air was the background material. The μ and σ for reconstructions shown in Fig. 7 are presented below in Table I. The values shown in Table II were extracted from Geant4 simulations of an identical slice, Fig. 6. The values in Tables I and II are displayed graphically in Figs. 9 and 10, respectively. The uncertainty bars shown in Fig. 9 and the following figures correspond to the extracted standard deviation values for each material.

Masks were used to measure the voxel values only within the wedges, and the complement mask was used to measure the values in the concrete without the wedges. The intensity falls off within the wedge boundaries, leading to a larger spread than solely from statistical variation. The concrete voxels have higher values near the wedges, leading to a larger variation for the concrete. The brass is closer in value to the concrete than the tungsten is, so there is less broadening and a smaller standard deviation. This represents the width of the voxel value distribution in each of the different regions. As an example, for 10 million simulated muons per view, over 24 views using CDOF, the

TABLE II. Average intensity and standard deviation values from simulated reconstructions created with all 24 unique detector-object orientations, 10 million muons per view, equivalent to Fig. 7.

	Backprojection Intensity (mrad)	Depth of field Intensity (mrad)
Tungsten	36.4 ± 1.9	41.9 ± 3.4
Brass	30.1 ± 0.6	32.0 ± 0.9
Concrete	27.5 ± 2.8	25.3 ± 3.3
Air	14.3 ± 1.4	12.1 ± 1.2

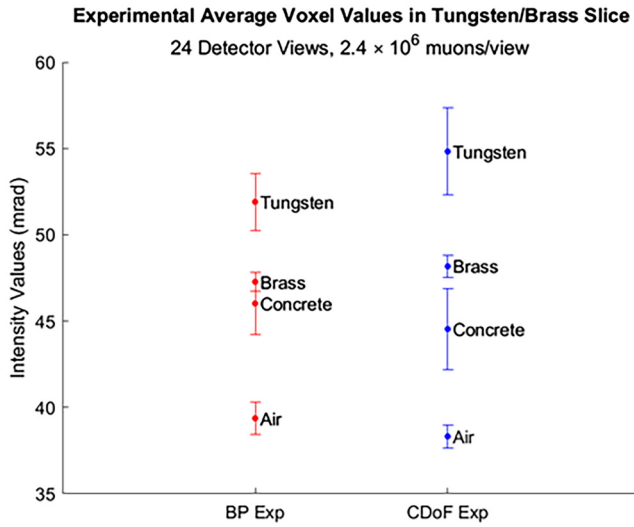


FIG. 9. Experimental average intensity values, uncertainties represent the standard deviation of intensity values for a material. Values were extracted from reconstructions using 24 unique detector-object orientations, with 2.4 million muons per view.

scattering intensity for concrete was 25.3, with $\sigma = 3.3$. For 100 000 simulated muons, over 24 views using CDOF, the scattering intensity was 25.2, with $\sigma = 3.7$. This shows that even with a 100 times increased counting statistics, σ is relatively unchanged.

The muon scatter is an integral of scatters along the entire path, and those scatter values are noted in the voxels along the entire muon path, leading to this edge-shadowing effect near the boundaries between different materials. This is not unusual; a similar smoothing is seen in raw x-ray CT

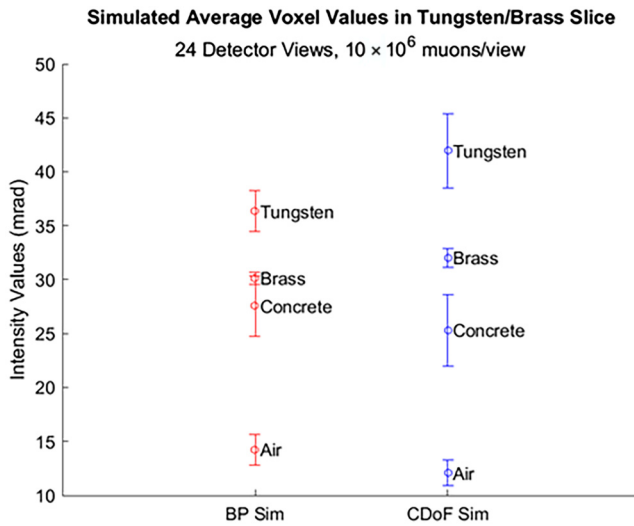


FIG. 10. Simulated average intensity values, uncertainties represent the standard deviation of intensity values for a material. Values were extracted from reconstructions using 24 unique detector-object orientations, with 10 million muons per view.

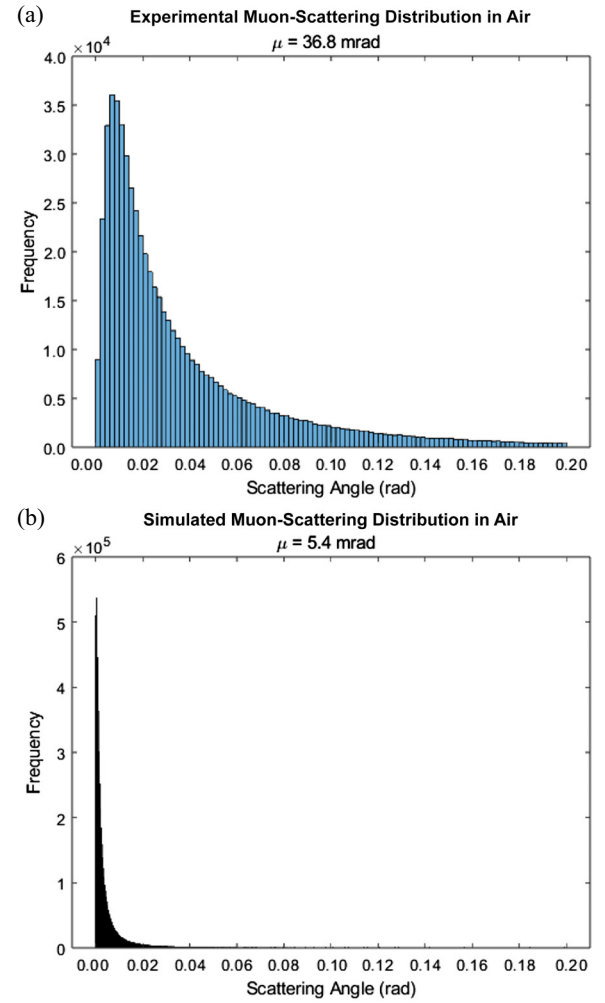


FIG. 11. (a) Experimental scattering distribution for muons only traversing the air region between detectors in a single detector-object dataset. (b) Simulated scattering distribution for muons only traversing the air region between detectors in a single detector-object dataset.

images. Edge filtering can be applied to reduce the shadowing in the image, which we avoided in the current work to more directly compare imaging techniques.

While the trends of the intensity values shown in Tables I and II are similar, the experimental values all have a higher average scattering value than simulation. To understand the offset in average scattering values, caused by detector resolution limitations, we studied the differences between simulated and experimental scattering distributions for muons traversing only air. For the plots shown in Fig. 11, the scattering angle of muons interacting with only air—well away from the barrel—were calculated and plotted in a histogram. A single detector-object orientation was used to avoid increases in the average scattering intensity, caused by muons that interact with the barrel. The average scattering angle of muons in the experimental measurement, 36.8 mrad, is significantly greater

TABLE III. Experimental and simulated CNR values from reconstructions created with all 24 orientations, calculated using values in Tables I and II. Experimental results used 2.4×10^6 muons per view, simulated results used 1×10^7 muons per view.

Foreground-background	Expt. backprojection	Sim. backprojection	Expt. depth of field	Sim. depth of field
Tungsten-concrete	3.3 ± 1.4	3.2 ± 1.2	4.3 ± 1.4	5.0 ± 1.4
Brass-concrete	0.7 ± 1.0	0.9 ± 1.0	1.5 ± 1.0	2.0 ± 1.0
Concrete-air	7.3 ± 2.2	9.4 ± 2.2	8.9 ± 3.6	11.0 ± 2.9

than the simulated equivalent, 5.4 mrad. This difference can be directly attributed to the angular resolution of the MMT system, which was reduced following several months of exposure to the high radiation field near a loaded spent nuclear-fuel dry-storage cask [16]. In the Decision Sciences proprietary FPGA level signal processing, the voltage pulse shape from the detector tubes is used to determine the position in each tube at the mm scale. Gas damage can affect this pulse shape and the reconstructed track angle and position assembled from several tube signals, and thus the subsequent imaging resolution. The steel-drum measurements were performed by the LANL collaborators in 2017, several years before the UNM collaborators analyzed the data, and new measurements were not possible. With a newly gassed system, intensity and CNR values should approach the ideal scenario that is shown in the presented simulations.

In summary, the scattering intensity recorded in a voxel is an average of the integrated scattering through each muon's entire path that intersects with that voxel. This leads to a shadowing effect similar to what is seen in x-ray CT. This is corrected in x-ray CT with edge filtering in backprojection imaging, which was avoided here for a clearer comparison between imaging techniques. The shadowing effect leads to a range of voxel values within a region associated with a single material that is near other materials, which gives a bigger standard deviation of values than if we were imaging a large, single material. The variation in each voxel due to statistics contributes only a small amount to this standard deviation. Finally, the resolution of the detector broadens the recorded scattering distribution values, raising the average scattering intensity reported for every material. Simulations show results from a more perfect detector, close to the possible experimental results with new gas and updated pulse-shape calibrations for the detector tubes.

Using the values in Tables I and II, CNR values were calculated using Eq. (3), and the resulting values are shown in Table III. Larger CNR values are desirable and represent a greater distinction of a particular object or material from its surroundings. In both experimental and simulated reconstructions, the combined depth-of-field technique shows greater contrast for each of the two wedges from the concrete.

The same analysis was repeated for the sparse data reconstructions, shown in Fig. 8, based on only two view

orientations and only one million muons per view, to see how the performance of these techniques changes with weaker data. The results are shown below in Table IV and Fig. 12.

The backprojection iradon function adds values in each voxel projected from each sinogram angle and is normalized by default in that function by dividing by 180, the number of projections for the 1° steps used in the sinogram. For the two-orientation view, the sinogram is sparsely populated, with only a 65.4% filling ratio between $r = -17$ and $+17$ cm, to cover the 34-cm-diameter steel drum, so dividing by 180 over divides the voxel values. This was corrected for by dividing backprojection voxel values by 0.654. Since 180 and 0.654 are constant divisors applied uniformly to the two orientation backprojection results, everything scales uniformly, and the CNR ratios were unaffected.

CNR values from this two-view reconstruction are shown in Table V. Visually, tungsten is still very clearly distinguishable from surroundings using the combined depth-of-field technique, and the difference between tungsten and concrete is larger than in the backprojection technique. The CNR values quantify this, with a tungsten-to-concrete CNR of 2.9 for combined depth of field compared with 1.3 for backprojection. This is worthwhile to note for applications where the goal is to identify and distinguish materials with high density and high atomic numbers from materials with lower density and lower atomic numbers, such as in verifying SNF cask contents. Simulated results show a larger performance gap between the two techniques. As angular resolution in the system is restored by replacing drift tube gas, we expect performance to improve toward the simulated results.

TABLE IV. Average intensity and standard deviation values from experimental reconstructions created with only two unique detector-object orientations, and only 1 million muons per view, as in Fig. 8.

	Backprojection Intensity (mrad)	Depth of field Intensity (mrad)
Tungsten	52.3 ± 2.9	54.7 ± 3.9
Brass	51.8 ± 2.6	48.1 ± 2.7
Concrete	47.0 ± 4.1	44.5 ± 3.5
Air	34.7 ± 3.5	37.3 ± 2.5

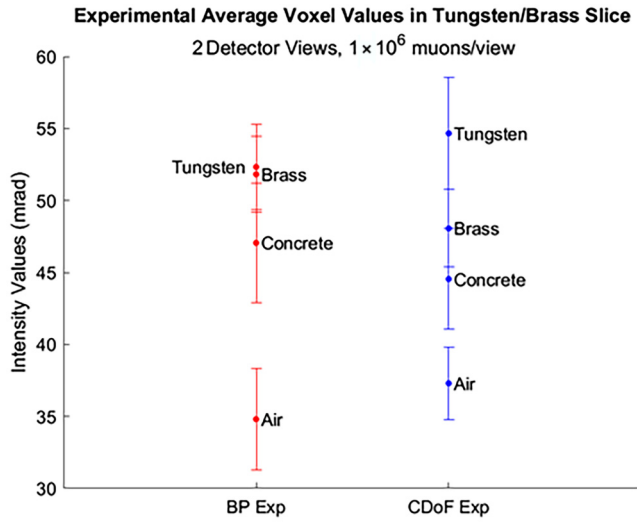


FIG. 12. Average intensity values, with error bars representing the standard deviation of intensity values for a particular material. Values were extracted from reconstructions using only two unique detector-object orientations, with only 1 million muons per view.

C. Spatial resolution

In x-ray-based computed tomography applications, line-pair phantoms or gratings with different spacings are imaged to find the spatial resolution of the system [38]. Without a grating, as in this study, the edge rise distance can be used. This distance is found between a neighboring low- and high-intensity region, examining the pixel distance between 10% and 90% intensity levels in the image (e.g., Refs. [39–41]). Since the muon scatter is due to all materials along its path, voxel intensities near high-Z and high-density materials may be higher due to a shadowing effect in those voxels. Within the high-Z and high-density materials the opposite effect is seen, and the intensity drops off near the edges. In order to compare spatial resolution, one-dimensional intensity slices were taken from the reconstructed images and image sharpness was compared. An example slice is taken through tungsten, but also containing concrete and air, from the 24-orientation data used in Fig. 7. Figure 13 shows the slice line in images from both imaging modalities.

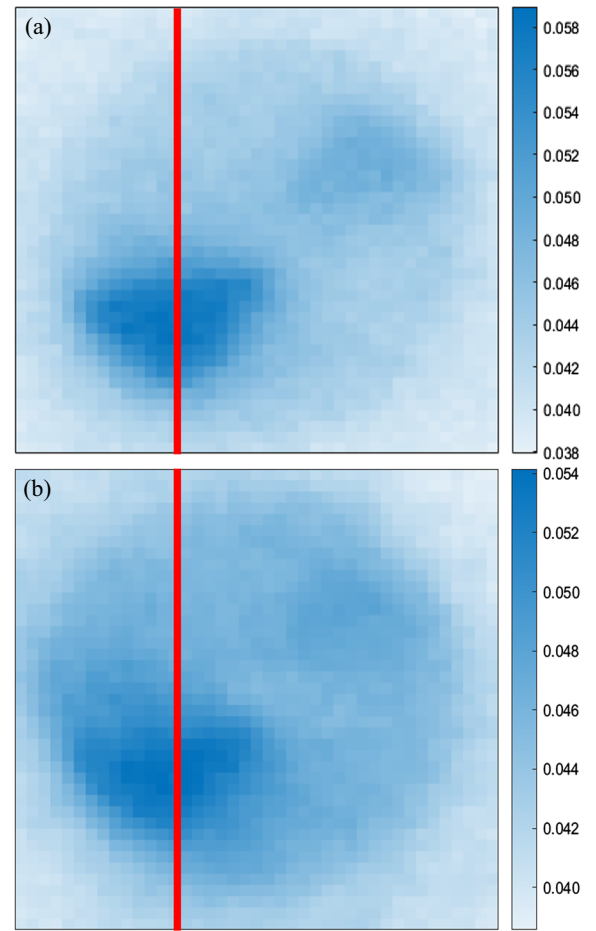


FIG. 13. Line shows the slice region used to create contrast plots. An identical slice was selected from each analysis method. Images used combined depth of field (a), and backprojection (b), from Fig. 7. Intensity is average scatter angle (rad) in each voxel.

The intensity profiles are presented in Fig. 14, where position refers to the pixel position in the z direction along the line marked in Fig. 13. The average tungsten and concrete values from Table I are chosen to be 1 and 0, respectively, for easier comparison between images. As seen in Fig. 14, there is little difference in the spatial resolution between the two reconstruction techniques. The edge rise distance for both techniques is approximately 7 pixels (cm) for the left boundary between concrete and the tungsten wedge in both techniques. On the right-side boundary

TABLE V. Experimental and simulated CNR values from reconstructions, both created with only two unique detector-object orientations, and only 1 million muons per view, calculated using values in Table IV.

Foreground-background	Expt. backprojection	Sim. backprojection	Expt. depth of field	Sim. depth of field
Tungsten-concrete	1.3 ± 1.2	1.9 ± 1.3	2.9 ± 1.5	4.3 ± 1.4
Brass-concrete	1.2 ± 1.2	0.7 ± 1.2	1.0 ± 1.3	1.8 ± 1.1
Concrete-air	3.5 ± 1.5	5.8 ± 1.8	2.9 ± 1.7	6.9 ± 2.3

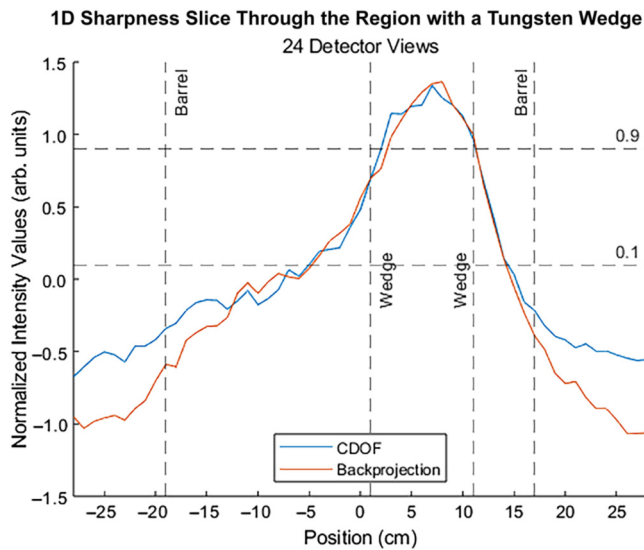


FIG. 14. Intensity profiles for combined depth-of-field imaging, and for backprojection imaging, through the line in Fig. 12. The top of Fig. 13 is a negative position and the bottom a positive position in this intensity profile.

between the wedge and concrete, the edge rise distance is approximately 3 pixels (cm) for both techniques. Sparse data-profile line values were too varied for clear analysis.

VI. CONCLUSION

Multiple-orientation experimental muon-tomography studies were performed using a concrete filled steel drum with tungsten, lead, and brass wedges. Data were taken at 24 different orientations in 15-degree steps, with 2.4 million muon tracks from each orientation. The data were agnostic as to view orientation; there is no difference in incident muon flux or spectrum for the different views. In this work, the steel drum was rotated while the detector faces were kept horizontal, and the near-vertical cosmic-ray muon flux was used. This can be applied to other view-agnostic imaging, such as spent fuel storage casks in which views are taken from different azimuthal angles and a constant zenith angle, as was demonstrated in prior simulation studies. This approach allowed the use of tomography techniques that use many different angles; backprojection using inverse Radon transform and an alternative combined depth-of-field approach were investigated to produce tomography images. While simulated reconstructions had been performed before on multiple-orientation muon tomography, this experimental study applied a combined depth-of-field approach.

The backprojection and combined depth-of-field approaches showed similar spatial resolution performance while there were ample data, 24 orientations, and 2.4 million muons per orientation. However, the combined

depth-of-field technique showed significantly better contrast resolution. Sparse data using fewer orientations and muons were examined to understand the effect on image quality with more realistic field-measurement limitations. The combined depth-of-field technique showed a great advantage over the backprojection technique in contrast resolution, more easily distinguishing high-density materials from concrete.

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

- [1] A. Bonneville, R. Kouzes, J. Yamaoka, C. Rowe, E. Guardincerri, J. M. Durham, C. Morris, D. Poulson, K. Plaud-Ramos, D. Morly, *et al.*, A novel muon detector for borehole density tomography, *Nucl. Instrum. Methods Phys. Res., Sect. A* **851**, 108 (2017).
- [2] A. Bonneville, R. Kouzes, J. Yamaoka, A. Lintereur, J. Flygare, G. S. Varner, I. Mostafanezhad, E. Guardincerri, C. Rowe, and R. Mellors, Borehole muography of subsurface reservoirs, *Philos. Trans. R. Soc., A* **377**, 20180060 (2019).
- [3] L. W. Alvarez, J. A. Anderson, F. E. Bedwei, J. Burkhard, A. Fakhry, A. Girgis, A. Goneid, F. Hassan, D. Iverson, G. Lynch, *et al.*, Search for hidden chambers in the pyramids: The structure of the second pyramid of Giza is determined by cosmic-ray absorption, *Science* **167**, 832 (1970).
- [4] K. Morishima, K. Mitsuaki, A. Nishio, N. Kitagawa, Y. Manabe, M. Moto, F. Takasaki, H. Fujii, K. Satoh, H. Kodama, *et al.*, Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons, *Nature* **552**, 386 (2017).
- [5] K. Nagamine, M. Iwasaki, K. Shimomura, and K. Ishida, Method of probing inner-structure of geophysical substance with the horizontal cosmic-ray muons and possible application to volcanic eruption prediction, *Nucl. Instrum. Methods Phys. Res., Sect. A* **356** (2), 585 (1995).
- [6] H. K. Tanaka, T. Uchida, M. Tanaka, H. Shinohara, and H. Taira, Cosmic-ray muon imaging of magma in a conduit: Degassing process of Satsuma-Iwojima Volcano, Japan, *Geophys. Res. Lett.* **36**, 1 (2009).
- [7] G. R. Lynch and O. I. Dahl, Approximations to multiple Coulomb scattering, *Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. At* **58**, 6 (1991).

- [8] G. E. Hogan, K. N. Borozdin, J. Gomez, C. Morris, W. C. Priedhorsky, A. Saunders, L. J. Schultz, and M. E. Teasdale, Detection of High-Z Objects using Multiple Scattering of Cosmic Ray Muons, in *AIP Conference Proceedings* (American Institute of Physics, New York, NY, 2004), Vol. 698, pp. 755–758.
- [9] L. J. Schultz, K. N. Borozdin, J. J. Gomez, G. E. Hogan, J. A. McGill, C. L. Morris, W. C. Priedhorsky, A. Saunders, and M. E. Teasdale, Image reconstruction and material Z discrimination via cosmic ray muon radiography, *Nucl. Instrum. Methods Phys. Res., Sect. A* **519**, 687 (2004).
- [10] C. Morris, C. C. Alexander, J. D. Bacon, K. N. Borozdin, D. J. Clark, R. Chartrand, C. J. Espinoza, A. M. Fraser, M. C. Galassi, J. A. Green, *et al.*, Tomographic imaging with cosmic ray muons, *Sci. Glob. Secur.* **16**, 37 (2008).
- [11] WCN Editorial, Nuclear Detection System Deployed at Freeport, <https://www.worldcargonews.com/safety-security/2012/08/nuclear-detection-system-deployed-at-freeport/?gdp=accept>.
- [12] P. La Rocca, V. Antonuccio, M. Bandieramonte, U. Bacciani, F. Belluomo, M. Belluso, S. Billotta, A. A. Blancato, D. Bonanno, G. Bonanno, *et al.*, Search for hidden high-Z materials inside containers with the Muon Portal Project, *J. Instrum.* **9**, C01056 (2014).
- [13] E. T. Rand, O. Kamaev, A. Valente, and A. Bhullar, Non-parametric dense-object detection algorithm for applications of cosmic-ray muon tomography, *Phys. Rev. Appl.* **14** (6), 064032 (2020).
- [14] K. Borozdin, S. Greene, Z. Lukić, E. Milner, H. Miyadera, C. Morris, and J. Perry, Cosmic ray radiography of the damaged cores of the Fukushima reactors, *Phys. Rev. Lett.* **109**, 152501 (2012).
- [15] J. Perry, M. Azzouz, J. Bacon, K. Borozdin, E. Chen, J. Fabritius, E. Milner, H. Miyadera, C. Morris, J. Roybal, *et al.*, Imaging a nuclear reactor using cosmic ray muons, *J. Appl. Phys.* **113**, 184909-1 (2013).
- [16] J. M. Durham, D. Poulson, J. Bacon, D. L. Chichester, E. Guardincerri, C. L. Morris, K. Plaud-Ramos, W. Schwendiman, J. D. Tolman, and P. Winston, Verification of spent nuclear fuel in sealed dry storage casks via measurements of cosmic-ray muon scattering, *Phys. Rev. Appl.* **9**, 044013 (2018).
- [17] D. Poulson, Interrogation of Spent Nuclear Fuel Casks Using Cosmic-Ray Muon Computed Tomography, Nucl. Eng. ETDs (2019).
- [18] M. A. McKinnon, J. M. Creer, C. L. Wheeler, J. E. Tanner, D. P. Batalo, D. A. Dziadosz, E. V. Moore, D. H. Schooner, M. F. Jensen, and J. H. Browder, The MC-10 PWR Spent Fuel Storage Cask: Testing and Analysis, No. EPRI-NP-5268, Pacific Northwest Lab., Richland, WA (USA); Virginia Power Co., Richmond (USA); EG and G Idaho, Inc., Idaho Falls (USA); Electric Power Research Inst., Palo Alto, CA (USA), 1987.
- [19] D. Poulson, J. M. Durham, E. Guardincerri, C. L. Morris, J. D. Bacon, K. Plaud-Ramos, D. Morley, and A. A. Hecht, Cosmic ray muon computed tomography of spent nuclear fuel in dry storage casks, *Nucl. Instrum. Methods Phys. Res., Sect. A* **842**, 48 (2017).
- [20] D. Poulson, J. Bacon, J. M. Durham, E. Guardincerri, C. L. Morris, and H. R. Trellue, Application of muon tomography to fuel cask monitoring, *Philos. Trans. R. Soc., A* **377** (2137), 20180052 (2019).
- [21] Z. Liu, S. Chatzidakis, J. M. Scaglione, C. Liao, H. Yang, and J. P. Hayward, Muon tracing and image reconstruction algorithms for cosmic ray muon computed tomography, *IEEE Trans. Image Process.* **28** (1), 426 (2018).
- [22] J. L. Autran, D. Munteanu, T. S. Saoud, and S. Moindjie, Characterization of atmospheric muons at sea level using a cosmic ray telescope, *Nucl. Instrum. Methods Phys. Res., Sect. A* **903**, 77 (2018).
- [23] S. Tsuji, T. Katayama, K. Okei, T. Wada, I. Yamamoto, and Y. Yamashita, Measurements of muons at sea level, *J. Phys. G: Nucl. Part. Phys.* **24** (9), 1805 (1998).
- [24] Y.-S. Tsai, Pair production and bremsstrahlung of charged leptons, *Rev. Mod. Phys.* **46** (815), 815 (1974).
- [25] J. H. Hubbell and S. M. Seltzer, *X-Ray Mass Attenuation Coefficients*, <https://physics.nist.gov/PhysRefData/XrayMassCoef/tab1.html>
- [26] J. Durham, E. Guardincerri, C. Morris, J. Bacon, J. Fabritius, S. Fellows, D. Poulson, K. Plaud-Ramos, and J. Renshaw, Tests of cosmic ray radiography for power industry applications, *AIP Adv.* **5**, 067111-1 (2015).
- [27] H. Miyadera and C. L. Morris, Muon scattering tomography, *Appl. Opt.* **61**, C154 (2022).
- [28] J. M. Durham, E. Guardincerri, C. L. Morris, D. Poulson, J. D. Bacon, J. Fabritius, S. Fellows, K. Plaud-Ramos, D. Morley, D. Chichester, *et al.*, Cosmic-ray muon imaging of spent nuclear fuel in dry storage casks, *J. Nucl. Mater. Manag.* **44**, 5 (2016).
- [29] S. Agostinelli, J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Arce, M. Asai, D. Axen, S. Banerjee, G. Bartrand, *et al.*, Geant4—a simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [30] J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Arce, M. Asai, G. Bartrand, R. Capra, S. Chauvie, R. Chytracsek, *et al.*, Geant4 developments and applications, *IEEE Trans. Nucl. Sci.* **53**, 270 (2006).
- [31] D. Pagano, G. Bonomi, A. Donzella, A. Zenoni, G. Zumerle, and N. Zurlo, EcoMug: An Efficient COsmic MUon Generator for cosmic-ray muon applications, *Nucl. Instrum. Methods Phys. Res., Sect. A* **1014**, 165732 (2021).
- [32] T. S. Durrani and D. Bisset, The Radon transform and its properties, *Geophysics* **49**, 1180 (1984).
- [33] S. R. Deans, *The Radon Transform and Some of Its Applications* (Courier Corporation, Garden City, NY, 2007).
- [34] The MathWorks Inc., MATLAB version: 9.13.0 (R2022b), (n.d.).
- [35] A. A. Hecht, J. Valencia, and D. Lioce, *Combined Plenoptic (Depth-of-Field) Assisted Tomography*, USPTO provisional patent application number 19/088,862.
- [36] J. Valencia, M.S.Thesis, University of New Mexico, 2024. [Online]. Available: To be posted at https://digitalrepository.unm.edu/ne_etds/.
- [37] C. Dillon, W. Breeden, J. Clements, and D. Cody, *Computed Tomography Quality Control Manual* (American College of Radiology, Reston, VA, 2017), Vol. 2017.
- [38] N. Desai, A. Singh, and D. J. Valentino, in *Medical Imaging 2010: Physics of Medical Imaging*, edited by E. Samei,

- and N. J. Pelc (SPIE, San Diego, CA, 2010), Vol. 7622, pp.76224Q.
- [39] F. Tatsugami, T. Higaki, Y. Nakamura, Z. Yu, J. Zhou, Y. Lu, C. Fujioka, T. Kitagawa, Y. Kihara, M. Iida, *et al.*, Deep learning-based image restoration algorithm for coronary CT angiography, *Eur. Radiol.* **29**, 5322 (2019).
- [40] H. Yeoh, S. H. Hong, C. Ahn, J.-Y. Choi, H.-D. Chae, H. J. Yoo, and J. H. Kim, Deep learning algorithm for simultaneous noise reduction and edge sharpening in low-dose CT images: A pilot study using lumbar spine CT, *Korean J. Radiol.* **22**, 1850 (2021).
- [41] L. M. Bischoff, J. M. Peeters, L. Weinhold, P. Krause-witz, J. Ellinger, C. Katemann, A. Isaak, O. M. Weber, D. Kuetting, U. Attenberger, *et al.*, Deep learning super-resolution reconstruction for fast and motion-robust T2-weighted prostate MRI, *Radiology* **308**, e230427 (2023).