

Tracking upgrades and results of muon imaging in more than 200 m depth

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Abstract

In this study, muon radiography was applied to image the overburden above a salt mine and to assess its potential for monitoring density distribution and structural integrity. We present recent upgrades of the MURAY detector and results from measurements performed in the Italkali salt mine in Realmonte, Sicily, where the detector collected more than 130 days of data at approximately 203 m depth.

The 1 m² detector was upgraded for long-term underground operation with new SiPMs and readout electronics, improved environmental monitoring, automated data processing, and a revised tracking algorithm.

The reconstruction now includes a new adaptive data representation we called Pantheon, an improved clustering, track-selection procedure, and recovery of tracks with one missing detector hit, increasing the usable statistics and enabling detector-efficiency studies. The developments were applied to a triangular section scintillator detector system but may also be applicable to other detector types after appropriate considerations.

Keywords: muography, transmission, algorithm

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1. INTRODUCTION

Muon radiography (muography) provides a non-invasive method for investigating large underground structures by measuring variations in the flux of cosmic-ray muons [1, 2]. We report recent upgrades of the MURAY detector [3] and the expected results of a deep-underground measurement performed in the Italkali salt mine in Realmonte, Sicily [4]. The site is an active halite mine and the Messinian evaporite succession hosting the mine is currently being evaluated as a potential host for underground hydrogen storage in salt caverns [5], for which muography could provide complementary information on subsurface geometry and structural integrity.

Among the available subsurface hydrogen storage options, salt caverns are particularly attractive because of their very low permeability and favorable physical and chemical properties [6, 7]. These artificial cavities are typically developed in salt formations at depths ranging from about 200 m to 2 km and could provide large storage capacities while limiting the surface footprint.

The characterization and monitoring of such underground structures remain challenging. Conventional geophysical methods, including seismic imaging, electrical resistivity tomography, magnetotellurics, and gravity surveys, can be limited by penetration depth, spatial resolution, or the physical properties of salt formations [8, 9]. In particular, gravity measurements generally provide limited resolution for small-scale structures, while electrical resistivity tomography is typically restricted to relatively shallow depths. Seismic signal (which

also require expensive data acquisition process) for onshore salt cavern are strongly affected by abrupt change from the overburden sediments producing strong refraction at the top-salt interface and limiting the imaging across the halite mostly transparent. A complementary technique capable of probing several hundred meters of rock with meter-scale sensitivity would therefore be valuable for the characterization and monitoring of underground salt caverns.

Muon transmission radiography, or muography, offers such a possibility by exploiting naturally occurring cosmic-ray muons. Due to their high penetration capability, muons can traverse hundreds of meters of rock. Their attenuation depends primarily on the integrated density along their trajectories; consequently, measurements of the underground muon flux can reveal variations in the density distribution and identify low-density structures such as cavities. Since its pioneering applications to rock-overburden measurements [10] and the search for hidden chambers in the Chephren pyramid [11], muography has been successfully applied in volcanology, geology, archaeology, mining, and engineering [12, 1, 2].

In this study, muon radiography was applied to image the overburden above the Italkali salt mine at Realmonte (Agrigento, southern Sicily) and demonstrate its capability for monitoring density distribution and structural integrity at large depths. A muon detector was initially operated at the surface to acquire a reference sample of free-sky muons and subsequently installed in an underground gallery at –106 m ASL. A known gallery located approximately 21 m above the detector provided a controlled target for validating the imaging capability in that environment. The measurement presented here focuses on recent detector and tracking-reconstruction upgrades

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and on imaging the overburden, as a step towards identifying the known cavity [4].

2. TRACKING UPGRADES

The new code builds on previous developments of the MURAY/MURAVES reconstruction framework, retaining its established detector-calibration, clustering, and tracking principles [14] while introducing substantial improvements in computational efficiency, automation, event recovery, and angular analysis. The input consists of ADC data previously extracted from the detector RAW files. Pedestal and single-photoelectron calibration constants are determined separately for every SiPM channel: the pedestal defines the zero-signal baseline, while the separation of the resolved photoelectron peaks provides the ADC-to-photoelectron conversion factor. After pedestal subtraction, each channel amplitude is therefore expressed in photoelectron-equivalent units, reducing channel-to-channel gain variations. The channel order is then mapped to the physical detector geometry and the acquisition live time is corrected for detector dead time. These procedures follow the detector concepts and calibration strategy established for the scintillator-bar and SiPM-based MURAY and MURAVES telescopes [14, 15, 16].

In each detector layer and projection, clustering begins from the strip with the largest signal above the seed threshold. Signals from adjacent strips are associated with the seed, subject to the cluster-energy threshold and special treatment of detector edges and known dead channels. Because the triangular scintillator bars are designed to produce charge sharing between neighboring strips, the transverse hit position is reconstructed from the photoelectron-weighted centroid of the cluster. The reconstructed positions are fitted independently in the XZ and YZ projections using the straight-line model $u(z) = az + b$. Track quality is quantified by

$$\chi^2 = \sum_i \left[\frac{u_i - (az_i + b)}{\sigma_i} \right]^2,$$

where u_i is the cluster position and σ_i is its assigned spatial uncertainty ($\sigma = 2.5$ mm [15]). The two fitted slopes are subsequently combined to determine the three-dimensional azimuth and zenith angles. Linear fitting and χ^2 -based track selection are consistent with the MURAVES reconstruction and “Golden Selection” approaches described previously [14, 17].

Technical upgrades include the reorganization of the analysis around preallocated MATLAB matrices, reduced memory consumption and file size. The analysis has also been incorporated into an automated cronjob–Python–MATLAB pipeline. New runs are downloaded automatically, converted from RAW to ADC format, processed through calibration, and monitored for performance, power or connections errors, abnormal event rates, calibration failures, or other anomalies, then alerts are issued when predefined checks fail. The postprocessing stage now integrates the reconstructed directions with a digital elevation model (DEM), calculates the rock length traversed by each angular bin, and derives the corresponding expected open-sky and transmitted fluxes using the modified sea-level muon parametrization of Guan et al. [18]. Consequently, detector reconstruction, topographic ray tracing, flux estimation, and transmission analysis form a single reproducible chain.

The plotting and binning solid angle data has likewise been extended. A regular θ - ϕ grid provides a simple rectangular representation with fixed angular increments [13], while a polar representation displays azimuth around the detector axis and zenith as the radial coordinate ($p_x = \theta \cos(\phi)$; $p_y = \theta \sin(\phi)$) [4]. We introduce a new adaptive “Pantheon” grid which uses a central angular cap surrounded by concentric zenith rings, and after the tracks are counted in these bins, the solid angles are represented with the usual polar projection. Examples of free-sky and underground muon count histogram data are shown in Fig. 1. Each ring is divided into an integer number of azimuthal sectors selected so that its radial and tangential dimensions remain approximately comparable and its prescribed solid angle is maintained. The bin solid angle may also be increased toward large zenith angles, to compensate for detector acceptance and muon statistics decrease. One can observe that Fig. 3 has uniform solid-angle binning, resulting in an order-of-magnitude decrease in statistics toward the edges, whereas with the increasing bin sizes used in Fig. 1, the statistics remain within a factor of two. Pantheon binning therefore avoids the strongly distorted cells of a rectangular angular map and improves the balance between angular resolution and statistical precision across the field of view in contrast with a simple polar grid.

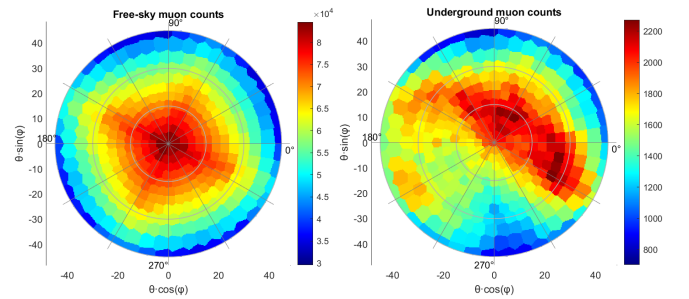


FIGURE 1: Free-sky and underground muon count angular histogram.

An important reconstruction limitation arises for clusters containing only one strip. For a two-strip cluster, the relative photoelectron signals provide a continuous position estimate within the strip pitch. However in practice, due to a finite dead-zone between the common triangle vertices (caused by the signal/noise threshold in a given strip), 20–25 percent of events are one-strip sized clusters for a given layer. Therefore, the actual position of such clusters are ambiguous within a pitch range based on only the deposited energy, mainly because different angle tracks will leave similar signal, as it is demonstrated in Fig. 2. Assign channel centroid to these clusters produces discrete reconstructed positions and therefore fluctuations in high resolution imaging (Fig. 3).

One possible treatment is to randomize the position uniformly within the strip pitch and assign the point a larger uncertainty. The increased uncertainty reduces the contribution of the ambiguous point to the χ^2 fit and suppresses angular quantization, but the method introduces stochastic event-by-event smearing and sacrifices statistics when χ^2 cut applied.

The new approach instead applies an iterative angle correction. A provisional track angle is obtained from the available cluster coordinates, then the position of each one-strip cluster is shifted according to that angle, the orientation of the triangular bar and its distance from the relevant strip edge. The track is

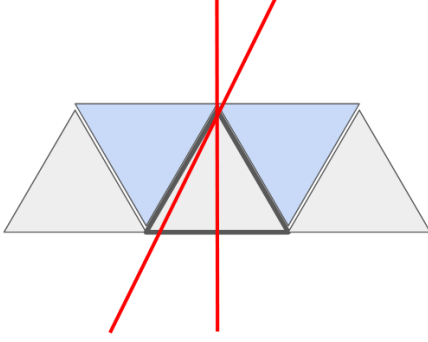


FIGURE 2: Demonstration of cluster position ambiguity for single-strip clusters: different angle tracks can leave similar single-strip signal when crossing vertex dead-zones but their position cannot be recovered from energy weighting within the pitch.

refitted based on the corrected one-strip cluster position. This deterministic procedure uses the consistency of the complete trajectory to constrain the otherwise unresolved coordinate. It does not remove the fundamental single-strip uncertainty, but it improves the position estimate without randomly broadening the angular distribution, decreases the fluctuation in the imaging, and provide more usable statistics after χ^2 cut. Fig. 3 contains free-sky high resolution (1 deg^2) count histogram with different correction methods. As can be observed, the aforementioned new approach to angle-based correction results in the smoothest distribution.

The reconstruction also performs a combinatorial search when more than one cluster is found in a layer. Selecting only the highest-energy cluster is not always reliable because SiPM dark current, electronic noise, optical cross-talk, or a background particle may generate a cluster that is larger than the true muon signal. A single incorrect choice can spoil an otherwise well-aligned track. The code therefore evaluates the allowed combinations, and retains the combination producing the lowest χ^2 in each projection. Combinatorially recovered events are flagged so that they can either be included in the main sample or removed for more conservative track selection.

A complete event normally provides three X and three Y coordinates, giving a six-point three-dimensional track. Requiring all six measurements, however, rejects a muon whenever one coordinate is lost because of imperfect efficiency, a dead channel, or an unusable cluster. The five-point hypothesis recovers such events by requiring one projection to contain three aligned points with a low χ^2 , thereby providing strong evidence for a through-going muon. The other projection is then reconstructed from its two valid coordinates, which is sufficient to determine its slope and hence complete the three-dimensional direction (Fig 4). A top-bottom pair provides the longest telescope length and is consequently more precise than a center-edge pair. The latter requires greater extrapolation and is more sensitive to position uncertainty, therefore these two cases also flagged separately.

Five-point tracks have intrinsically lower quality because a two-point line has no residual degree of freedom with which to test linearity. Nevertheless, their inclusion increases statistics, enables layer- and channel-efficiency estimation, reduces acceptance losses caused by localized detector inefficiencies, and

increases total tracking efficiency [19]. Note, that the effectiveness of the five-point method also depends on the trigger condition. In the case of MURAY detector, it is not optimal because the condition is fixed to require $(top|_x \wedge top|_y) \wedge (bottom|_x \wedge bottom|_y) \wedge (middle|_x \vee middle|_y)$ layers [4], whereas optimal would be to put the trigger condition in OR for all layers and require at least 5 out of 6.

The developed tracking software propagates explicit quality information: full combinatorial six-point tracks are distinguished from five-point tracks, while the latter are separated according to whether the two-point projection uses a center-edge pair or the preferred top-bottom pair. Invalid extrapolations and events with multiple missing measurements receive separate status values. These flags support hierarchical filtering: high-purity analyses may retain only complete low- χ^2 tracks, intermediate selections may include top-bottom five-point events, and efficiency studies or statistically limited muograms may use the broader five-point sample. The recovery thus increases usable exposure without concealing the reduced constraint of the reconstructed trajectory.

3. IMAGING COMPARISON OF DIFFERENT TRACK SELECTIONS

Figure 5 shows the digital elevation model (DEM) of the measurement site, including the detector position and the intersections of three representative viewing cones with the terrain surface. The topography determines the rock path length, and hence the integrated density (opacity), encountered by muons arriving from each direction. Directions intersecting higher or more extended topographic structures generally correspond to greater opacity and stronger muon attenuation, whereas directions crossing valleys or thinner sections of rock are expected to exhibit higher transmission. A particularly useful feature of the measurement geometry is a 15 m hill with a steep flank located directly above the detector, causing high gradient in the transmission, which also provides a useful indication of the imaging resolution.

Following Ref. [4], the transmission in an angular bin (θ, ϕ) is defined as the ratio of the underground and free-sky count rates,

$$T(\theta, \phi) = \frac{N_{\text{UG}}(\theta, \phi)/t_{\text{UG}}}{N_{\text{FS}}(\theta, \phi)/t_{\text{FS}}}, \quad (1)$$

where N_{UG} and N_{FS} are the underground and free-sky event counts, respectively, and t_{UG} and t_{FS} are the corresponding live times. Applying the same reconstruction and selection criteria to both datasets allows the ratio to cancel, to first order, the directional detector acceptance and persistent channel-to-channel efficiency variations.

Table 1 summarizes the track selections used to evaluate the effects of the different reconstruction methods. Selection A represents the original reconstruction. It uses six-point tracks, with three measurements in both projection, and uses only the highest-energy cluster in every layer. Both projected tracks are required to satisfy $\chi^2 < 5$.

Selection B applies the same six-point quality requirement after a combinatorial cluster search. When two clusters are reconstructed in one or more layers, the algorithm examines the possible combinations of the first- and second-highest-energy clusters and retains the combination with the lowest projected

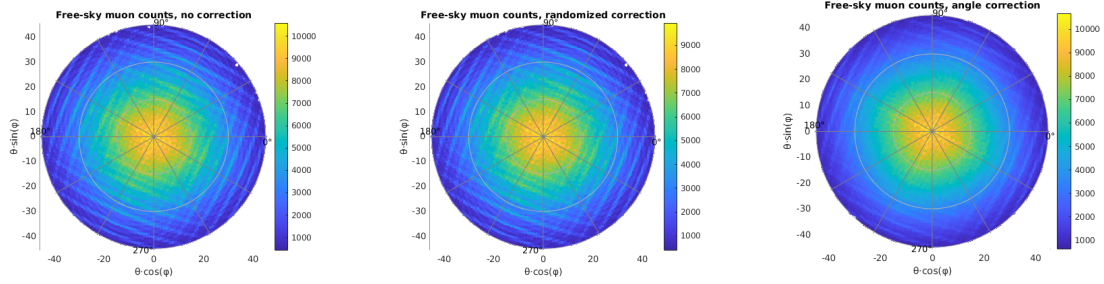


FIGURE 3: Imaging results obtained using different position treatments for single-strip clusters: no position correction (left), randomized positioning within the strip pitch (centre), and the new angle-dependent position correction (right).

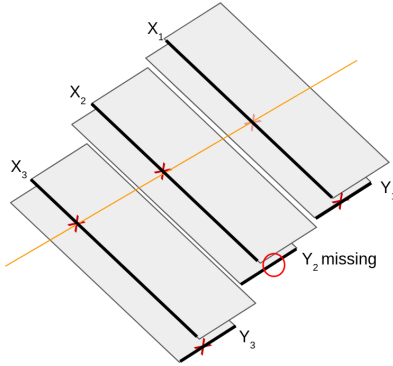


FIGURE 4: Schematic of five-point track reconstruction. Three aligned hits in the X projection define a low- χ^2 track, while the missing Y_2 hit is compensated by fitting the two available Y measurements. The two projected fits are then combined to reconstruct the three-dimensional muon trajectory (orange line).

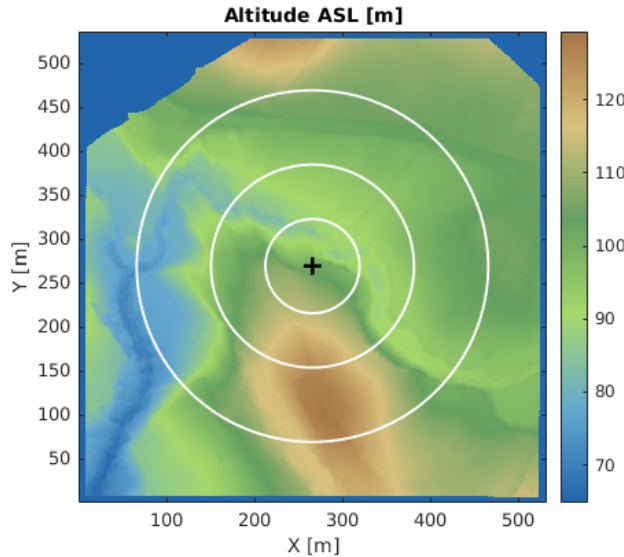


FIGURE 5: Digital elevation model of the measurement site, expressed in metres above sea level. The black cross marks the detector position, approximately 203 m below the local surface. The white contours show the intersections of viewing cones with opening angles of 30° , 60° , and 90° with the terrain surface.

χ^2 . This procedure is intended to recover otherwise valid muon tracks for which dark counts, electronic noise, or coincident background particle caused the highest-energy cluster to be incorrectly assigned to the track.

Selection C is the inclusive reconstruction sample containing both six-point tracks (after combinatorial search) and recovered five-point tracks. For a five-point candidate, one projection must contain three measurements forming a track with $\chi^2 < 5$. If the other projection has only two usable layers, or its original three-point fit has $\chi^2 \geq 10$, that projection is reconstructed from its two highest-energy clusters. Since a straight line through two points has no residual degree of freedom, such tracks are explicitly flagged and kept distinguishable from fully constrained six-point tracks.

Selection A_r applies the original selection A after restricting the accepted trajectories to a reduced $95 \times 95 \text{ cm}^2$ fiducial area. It is used to test whether less efficient or less uniform detector-edge regions significantly affect the transmission image. Selection F is a control sample containing tracks that fail the nominal $\chi^2 < 5$ requirement but remain below the loose upper limit $\chi^2 < 50$. Finally, selection G contains only recovered five-point tracks and is used to evaluate whether these lower-quality events retain physically meaningful directional information.

	Points	χ^2 cut	Combi.	Tracks/h
A	6	5	no	190
A_r	6	5	no	156
B	6	5	yes	213
C	6 or 5	5	yes	298
F	6 or 5	$50 > \chi^2 > 5$	yes	7.3
G	5	10	yes	84.5

TABLE 1: Definitions and underground event rates of the track selections. A_r denotes the reduced $95 \times 95 \text{ cm}^2$ fiducial area.

The combinatorial procedure reduced the fitted χ^2 in 8.7% of the events per projection. In 3.8% of the events, the reconstructed projection was moved from $\chi^2 > 5$ to below the nominal acceptance threshold. When both projections are considered, at least one projected fit was improved in 17% of the events, while 10.2% of the events were recovered into the accepted track sample. These results indicate that incorrect cluster assignment constitutes a significant source of track rejection in the original highest-energy-cluster reconstruction.

Figure 6 compares the transmission maps obtained with the different selections. For every map, the same selection was applied independently to the underground numerator and the

free-sky denominator. The purpose of this qualitative comparison is to assess whether the additional reconstruction methods preserve the expected spatial transmission pattern. A detailed quantitative comparison with the DEM-derived opacity and expected transmission is beyond the scope of the present paper.

Selection **A** reproduces the main structures expected from the surface topography: directions corresponding to thicker rock show lower transmission, while directions intersecting thinner regions and valleys show higher transmission. Selection **B** produces a very similar distribution while increasing the underground track rate from 190 to 213 tracks h^{-1} , corresponding to an increase of approximately 12%. No evident spatial distortion is introduced by the combinatorial cluster search, supporting its use for recovering tracks rejected because of an incorrect initial cluster assignment.

The inclusive selection **C** retains the principal spatial features observed with selections **A** and **B** and increases the event rate to 298 tracks h^{-1} so 40% more tracks than **B** tracking. However, its transmission exhibits a systematic downward shift. Because the same nominal selection is applied to the underground and free-sky datasets, this change indicates that five-point recovery does not cancel identically between the two measurement configurations. Possible contributions include differences in background or noise composition, affecting differently in free-sky or underground conditions. Consequently, five-point events should remain separately flagged and should not be combined with six-point tracks without a dedicated efficiency and normalization study.

The transmission map obtained with selection **A_r** is consistent with that of selection **A**, but its event rate is reduced from 190 to 156 tracks h^{-1} . Restricting the fiducial area therefore produces no visible improvement in the reconstructed image while substantially decreasing the available statistics. Within the precision of the present comparison, the detector-edge regions do not introduce a sufficiently large bias to justify their removal.

Selection **G** provides a direct test of the five-point reconstruction. Its transmission map retains several of the large-scale structures visible in the six-point samples, indicating that the reconstructed directions remain correlated with the physical muon trajectories and that the method does not introduce an obvious rotation, reflection, or other large angular distortion. Nevertheless, the image has weaker contrast, some smaller-scale structures are no longer resolved, and its absolute transmission is systematically lower. The observed morphological agreement supports the interpretation that a substantial fraction of the five-point candidates are genuine cosmic muons traveled through the overburden, but it does not by itself establish the purity or efficiency of this sample. Five-point tracks therefore can be useful for increasing statistics for low-resolution imaging and studying detector efficiency, provided that they remain explicitly flagged and are assigned a separate systematic uncertainty. There can be also room for improvement, with dedicated Monte Carlo simulations, threshold study, or the previously mentioned trigger coincidence adjustment.

In contrast, selection **F** does not reproduce the topography-correlated structures observed in the higher-quality samples. Its very low rate of 7.3 tracks h^{-1} also results in large statistical fluctuations. The absence of a recognizable transmission pattern is consistent with this sample being dominated by noise, secondary particles, and other backgrounds. Tracks fail-

ing the nominal quality requirement are therefore not suitable for quantitative muographic imaging.

4. CONCLUSIONS

The upgraded MURAY detector and analysis chain operated stably in both the deep-underground and free-sky measurement configurations. The standard six-point reconstruction produced transmission images correlated with the overlying topography, demonstrating the capability of the system to reconstruct the directional attenuation of cosmic-ray muons after propagation through more than 200 m of rock.

The angle-dependent correction of single-strip clusters and the adaptive Pantheon binning provide complementary improvements to the imaging chain. The position correction reduces the angular discretization and image artefacts produced when a single-strip cluster is assigned to the strip centre, while avoiding the additional stochastic smearing introduced by randomized positioning. At the angular-distribution level, Pantheon binning preserves approximately comparable radial and tangential bin dimensions and permits the solid angle to increase toward the edge of the field of view, where the detector acceptance and muon flux decrease. This reduces the variation in bin statistics from approximately one order of magnitude with uniform solid-angle binning to within a factor of two, providing a more effective compromise between angular resolution and statistical precision. Together, these methods improve both the directional fidelity of individual reconstructed tracks and the statistical uniformity of the resulting muographic images.

The combinatorial cluster search improved the reconstruction efficiency without introducing a visible distortion of the transmission image. Relative to the original highest-energy-cluster method, it increased the accepted underground track rate by approximately 12%. The combinatorial six-point selection therefore provides the most favorable balance between event statistics and reconstruction quality among the selections considered here. Reducing the detector fiducial area produced no evident improvement and unnecessarily decreased the available statistics, whereas tracks failing the nominal χ^2 requirement did not retain a recognizable topographic signature.

Five-point recovery provides a 40% additional event sample and preserves the principal structures of the transmission image. However, its poorer image contrast and systematic transmission shift show that these tracks have different reconstruction and selection efficiencies from fully constrained six-point events. They should therefore remain separately flagged and require dedicated acceptance, efficiency, and background corrections before being incorporated into a precision transmission or density analysis. As an additional benefit, the five-point track rate can also serve as an indicator for non-uniformities in the detector's tracking efficiency.

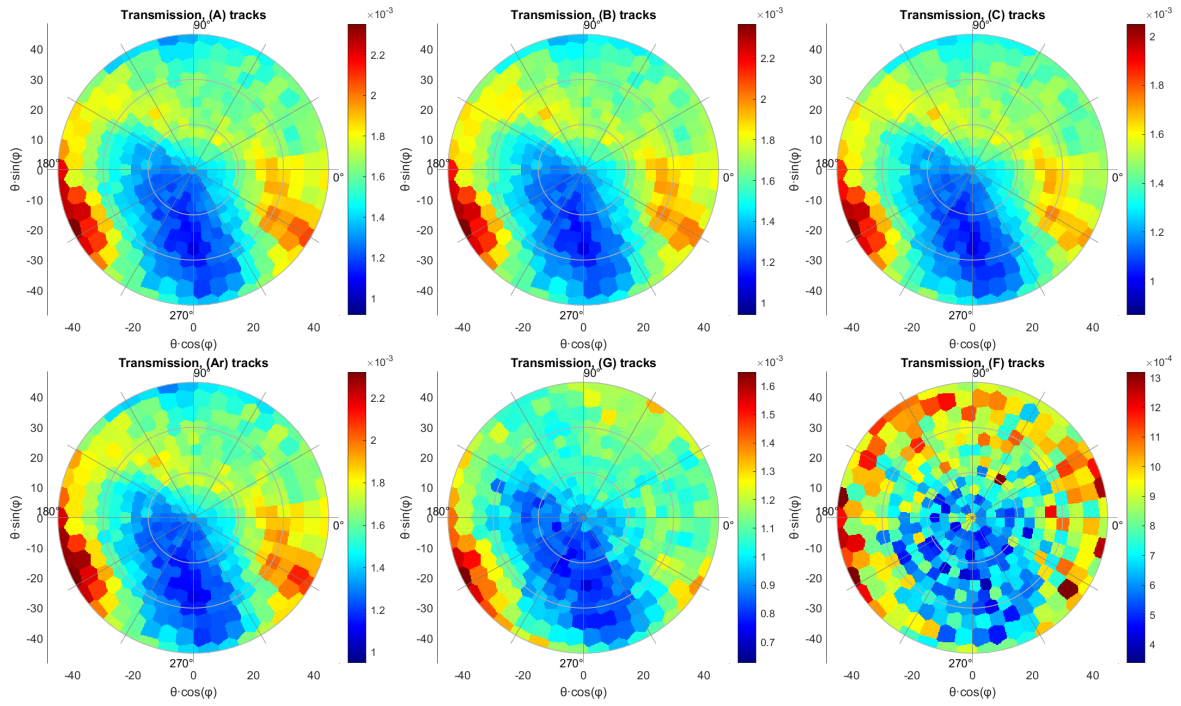


FIGURE 6: Transmission maps obtained with track selections A, B, C, A_r, G, and F, shown from the upper left to the lower right. The same track-selection criteria were applied to the underground and free-sky datasets used in the numerator and denominator of each transmission map.

Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

Declaration of AI Tool Use

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) solely to improve English language, grammar, and readability. All scientific content, data analysis, results, and conclusions were developed and verified by the authors. The authors reviewed and edited the AI-assisted text and take full responsibility for the content of the manuscript.

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References

- [1] L. Bonechi, R. D'Alessandro, and A. Giammanco, "Atmospheric muons as an imaging tool," *Reviews in Physics*, vol. 5, p. 100038, 2020.
- [2] L. Oláh, H. K. M. Tanaka, and D. Varga, *Muography: Exploring Earth's Subsurface with Elementary Particles*. Wiley AGU Books, 2022.
- [3] L. Cimmino, F. Ambrosino, A. Anastasio, C. Aramo, V. Bottiglieri, D. Iacopini, V. Masone, M. Mirra, G. Nyitrai, L. Repola, G. Saracino, and V. Tramontano, "Characterization and Performance Assessment of a SiPM-Based Muon Detector," *Instruments*, vol. 10, no. 2, p. 27, 2026, doi: 10.3390/instruments10020027.
- [4] G. Saracino et al., "Detection of cavities in a salt mine with cosmic muons: expected results and first data," *Scientific Reports*, vol. 15, p. 34147, 2025, doi: 10.1038/s41598-025-11685-5.
- [5] G. Anzelmo, G. M. Cella, C. Magistroni, A. Da Pra, and D. Iacopini, "CRS methodology applied to the Realmonte salt mine, south-western Sicily: an application for a hydrogen storage potential site in Italy," submitted to *International Journal of Hydrogen Energy*, preprint available on EarthArXiv, doi: 10.31223/X59791.
- [6] M. Amro, C. Freese, and F. Häfner, "Tightness of salt rocks using different gases for the purpose of underground storage," *Oil Gas European Magazine*, vol. 2, pp. 78–81, 2016.
- [7] U. Bunger et al., *Compendium of Hydrogen Energy*. Elsevier, 2016.
- [8] L. Driad-Lebeau et al., "Geophysical detection of underground cavities," in *Proc. Post-Mining Symposium*, Nancy, France, 2008.
- [9] I. Jones, "Seismic imaging in and around salt bodies," *Interpretation*, vol. 2, no. 4, 2014.
- [10] E. P. George, "Cosmic rays measure of overburden of tunnel," *Commonwealth Engineering*, pp. 455–457, 1955.
- [11] L. W. Alvarez et al., "Search for hidden chambers in the pyramids," *Science*, vol. 167, pp. 832–839, 1970.
- [12] G. Bonomi, P. Checchia, M. D'Errico, D. Pagano, and G. Saracino, "Applications of cosmic-ray muons," *Progress in Particle and Nuclear Physics*, vol. 112, 2020, doi: 10.1016/j.pnpnp.2020.103768.
- [13] L. Cimmino et al., "3D Muography for the Search of Hidden Cavities," *Scientific Reports*, vol. 9, p. 2974, 2019, doi: 10.1038/s41598-019-39682-5.
- [14] A. Samalan et al., "End-to-end simulations of the MUon RAdiography of VESuvius experiment," arXiv:2109.14324, 2021.
- [15] A. Anastasio et al., "The MU-RAY detector for muon radiography of volcanoes," *Nuclear Instruments and Methods in Physics Research Section A*, vol. 732, pp. 423–426, 2013, doi: 10.1016/j.nima.2013.05.159.
- [16] G. Saracino et al., "The MURAVES muon telescope: technology and expected performances," *Annals of Geophysics*, vol. 60, p. S0103, 2017, doi: 10.4401/ag-7378.
- [17] Y. Hong et al., "Updates on MURAVES Project at Mt. Vesuvius," *Journal of Applied Physics*, vol. 138, p. 064906, 2025.
- [18] M. Guan et al., "A parametrization of the cosmic-ray muon flux at sea-level," arXiv:1509.06176, 2015.
- [19] D. Varga, G. Nyitrai, G. Hamar, and L. Oláh, "High Efficiency Gaseous Tracking Detector for Cosmic Muon Radiography," *Advances in High Energy Physics*, vol. 2016, Art. no. 1962317, 11 pages, 2016, doi: 10.1155/2016/1962317.