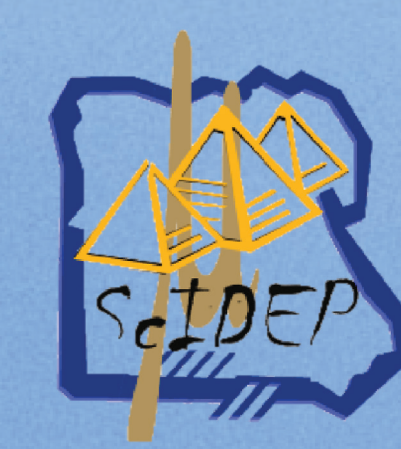


The ScIDEP Muon Radiography Project at the Egyptian Pyramid of Khafre

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BACKGROUND

Pyramid of Khafre

On Giza Plateau in Greater Cairo, Egypt;
 2nd tallest pyramid of Egypt.

Original Height: 143.5 m
 Current Height: 136.4 m
 Length of Side: 215.25 m
 Slope angle: 53° 10'



Constructed between 2600 and 2500 BC, during Fourth Dynasty of the Old Kingdom of Ancient Egypt.

Built of pink granite bottom course, rest is Tura limestone; most of outer limestone casing was stripped.

Two entrances and two rooms, i.e. subsidiary room and burial chamber (14 x 5 x 6.8 m³), slightly off-centered at bottom of pyramid.

The pyramid's internal structure is less complex than that of the Pyramids of Khufu and Snefru. **Architectural simplicity after the construction of the Great Pyramid or hidden chambers?**

Muon radiography

Principle: measuring the differential attenuation of the cosmic-ray muon flux as a function of the amount of material crossed along different directions, allows to determine the **density distribution of the interior of a large object**.

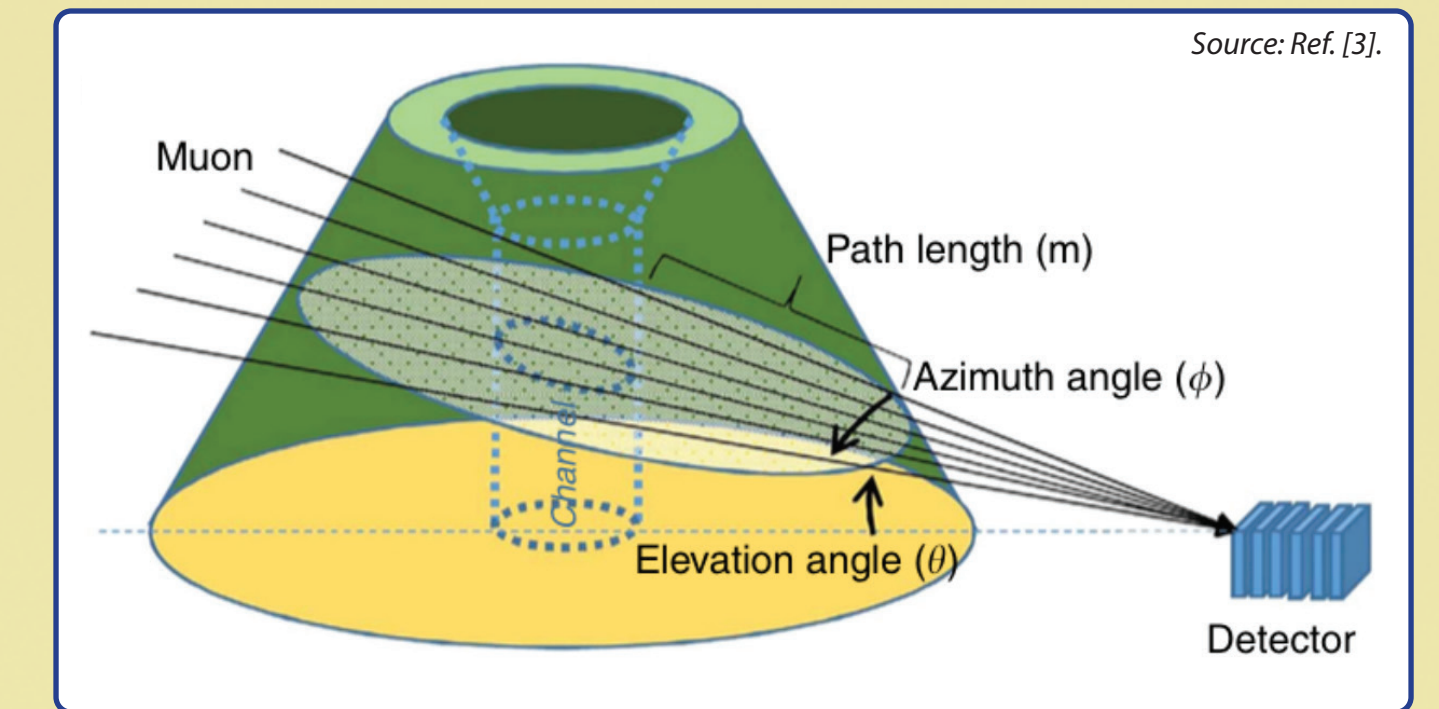
Tracks of through-going muons are measured and the angular distribution of the reconstructed trajectories is compared to that expected in the absence of absorption (obtained from a detector pointing directly to the free sky or from Monte Carlo simulations, or both). Requires a muon telescope, i.e. multiple layers of position sensitive muon detectors.

An expected muon flux is then obtained from a map of the average density and traversed thicknesses as given by a Digital Terrain Model (DTM).

- Low density region (e.g. cavity): excess in muon transmission
- High density region: deficit in muon transmission

Application to the Egyptian Pyramids

In 2017-2021, the ScanPyramids[1] collaboration discovered hidden voids (30 m and 9 m long) in the Pyramid of Khufu using muography, validated by multi-technique analysis.



Muon transmission

N_m : measured counts transmitted through target
 N_{FS} : measured counts without target (= free sky)
 ϵ : detector efficiency
 t : data acquisition time

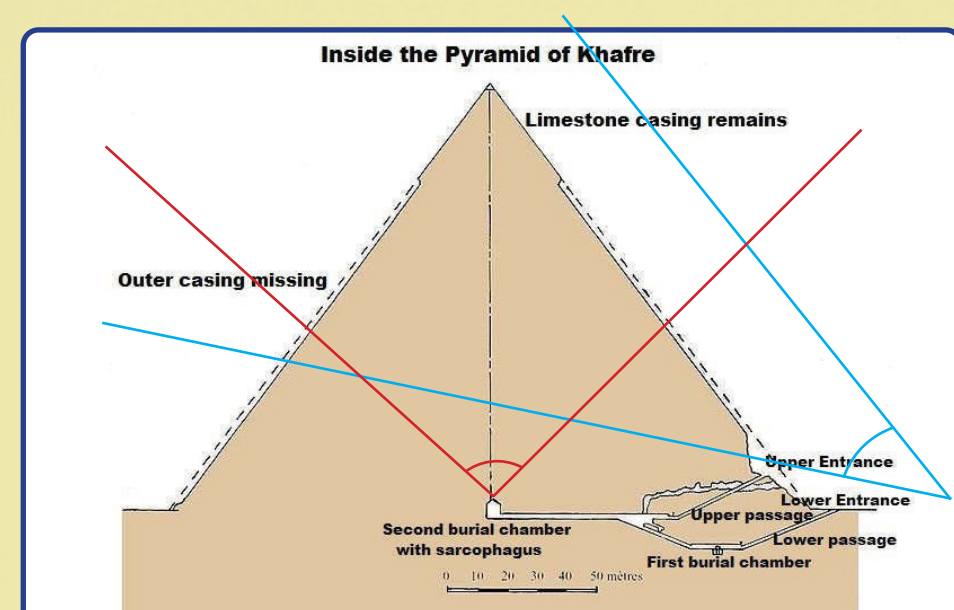
$$T_m(\theta, \phi) = \frac{\epsilon_{FS} t_{FS} N_m(\theta, \phi)}{\epsilon t N_{FS}(\theta, \phi)}$$

METHODS

Scintillator Imaging Detector for the Egyptian Pyramids (ScIDEP)

Initiated in 2020 to target the Pyramid of Khafre. Current collaborators from Egypt, USA, Belgium and Romania.

Install muon telescopes outside pyramid and inside burial chamber (same location as Alvarez [2] measurements).



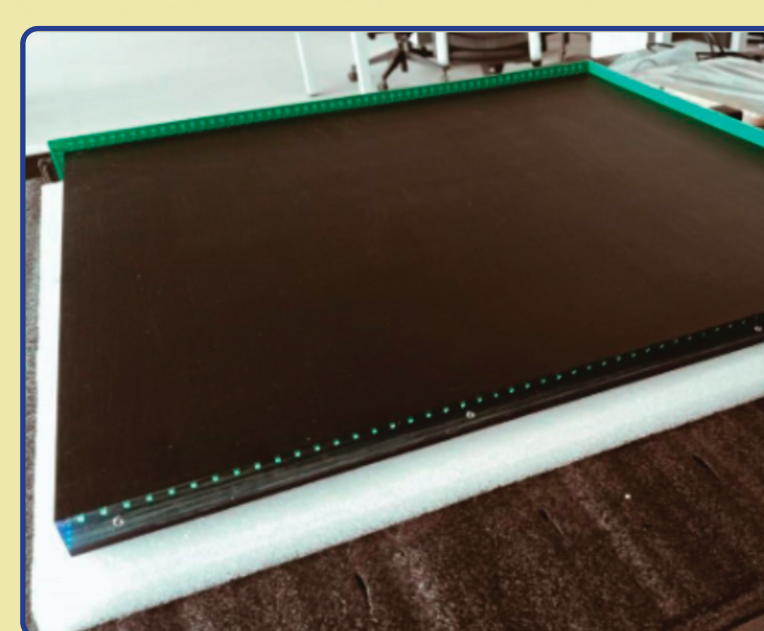
Non-destructive imaging of the interior of the Pyramid of Khafre.

Muon telescopes

Two scintillator-based detectors: option for 3D imaging.

Detector 1:

- PVT scintillator plates
- WLS fibers spaced 1 cm apart
- SiPMs for signal read out



Detector 2:

- Plane made up of scintillator bars
- 1 WLS fiber & SiPM per bar

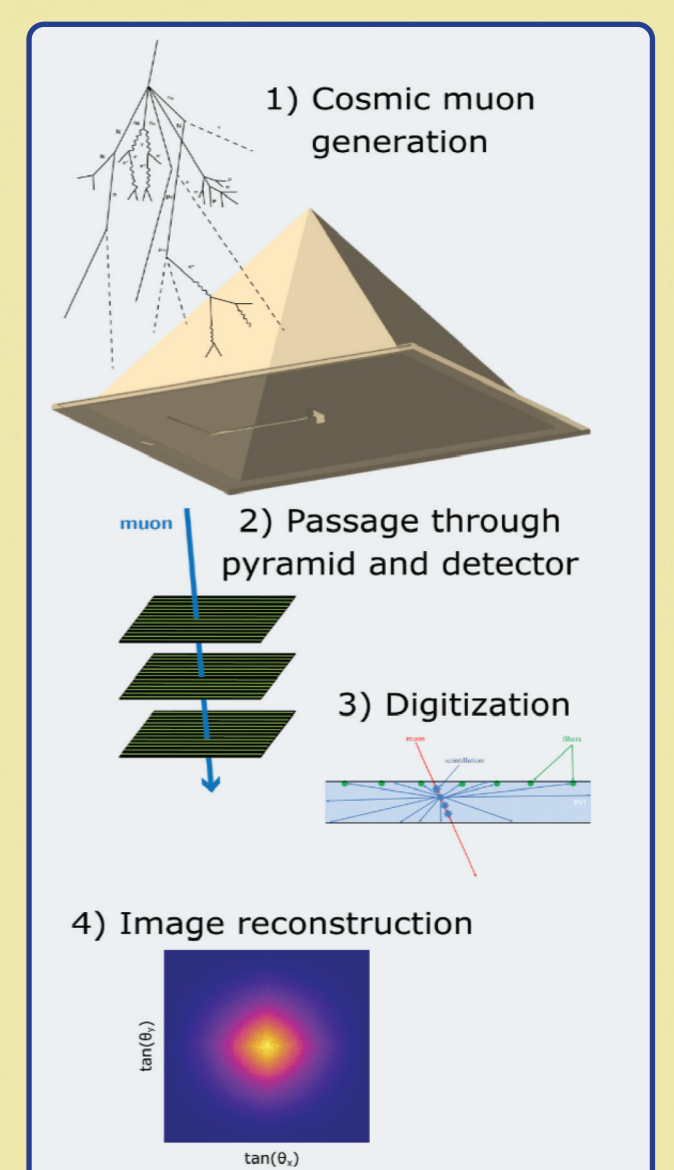


Orthogonal placement of WLS fibers for hit coordinate reconstruction.

Monte-Carlo simulation pipeline

Development of full simulation chain ongoing.

1. Cosmic muon generation: EcoMug
2. Passage of muons through matter: Geant4
 - Detailed detector model
 - Pyramid imported as CAD model
3. Digitization:
 - Hit coordinate reconstruction: weighted average of fiber positions
 - Track reconstruction: based on Hough transform principle
4. Image reconstruction
 - Transmission image



Result: 2D map of opacity & 3D map of density.

INITIAL SIMULATION STUDIES: RESULTS

Quantitative region-of-interest (ROI) evaluation

How well can a target cavity be resolved in a reconstructed image?

Look at a signal region-of-interest (ROI) covering the expected cavity location, and a nearby background ROI in a region free of cavity structure.

To quantify visibility and significance:

- Contrast-to-noise ratio CNR: ability to distinguish target signal from its background noise.
- Z_{ROI} : standardized distance between two regional means.

$$CNR = \frac{|\bar{\rho}_s - \bar{\rho}_b|}{\sqrt{\sigma_s^2 + \sigma_b^2}}$$

$$Z_{ROI} = \frac{|\bar{\rho}_s - \bar{\rho}_b|}{\sqrt{\sigma_s^2/N_s + \sigma_b^2/N_b}}$$

To compare the cavity signal strength across different detector positions, different exposure statistics or different reconstruction settings:

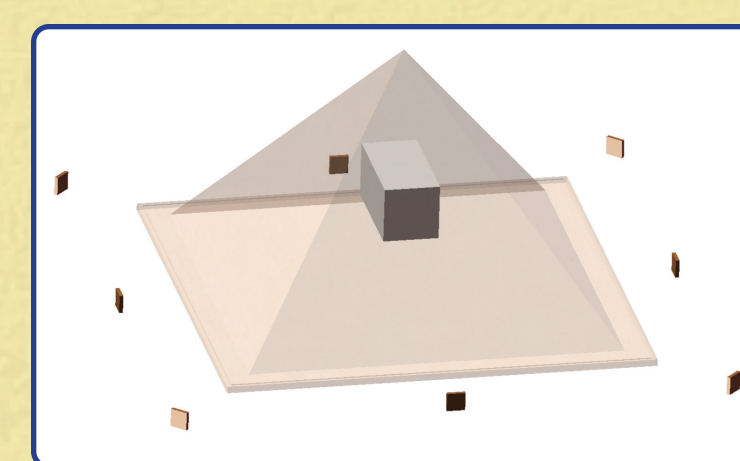
- C_{rel} : fractional reduction of ROI density w.r.t. background.

$$C_{rel} = \frac{\bar{\rho}_b - \bar{\rho}_s}{\bar{\rho}_b}$$

2D: Truth opacity distributions

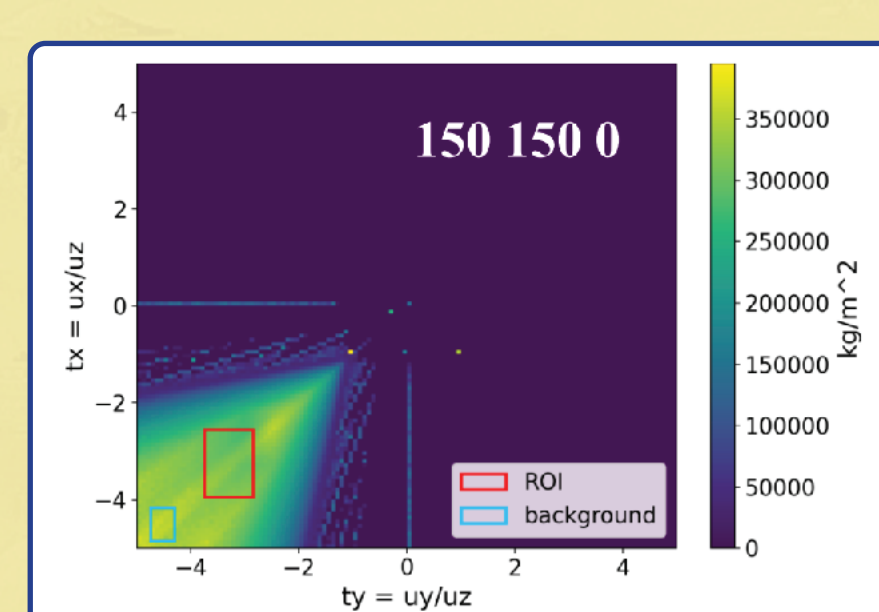
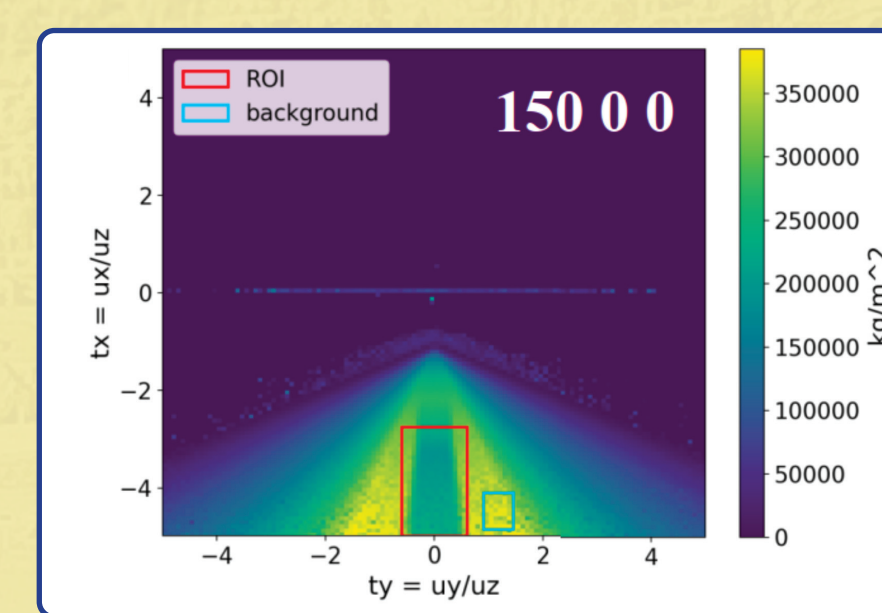
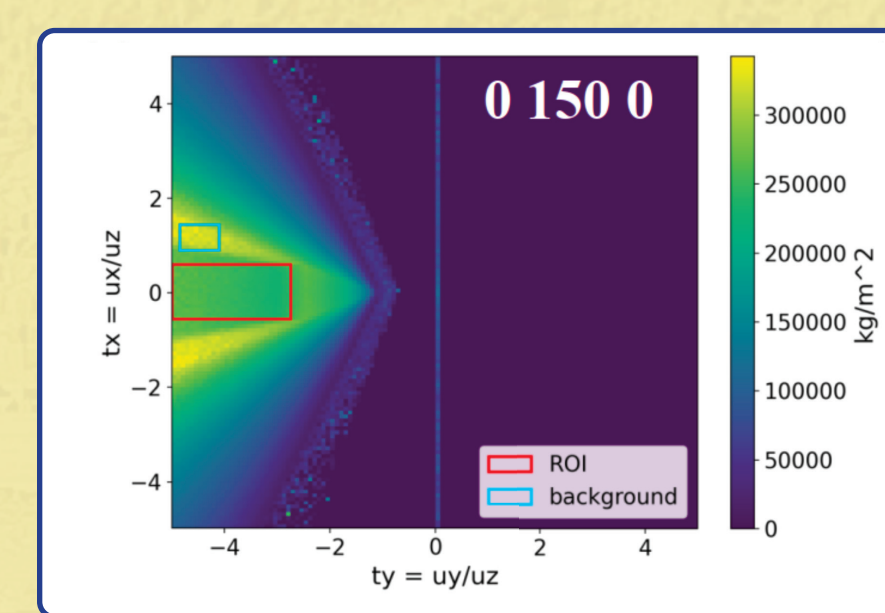
Objective: simulate transmission through pyramid, to gain preliminary insights on feasibility of void detection.

Muon back-sampling algorithm: muon generation restricted to field of view of detector, resulting in faster data acquisition.



- Hypothetical void: 30 m x 30 m x 60 m
- 8 detectors placed around pyramid

Truth opacity distributions: integrating geometrical model along each emission direction to assess geometrical sensitivity to the cavity.

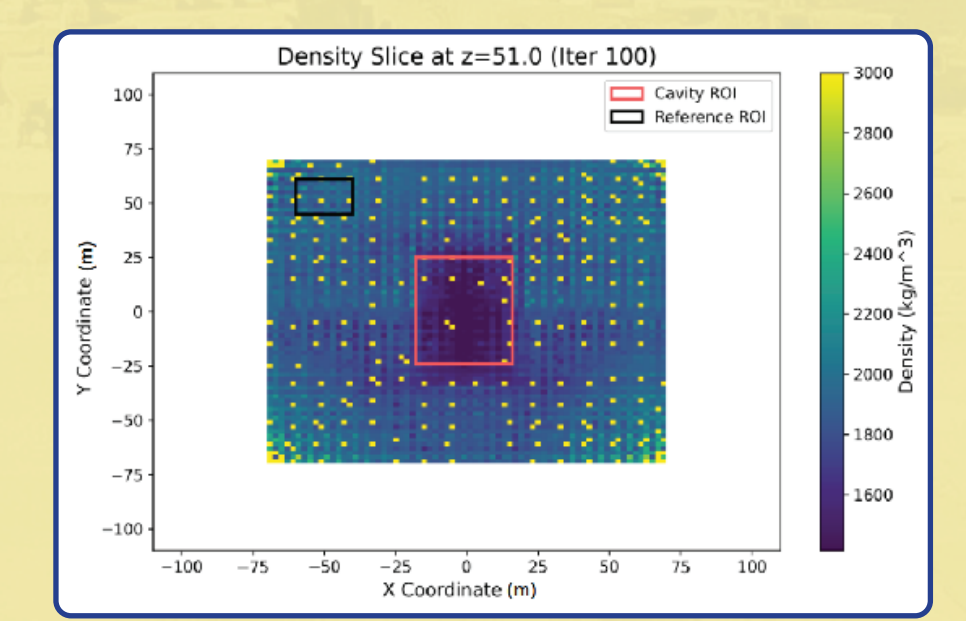
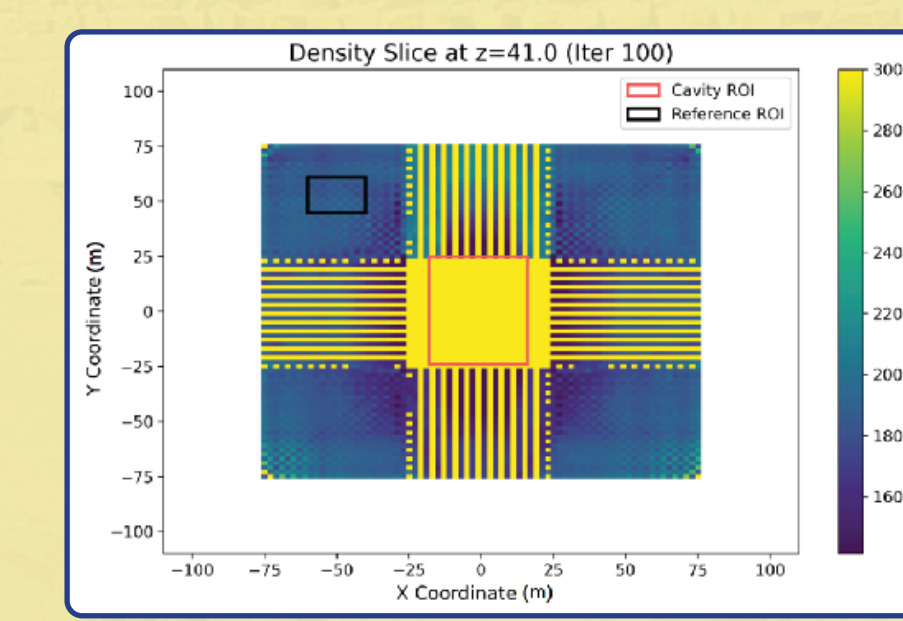
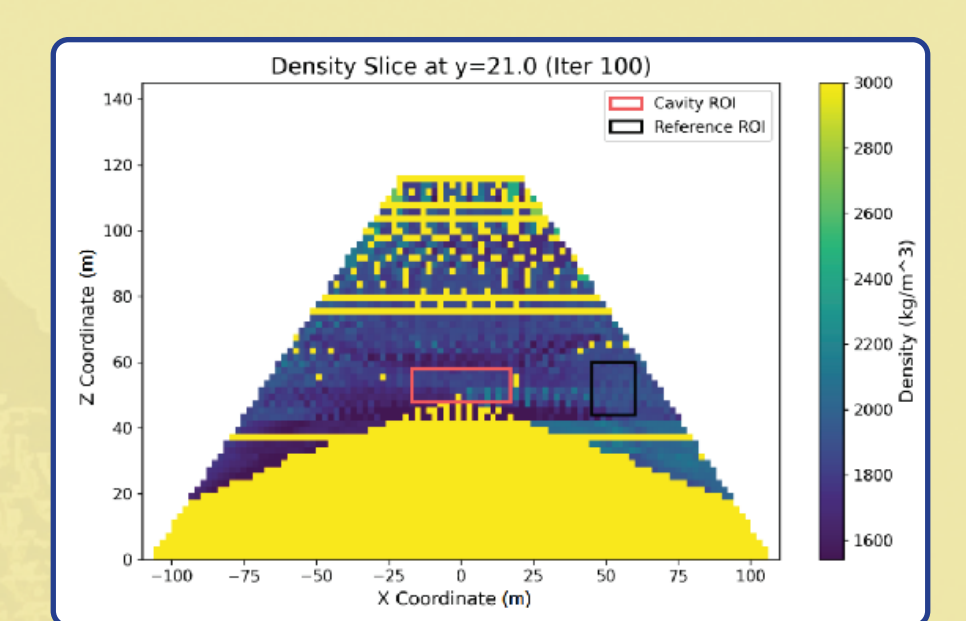
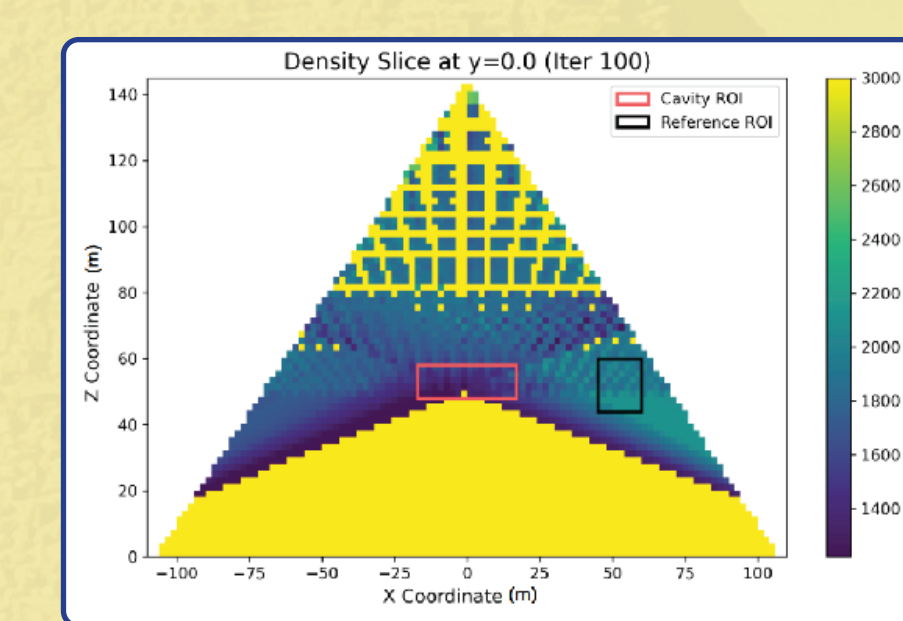


Edge-midpoint directions accumulate the cavity-induced opacity deficit more efficiently, while oblique corner views dilute the signal with longer solid paths.

3D: Density map using SART

Simultaneous algebraic reconstruction technique (SART): updates all voxel opacity values simultaneously at each iteration by distributing the difference between measured and projected muon flux across all contributing voxels, weighted by their path lengths.

Well-suited for muography data (sparse and noisy).



- Strongest low-density responses in central slices ($y = 0$ m, $z = 51$ m), confirming cavity's spatial recovery.
- Contrast weakens in off-center slices ($y = 0$ m) due to asymmetric ray coverage.
- Relative density sign reversals at upper and lower boundaries ($z = 41$ m) reflect the cavity's finite vertical extent rather than reconstruction failure.

The reconstructed anomaly recovers the main spatial position of the hypothetical cavity in 2D and 3D; fine boundaries should be interpreted with caution under limited-angle SART.

References & further reading

- [1] K. Morishima et al, Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons, Nature (2017) 386-390; DOI: 10.1038/nature24647
- [2] L. W. Alvarez et al, Search for Hidden Chambers in the Pyramids, Science (1970) 832-839; DOI: 10.1126/science.167.3919.832
- [3] D. Hatzifotiadou, Muon radiography—muon tomography, in 19th IPPOG Meeting, 2020
- [4] De Morgen, "Zo groot als een Boeing: kosmische straling onthult enorme ruimte in piramide van Cheops," De Morgen, 2024.

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OUTLOOK

The next steps are to finalize detector construction and preparation, including field logistics, and pyramid access permissions must be arranged with the Egyptian authorities to start initial field measurements.