Application of Muography in Geological Monitoring During Shield Tunneling: Long-Term Field Validation in Complex Urban Environments

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Outline

Introduction-Muography

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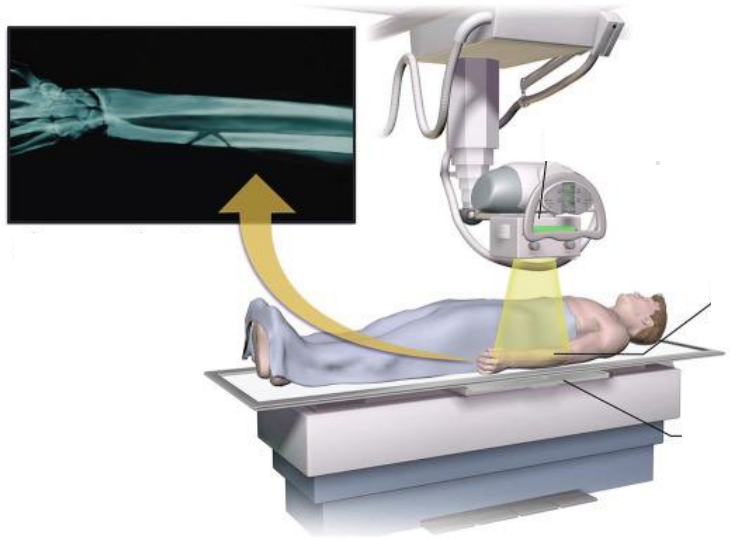
All-weather, Non-destructive, Wide range, Anti-interference

CT Imaging

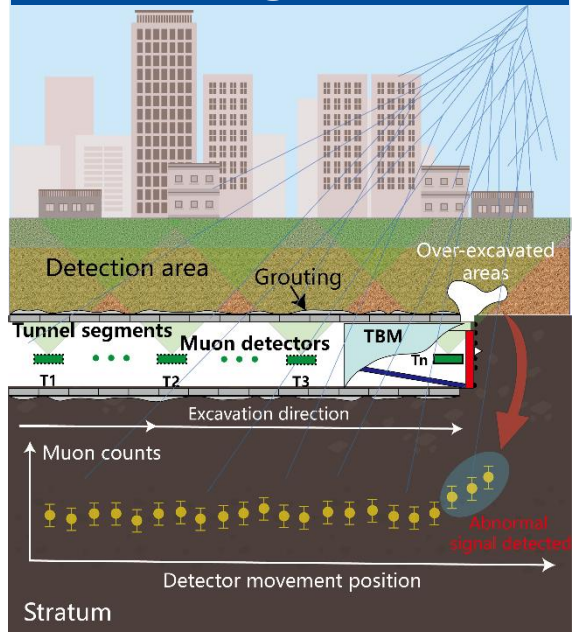


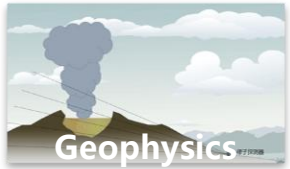
X-ray Source→ Natural Muons

Human Body → Subsurface Strata

X-ray Detector→ muon Detector

Muography





Introduction-Undergroud safety

Urban Underground Infrastructure

Driven by rapid urbanization and growth of subways and integrated utility tunnels.

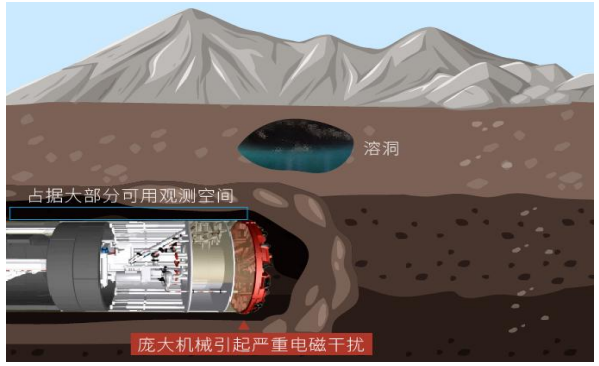
Gushing water

Ground collapse

Deep **Large** **Many** **Hidden**

3D detection and dynamic monitoring of concealed spaces for underground safety.

Geological Investigation



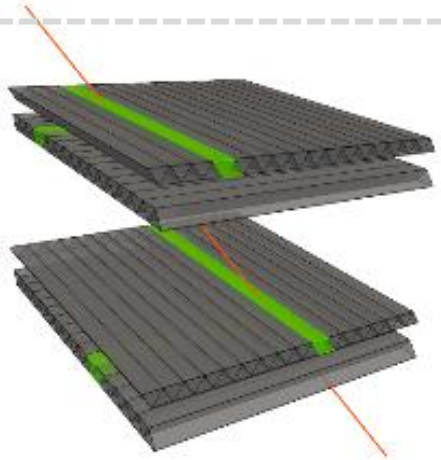
Tunnel Construction

Operations & Maintenance

Hardware and Software

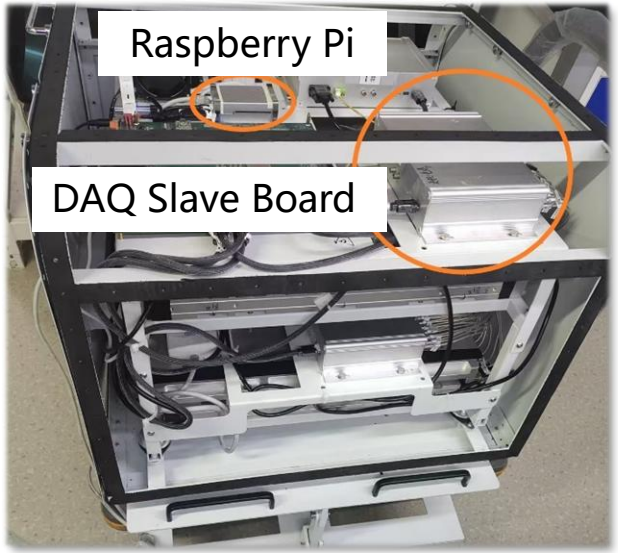
Parameters of the Muon Detector

Detector Size	50 * 50 * 5 cm^3	Power Consumption	≤ 30 W
Detector Weight	20 Kg * 4	Position Resolution	2.5 mm
Overall Size	1 * 0.8*1 m^3	Efficiency(Each layer)	≈97.98%
Overall Weight	100 Kg	Acceptance Angle	120° Cone



Accurate reconstruction of muon tracks

Internal Structure of the Detector

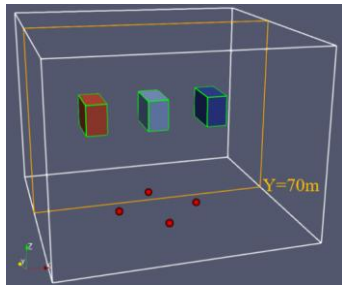


Customized Standards for Subway Tunnels and Underground Engineering:

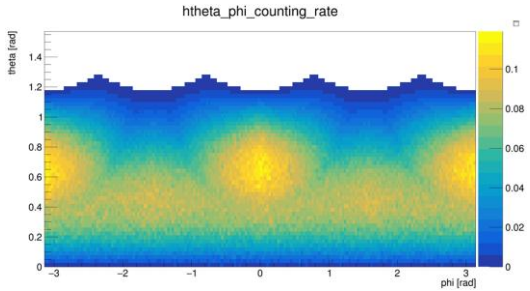
- Anti-vibration
- Dust-proof
- Moisture-proof
- Modular Design
- High Compatibility

Hardware and Software

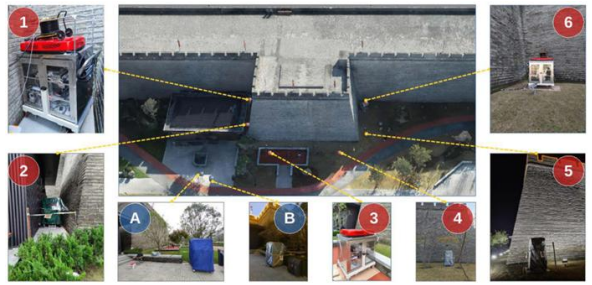
Forward Algorithm



Hypothetical Model



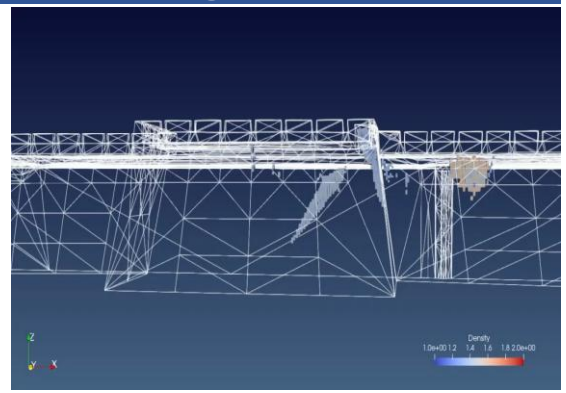
Simulation Data



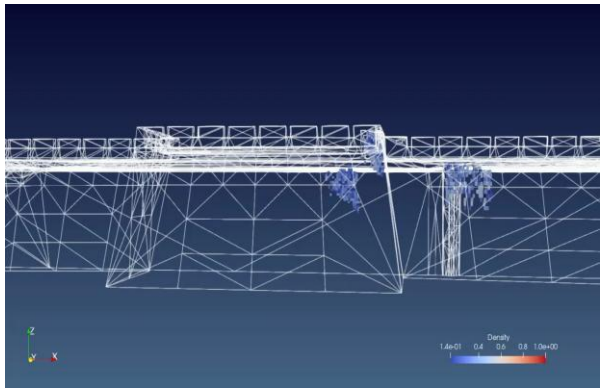
Deployment Plan

Conduct a comprehensive and rational feasibility analysis utilizing the forward algorithm to establish the optimal deployment strategy.

Inversion Algorithm Results

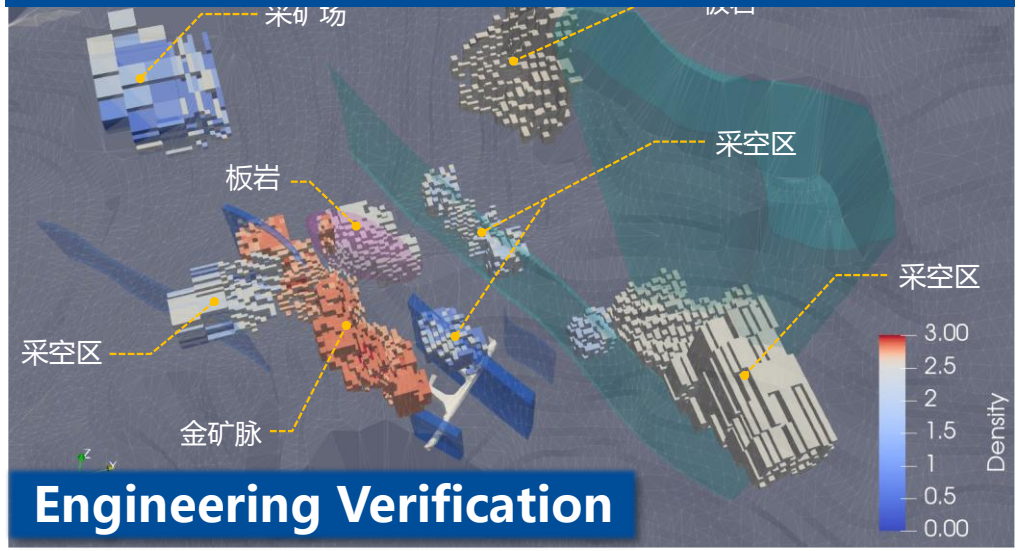


L-BFGS Algorihem
Fast



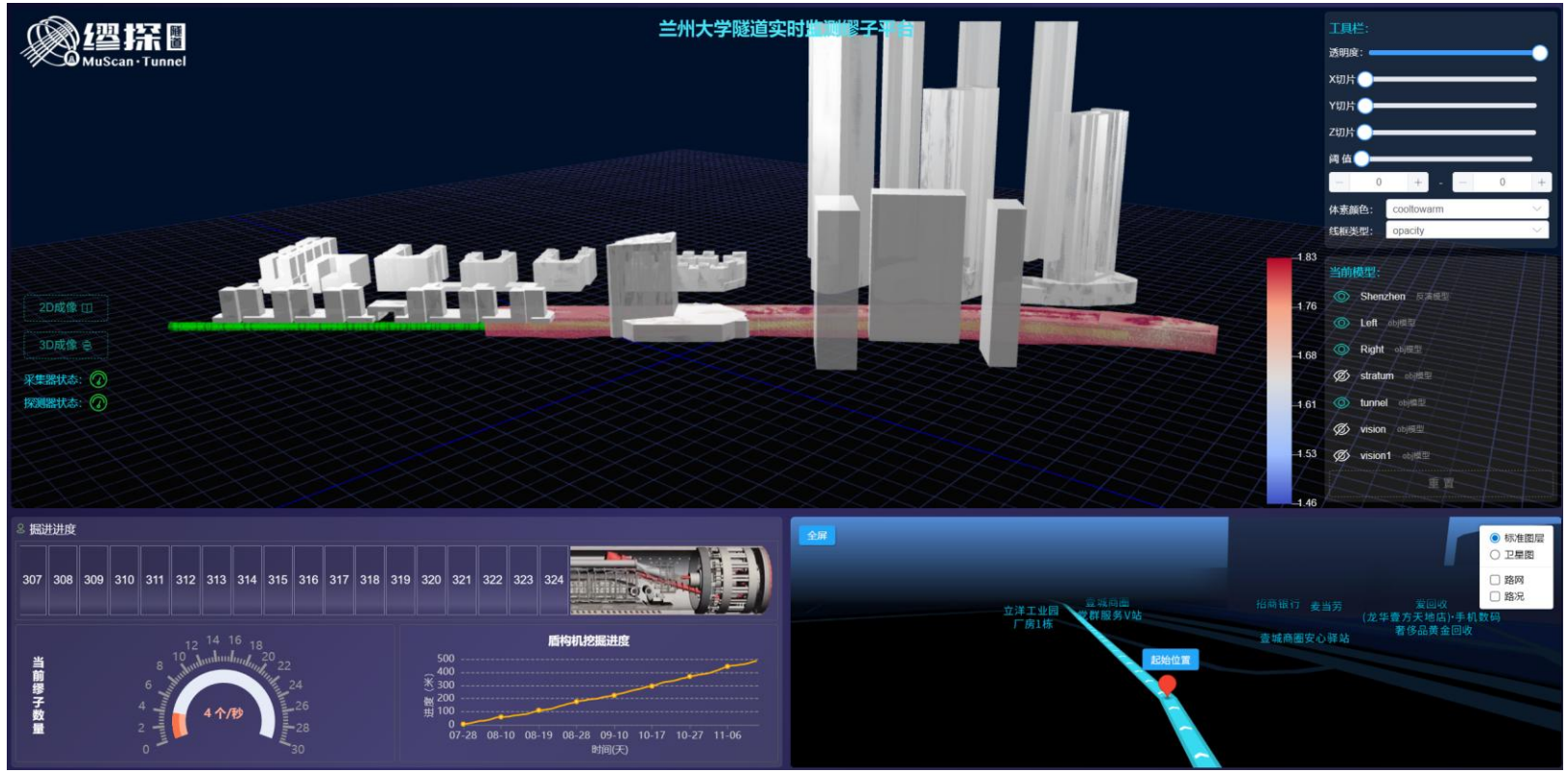
Seed Algorihem
Accurate

Results of the Zaozigou Gold Mine (200+m Depth)



Engineering Verification

Experiment-Platform

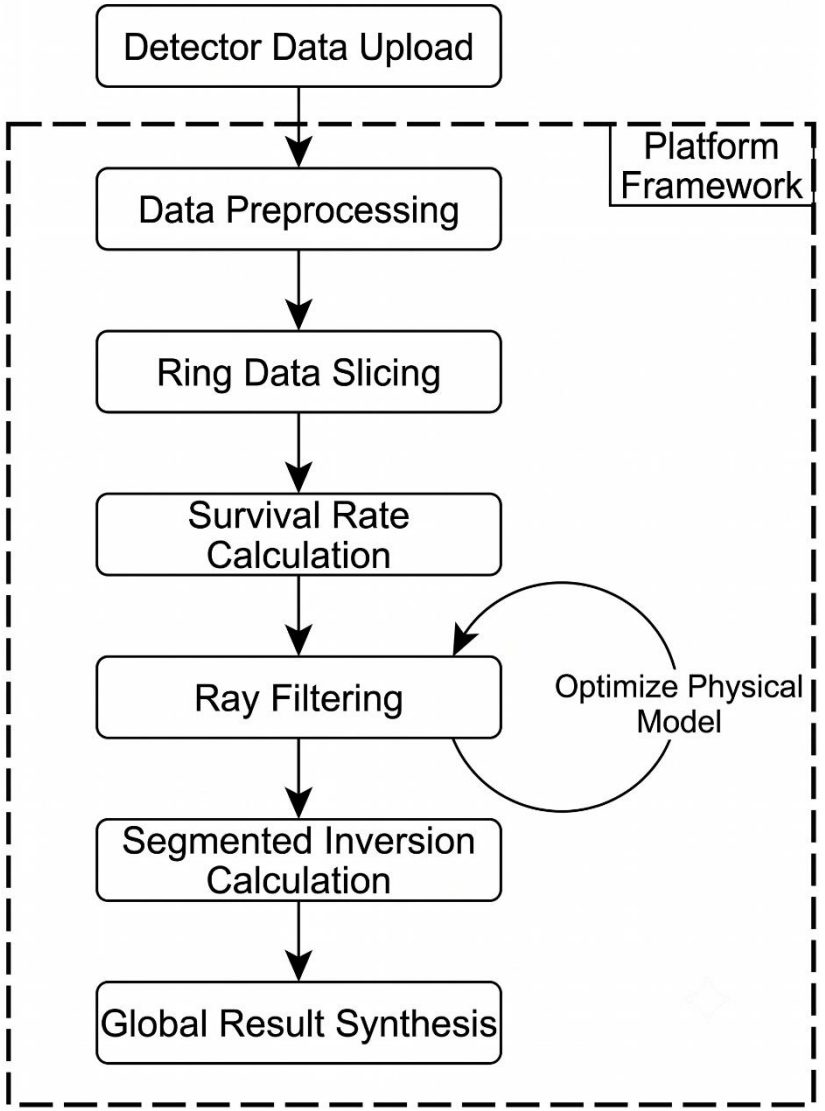


Fully Automated 3D Muography

It performs imaging and data inversion in dynamic during tunneling, requiring zero manual effort.

Cloud-Powered Processing

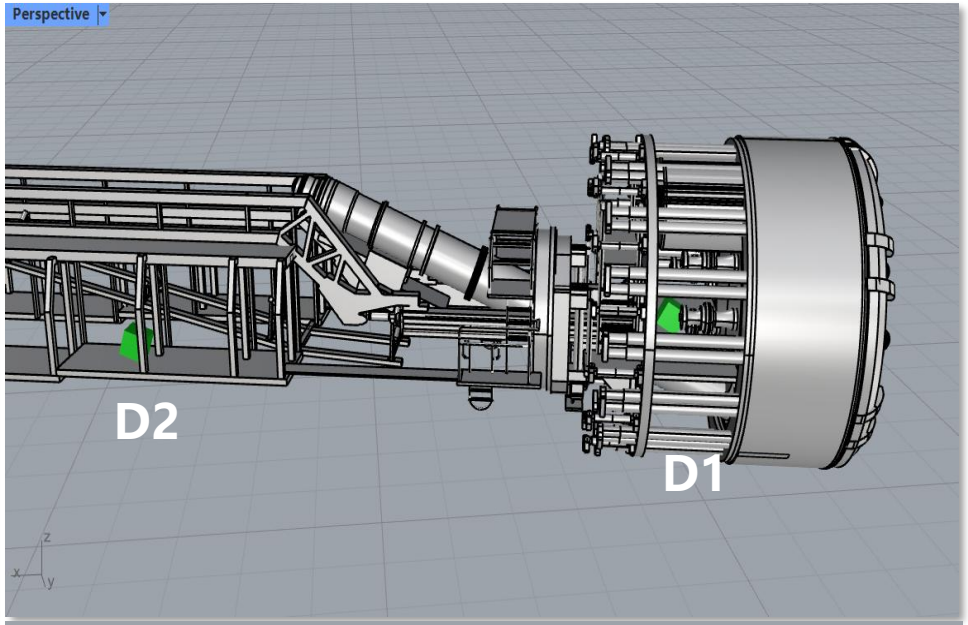
It uses cloud computing to speed up data inversion and 3D visualization.

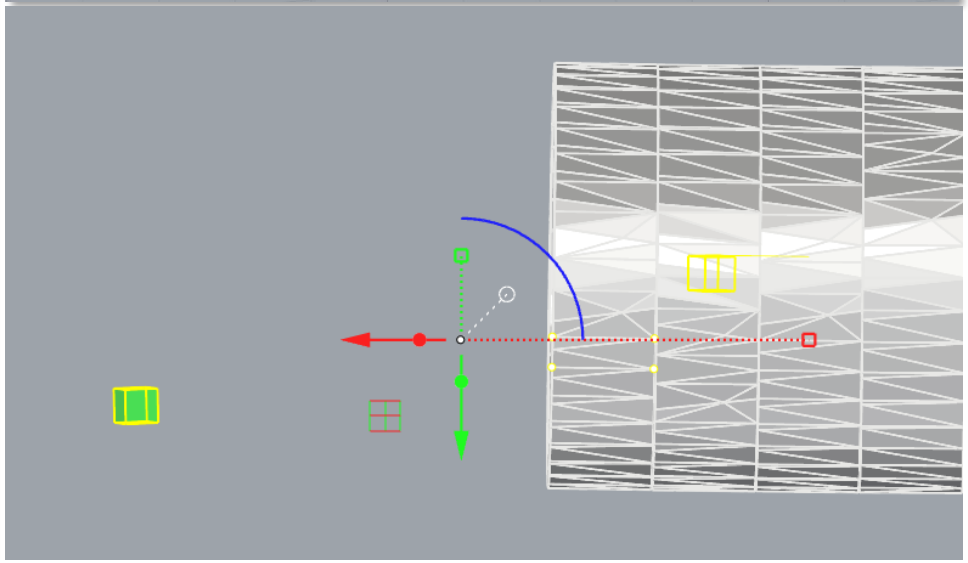


Experiment-Detector Layout

Detector No. 2 (D2)

Detector No. 1 (D1)

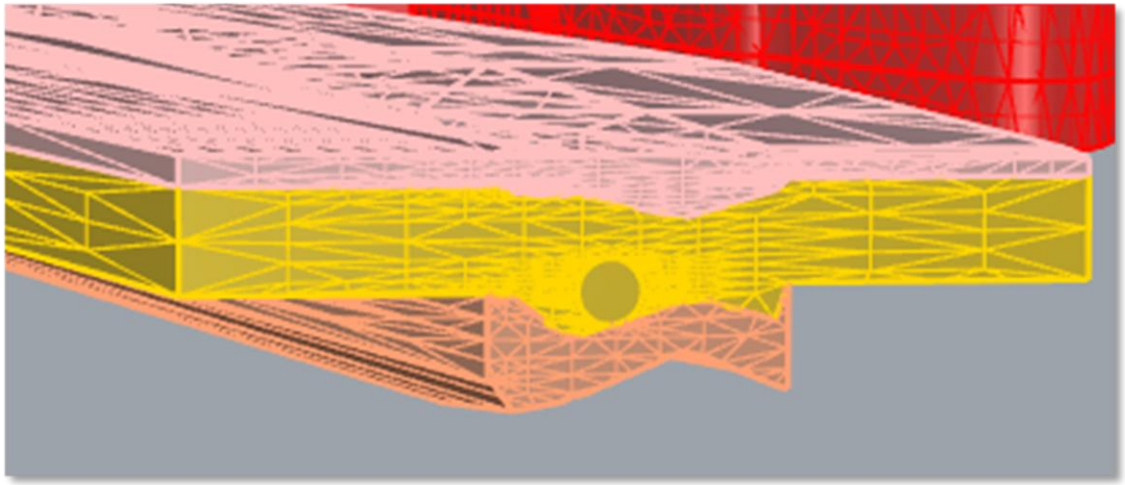


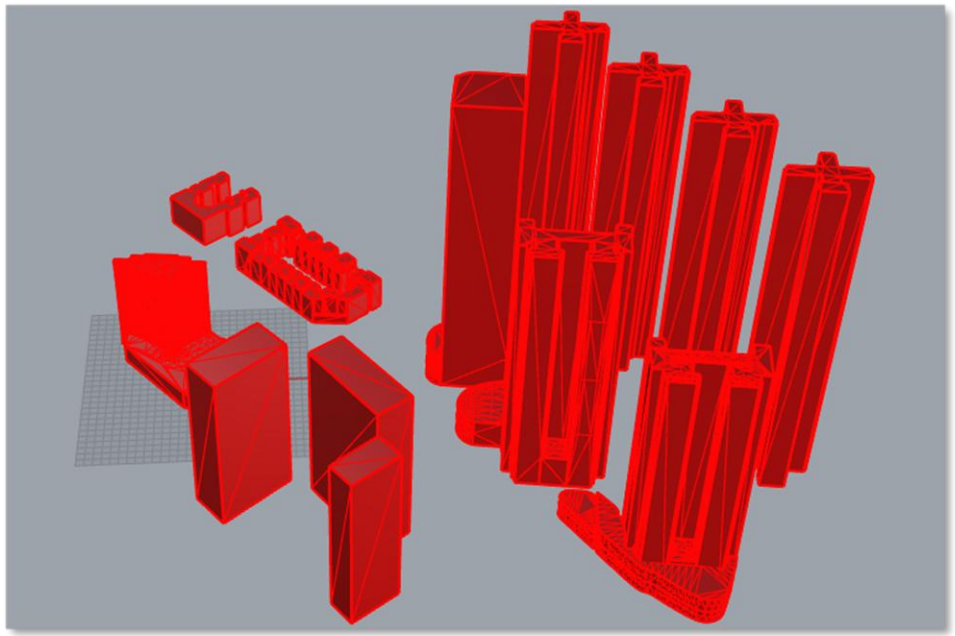


- **D1** is approx. 4.5m from the cutterhead at a 20° inclination;
- **D2** is approx. 15m from D1 at a 30° inclination.

The position of **D1** is approximately 0.75 meters ahead of the most recently installed segment ring.

Experiment-Models





A stratigraphic model was generated using provided datas, consist of plain fill, Gravelly Cohesive Soil, and Completely Weathered Granite. Simultaneously, 3D models of surrounding buildings were built utilizing CAD files and story counts.

Components	Color	Reference Density(g/cm^3)
Plain Fill	Pink	1.8
Gravelly Cohesive Soil	Yellow	1.82
Completely Weathered Granite	Orange	1.88
Office Building	White	0.2
Residential Building	Red	0.15–0.25
Construction in Progress	Green	0.15

Experiment-Muon Counts

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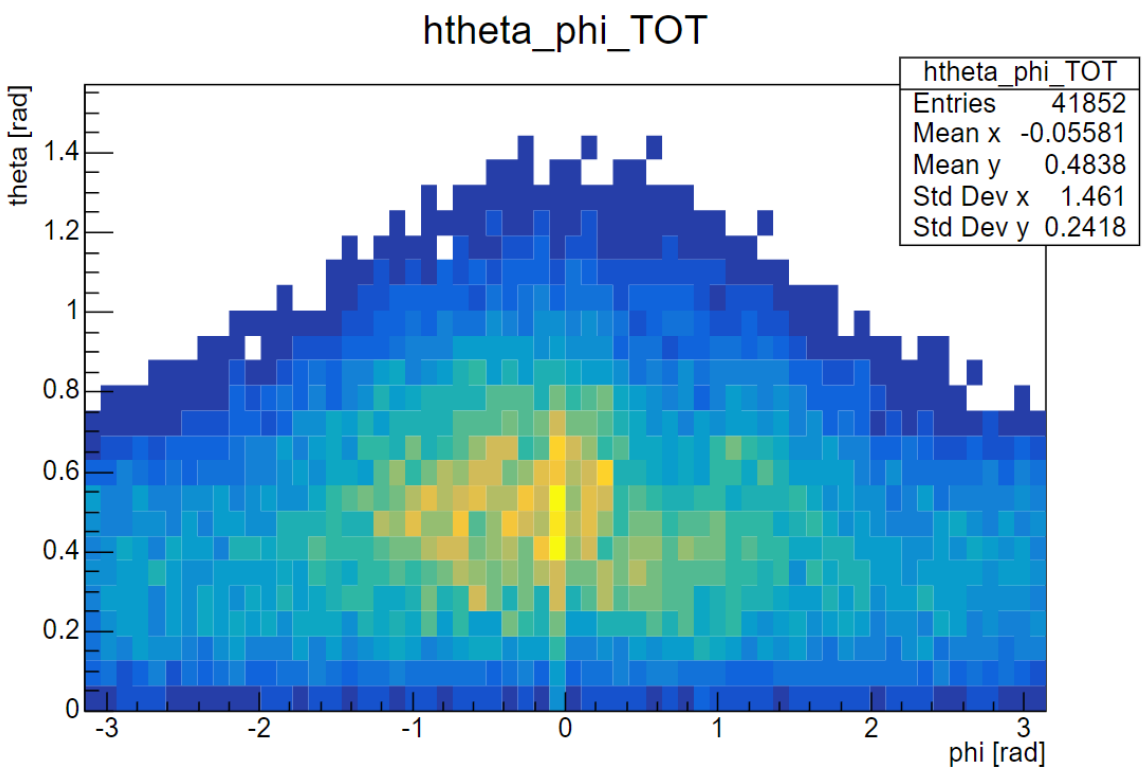
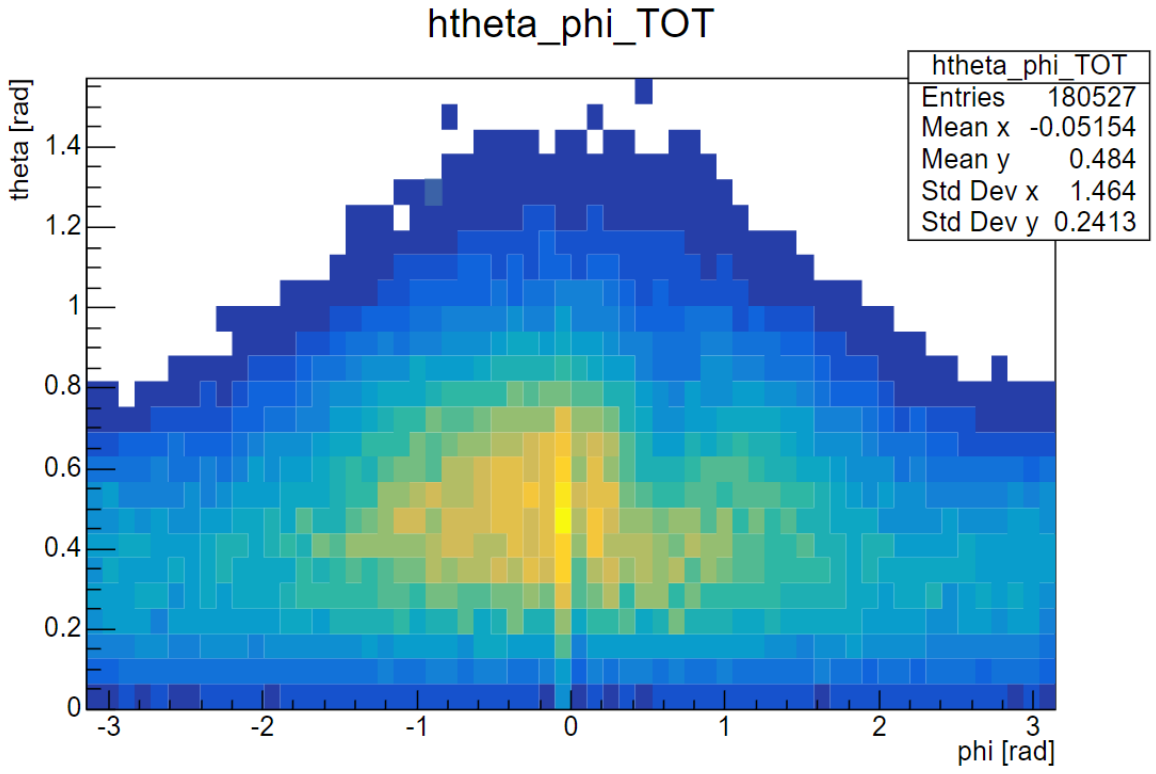
Measured Count Distribution for D1 at Ring 220



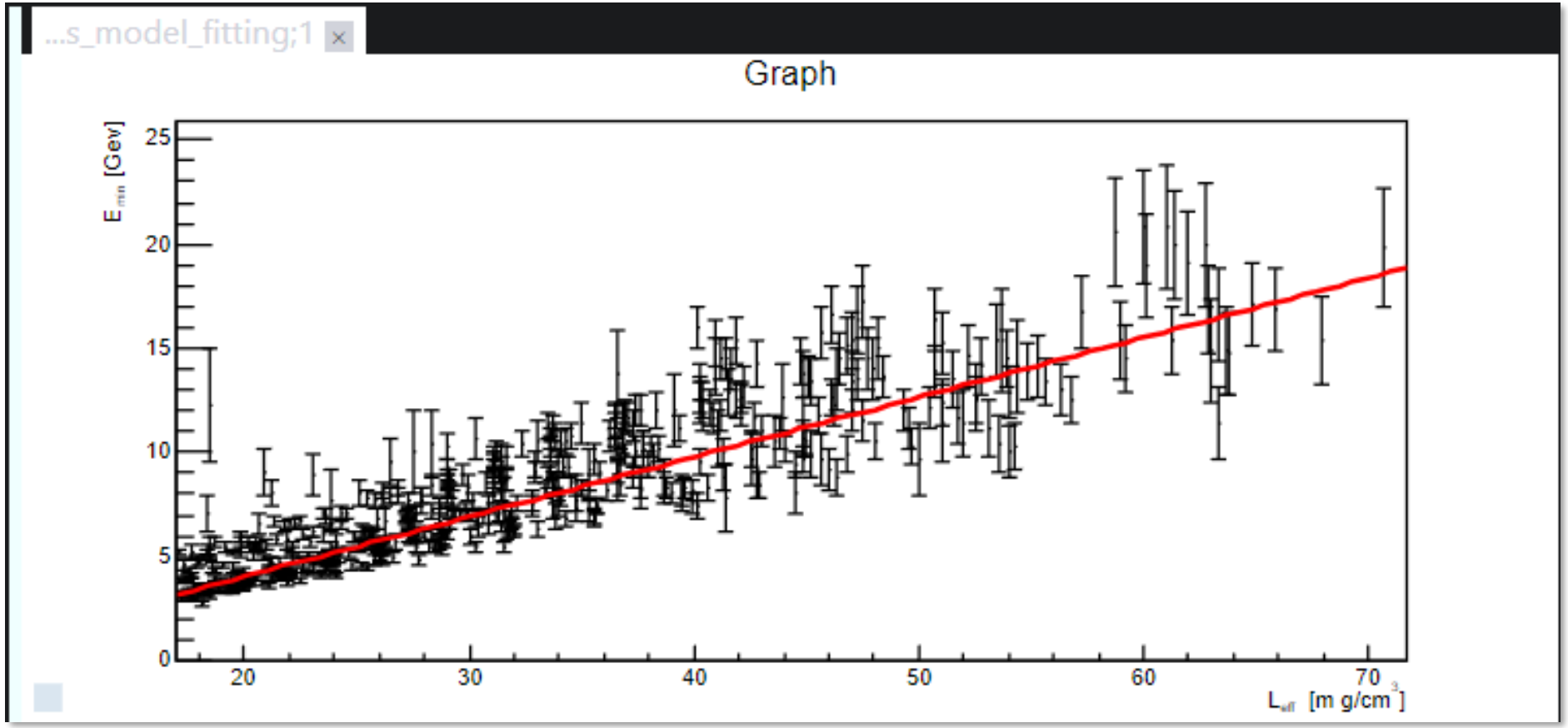
Measurment Time：3.63 h

Measured Count Distribution for D1 at Ring 221



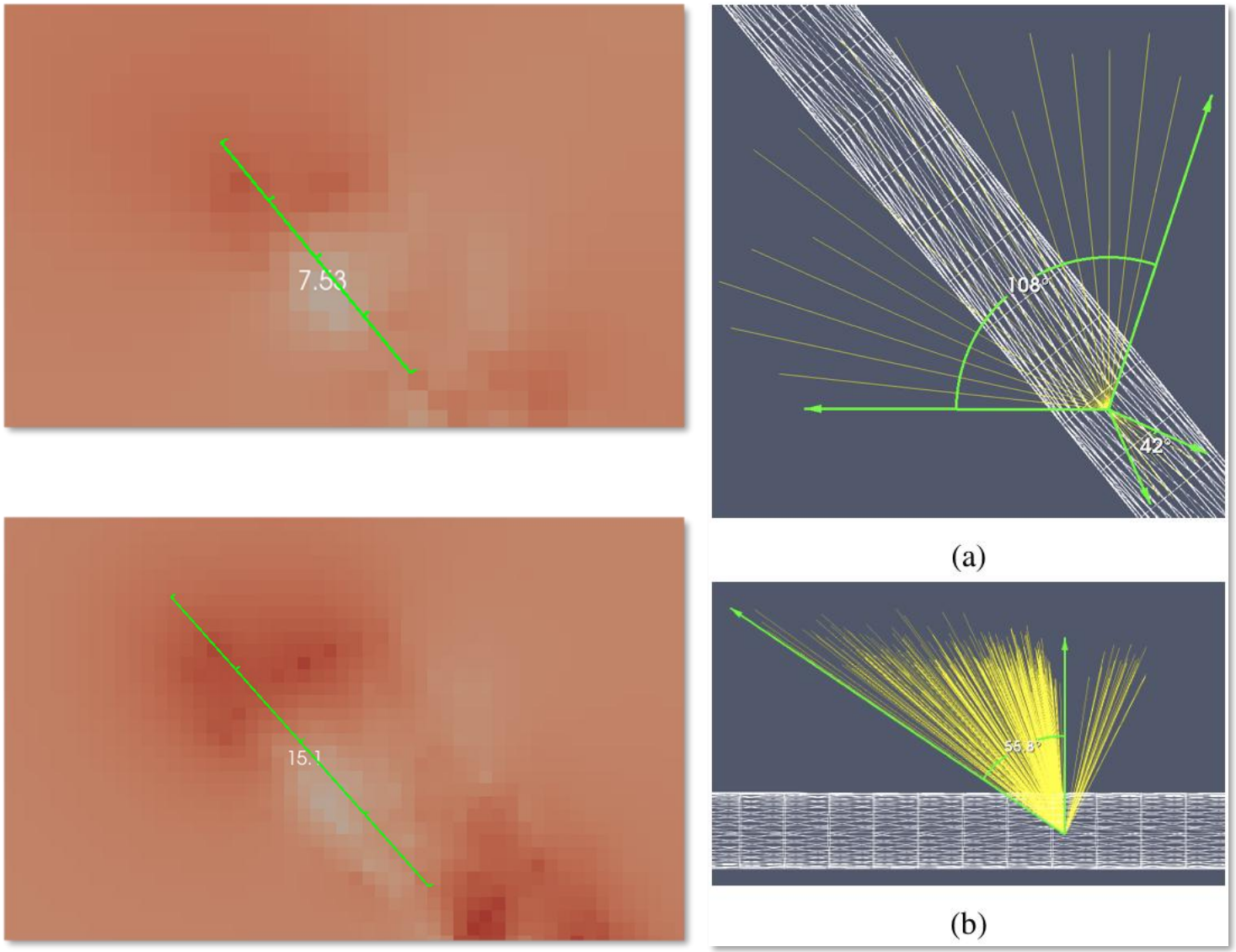
Measurment Time：15.2 h

Experiment-Physics Model Fitting



Physical model fitting is used to ensure simulated data matches measurements in anomaly-free zones, and help transforming the survival rate to effective density length.

Results Discussion-Advance Probing Capability



(a)

(b)

- **Advance Probing Distance:**

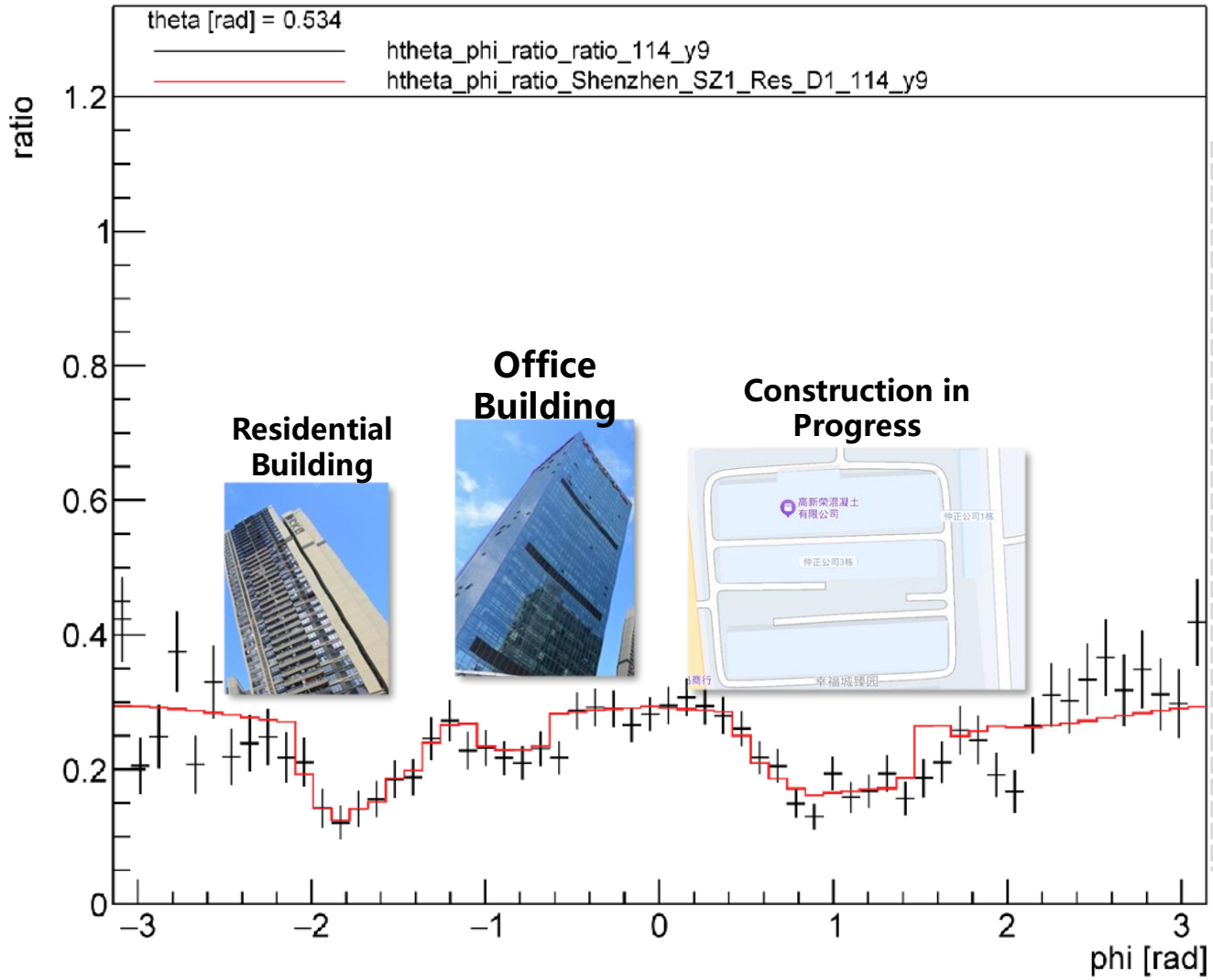
  Approximately 8–15m ahead;

- **Effective Probing Scope:**

  ~55° ahead

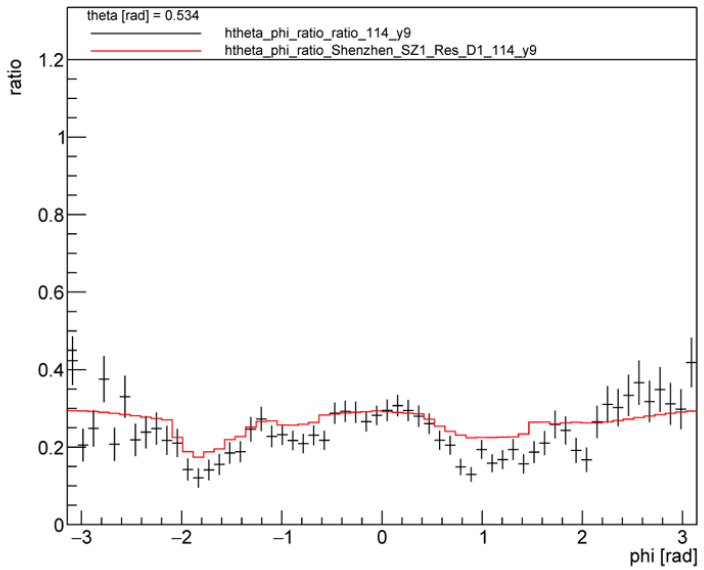
  ~108° sector

Results Discussion-Influence of Buildings

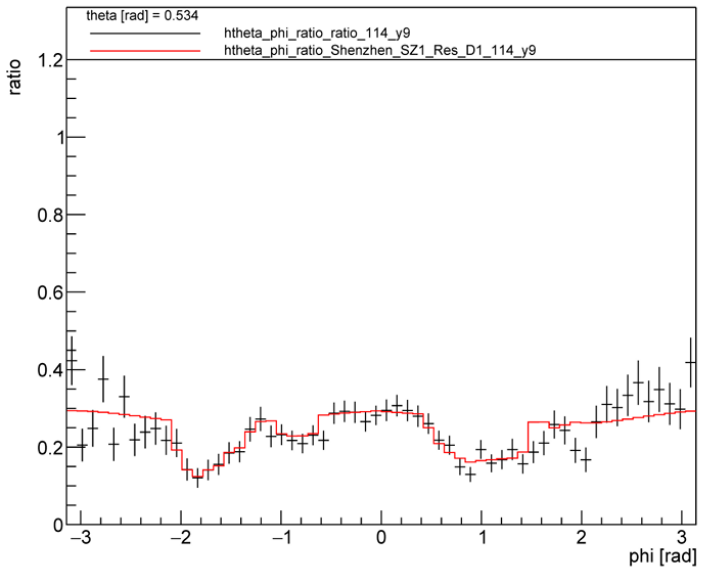


The material composition, design, physical state, and geometric profiles of individual buildings directly impact the imaging results. Inaccurate modeling of these surface structures causes significant deviations between predicted and measured data, ultimately degrading the final imaging precision.

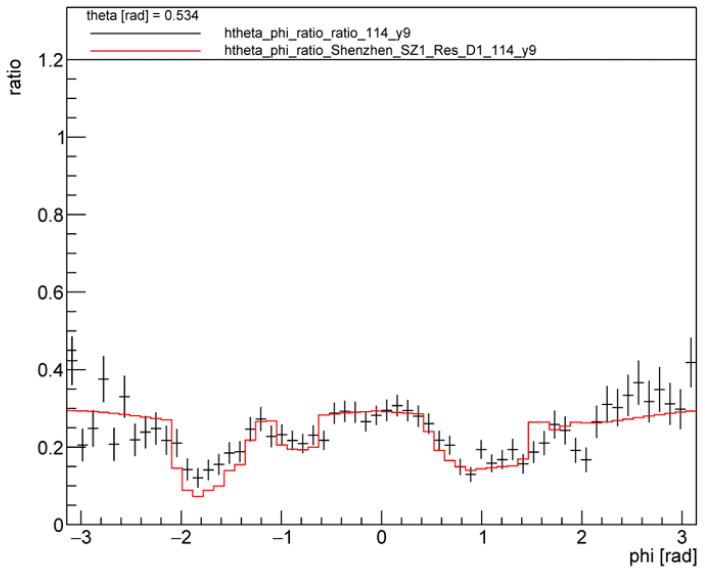
Results Discussion-Influence of Buildings



(a)



(b)

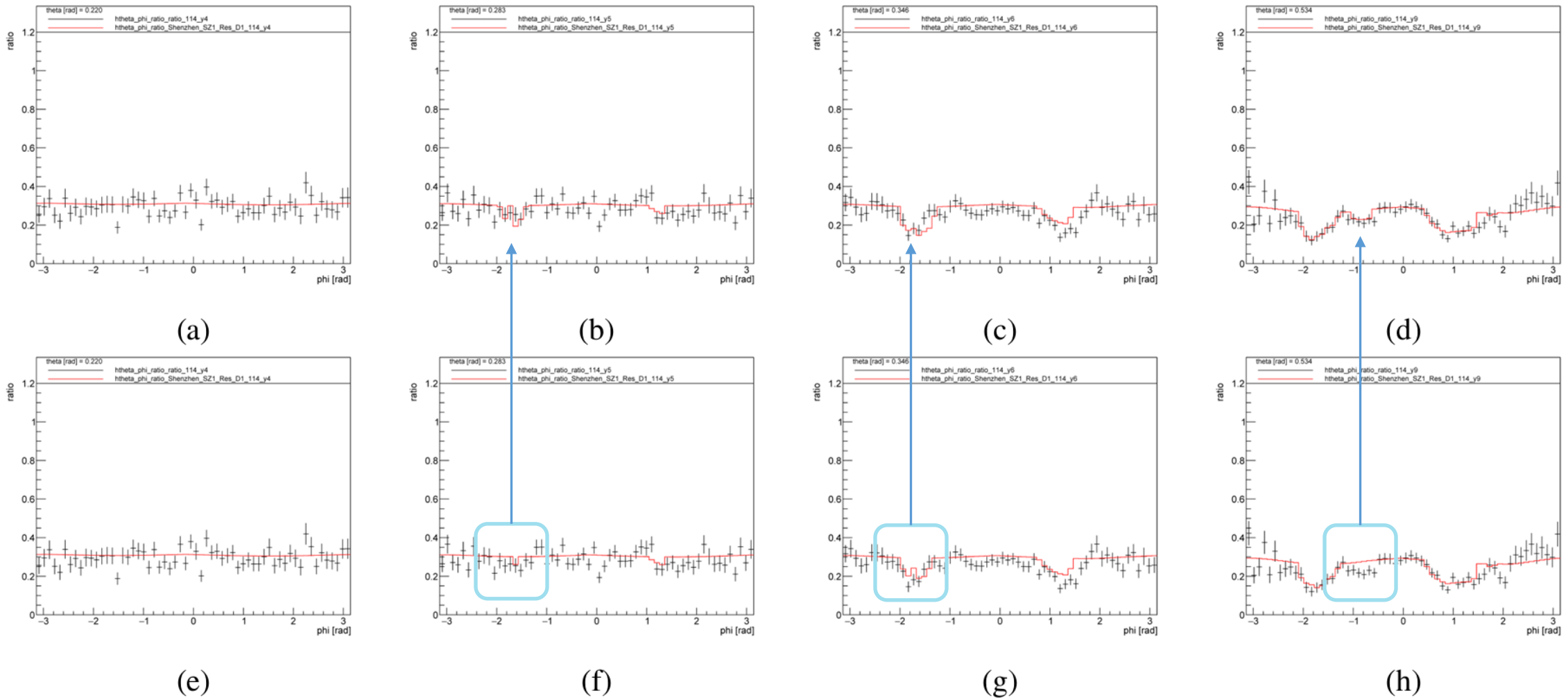


(c)

Building Type	Low Density(g/cm^3)	Accept Density(g/cm^3)	High Density(g/cm^3)
Office Building	0.1	0.2	0.5
Residential Building	0.05-0.15	0.15-0.25	0.3-0.5
Construction in Progress	0.05	0.1	0.2

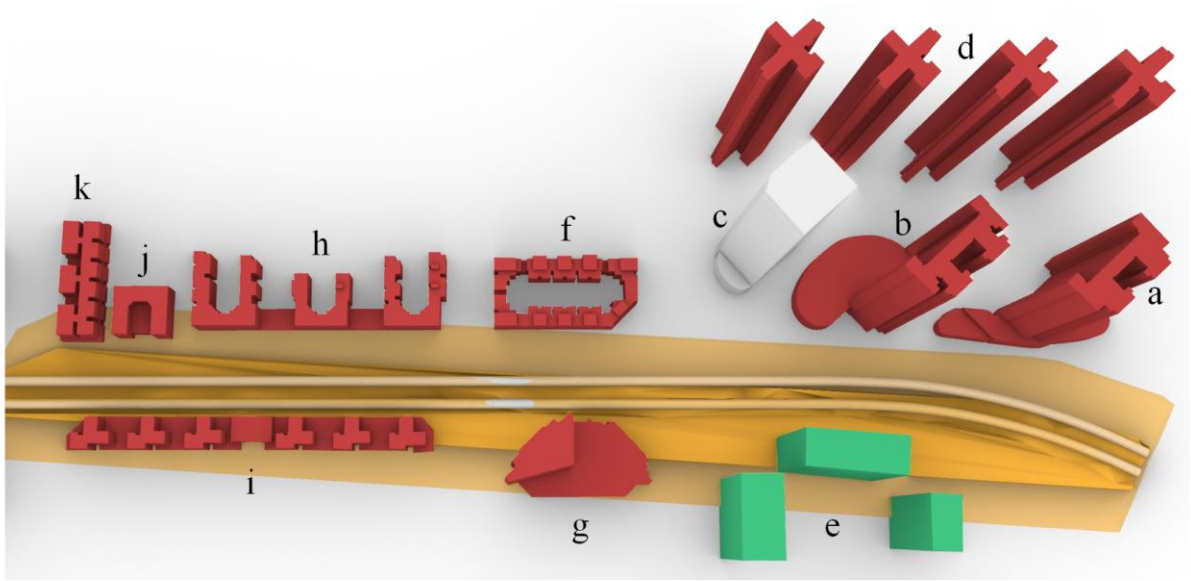
At larger θ angles, muon survival rates is independent of building height, but are significantly impacted by density.

Results Discussion-Influence of Buildings



a-d:Final Height; e-h:Reduce 20 m. Have to make the simulation and measured data changes synchronously

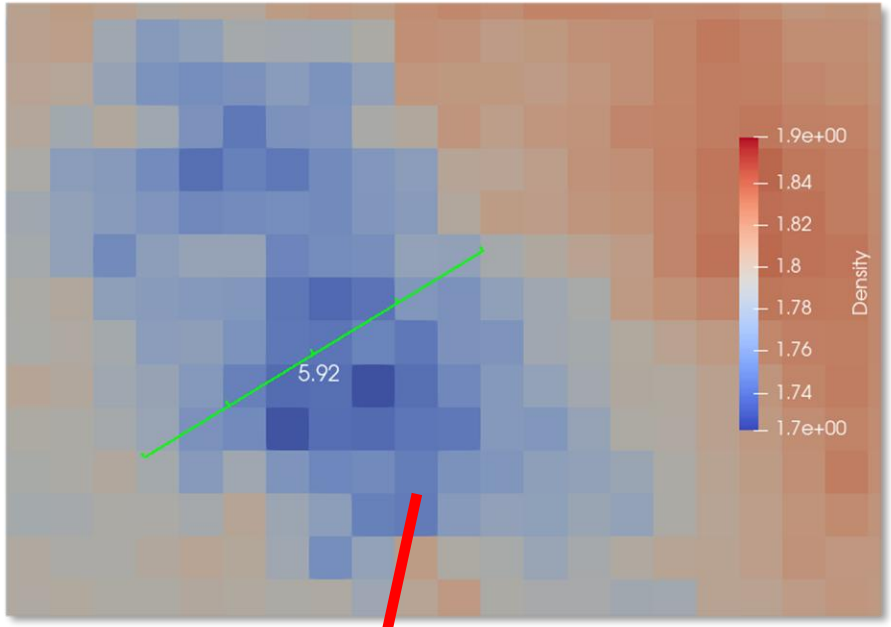
Results Discussion-Influence of Buildings

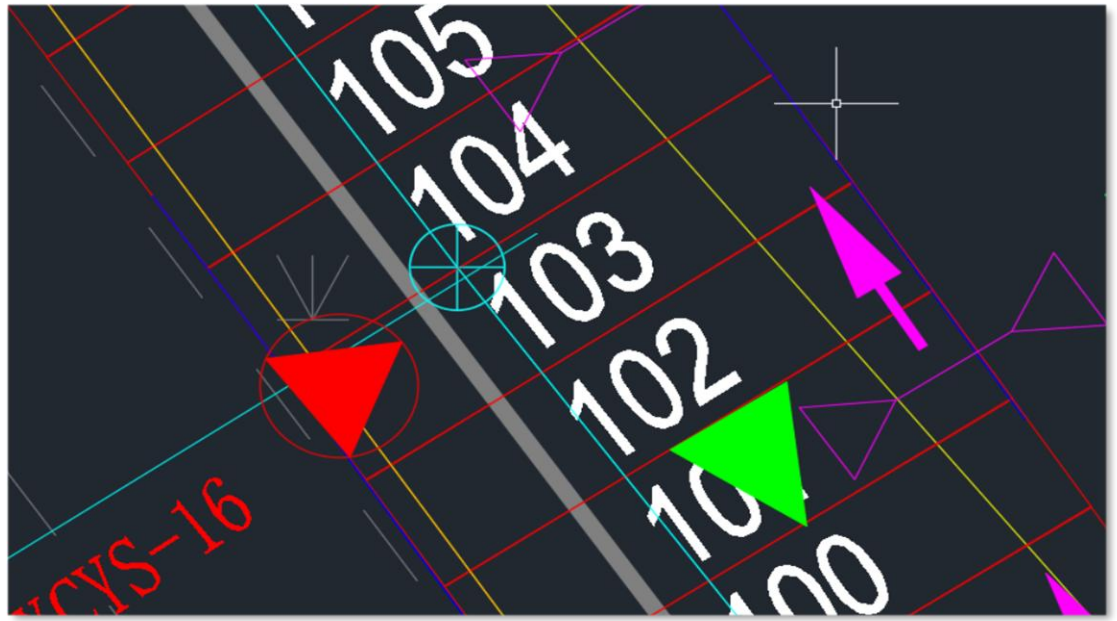


Correspondence between model components, color representation, and assigned density values.

ID	Density(g/cm^3)	Height(m)
a	0.25	123
b	0.20	152
c	0.15	190
d	0.15	200
e	0.15	100
f	0.25	21
g	0.25	60
h	0.25	26.1
i	0.25	22.9
j	0.25	22.9
k	0.25	27.1

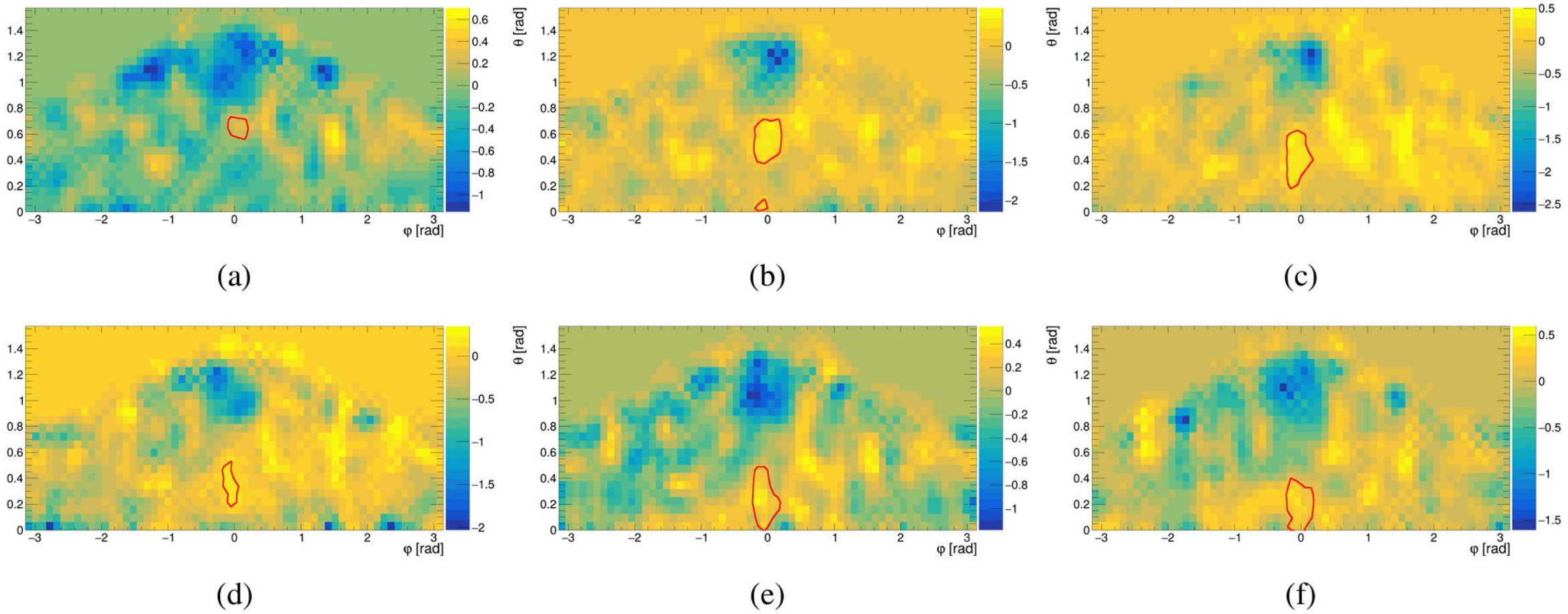
Results Discussion-Ring 101-104





- **Location:** ~3m above rings 101-104.
- **Anomaly Dimensions:** 27.6 m³.
- **Density Range:** 1.73–1.76 g/cm³.
- **Engineering Correlation:** Corresponds to a pipeline intersection in the site diagrams.

Results Discussion-Ring 101-104

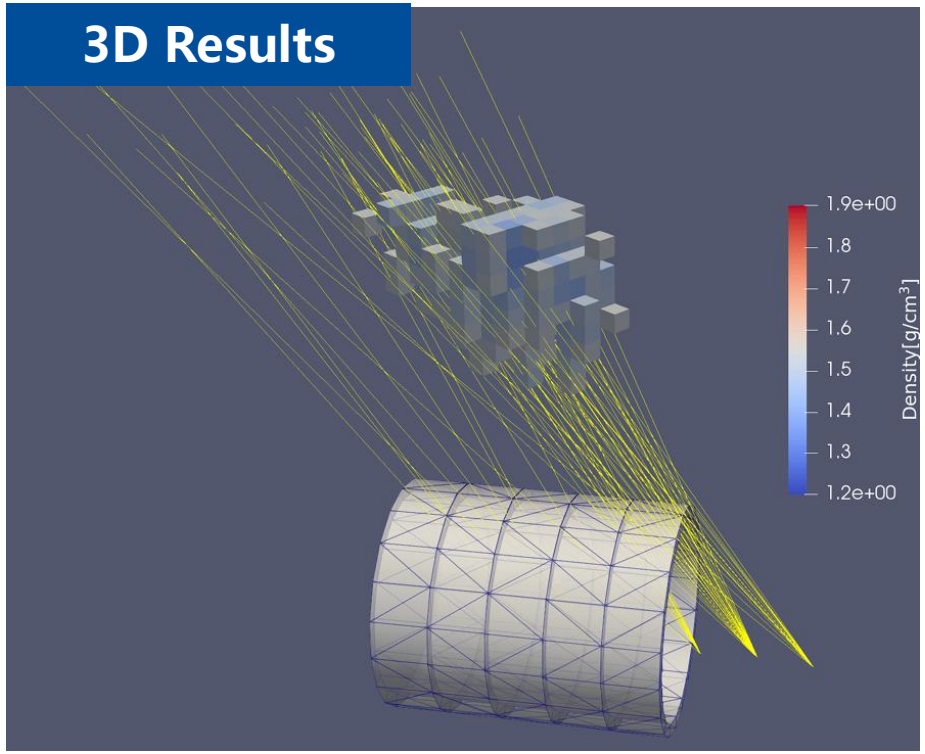


$$Sig = \frac{R_{\text{emp}} - R_{\text{fwd}}}{R_{\text{emp}}\sqrt{\frac{1}{C_{\text{obs}}} + \frac{1}{C_{\text{ref}}}}}$$

Red outline: Region with Sig > 0.125. As the detector advances (Rings 97-102), the anomaly shifts toward lower θ angles.

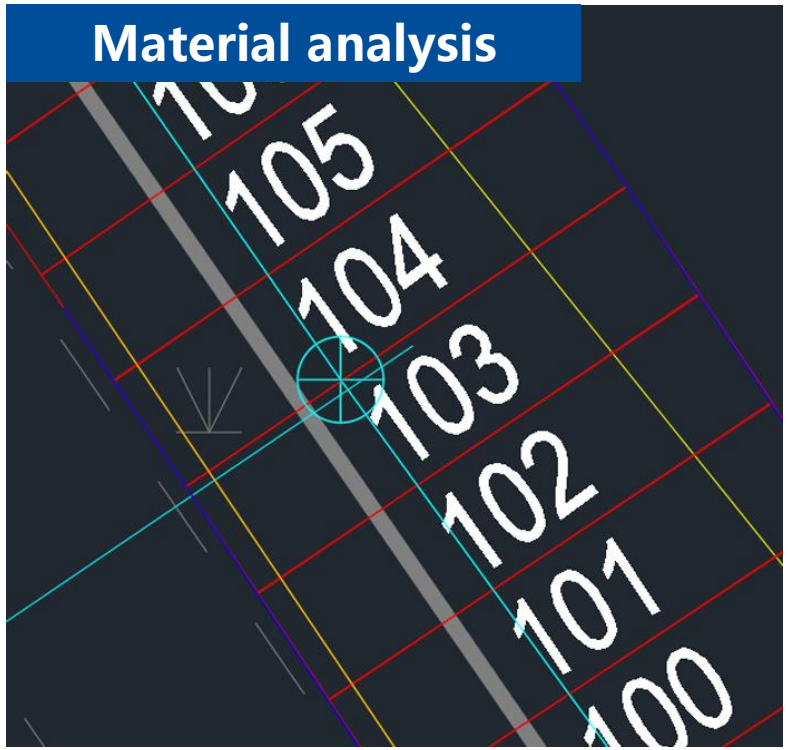
Results Discussion-Ring 101-104

3D Results



Field investigation

Material analysis

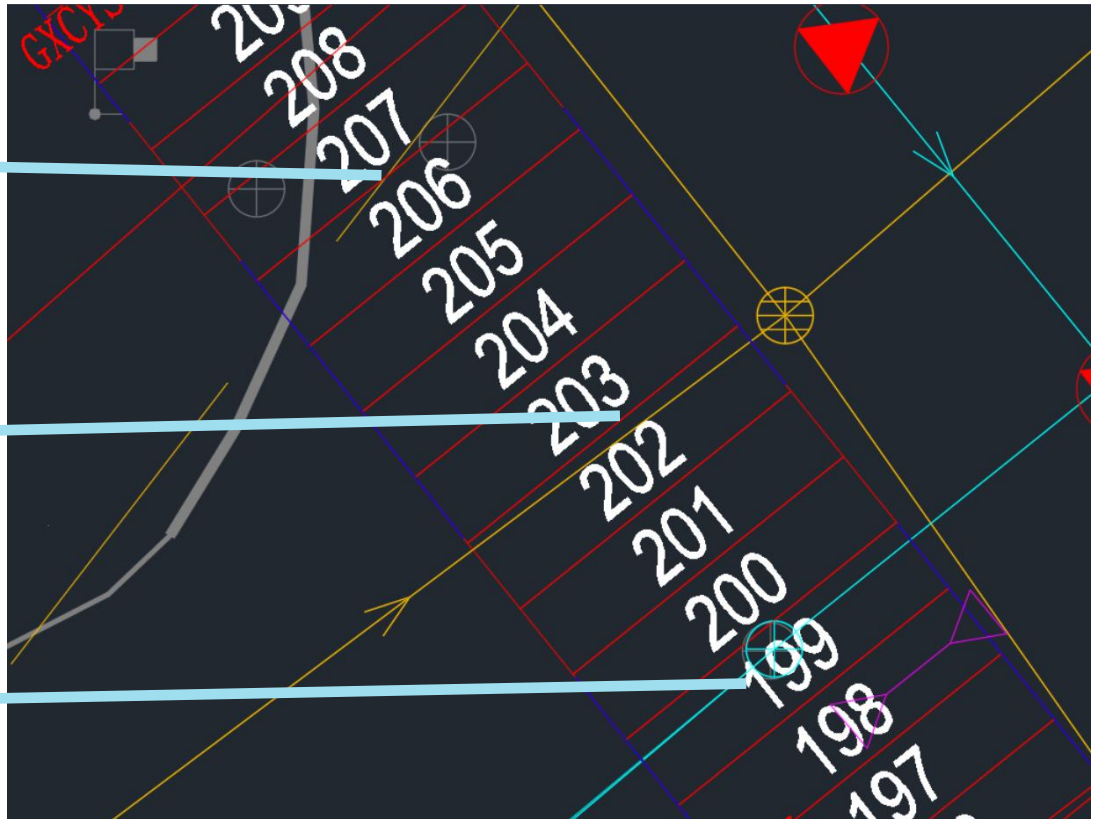


The 3D imaging results are highly consistent with on-site investigations and provided engineering materials, confirming the region formed by intersecting pipelines.

Results Discussion-Section Pipelines (Class III)

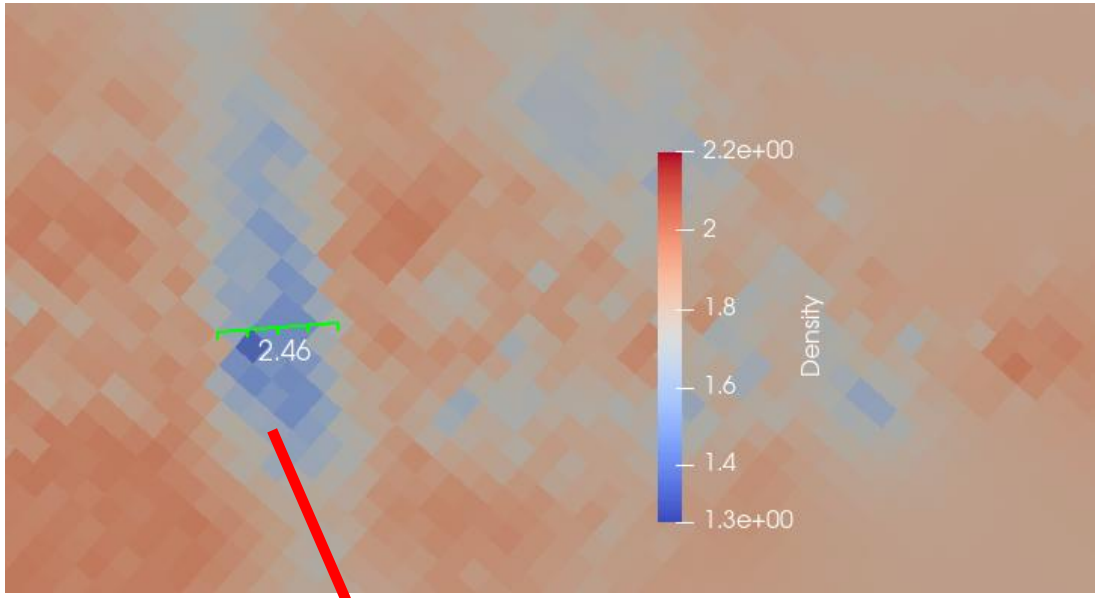
On-site Aerial View

- Φ2200 stormwater pipe; depth: 6.5m; clearance to tunnel roof: 2.59m.
- DN600-1000 stormwater pipe; depth: 3m; clearance to tunnel: 6.69m
- DN400-800 sewage pipe; depth: ~3.4m; vertical clearance to tunnel roof: ~5.8m

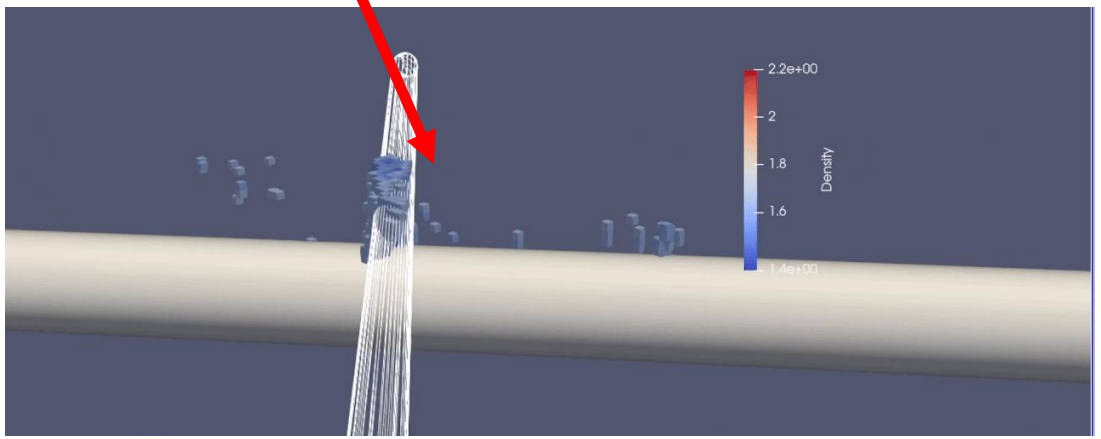


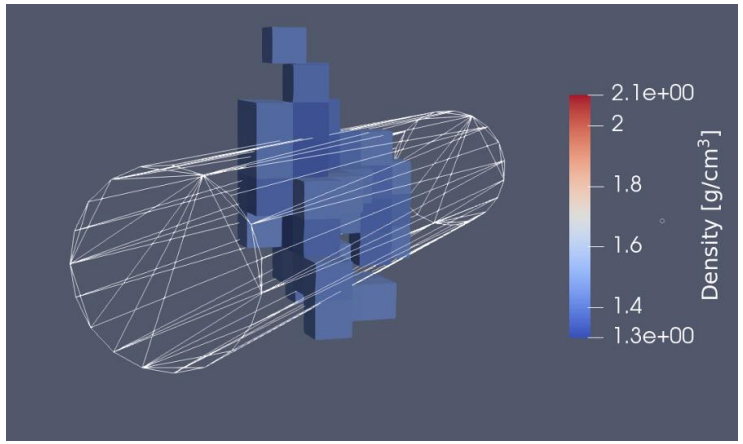
Complex on-site pipeline network; Muography is a feasible imaging technique.

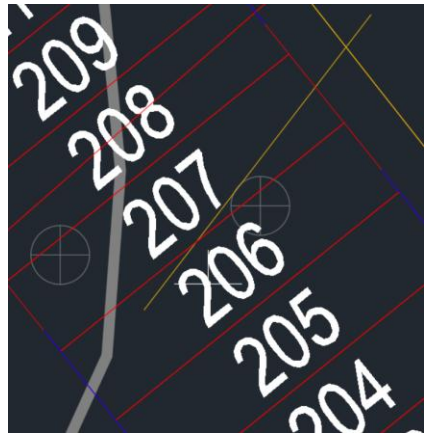
Results Discussion-Section Pipelines (Class III)



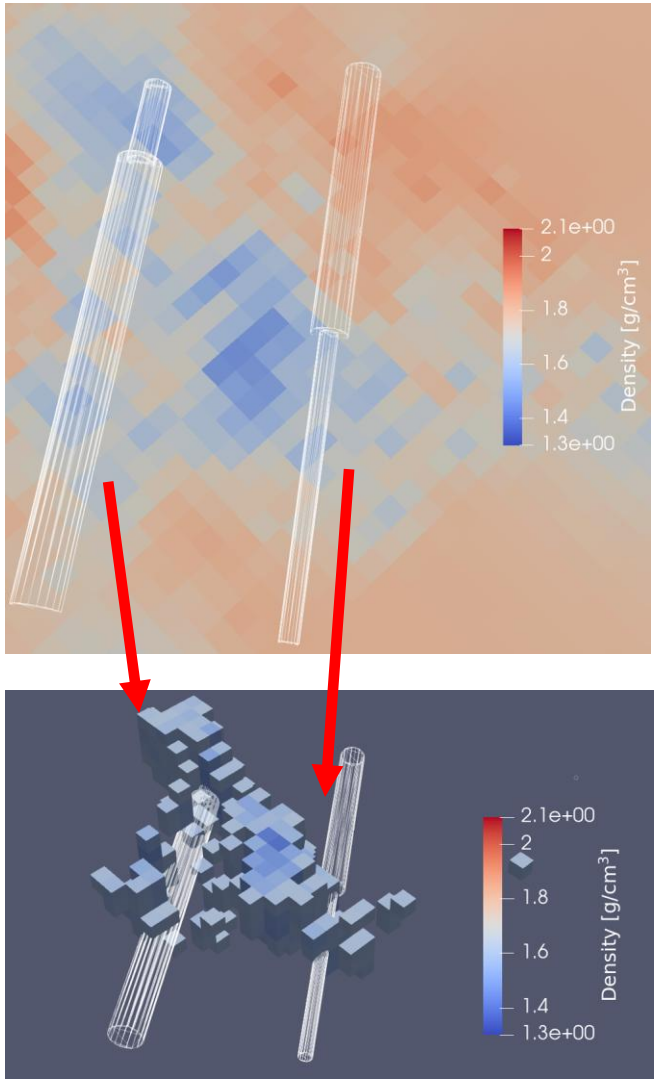
- **Results:** Accurately reconstructed the Φ2200 stormwater pipe above Rings 206-207.
- **Clearance above tunnel:** 2.3m.
- **Width:** ~2.46m.







Results Discussion-Section Pipelines (Class III)



Result: Accurately reconstructed the DN1000-1500 stormwater pipe above Ring 202.

Clearance above tunnel: ~4.8m.

Width: 1.4-2m.

Result: Reconstructed a small low-density anomaly at the DN800 sewage pipe location above Ring 199.

Clearance above tunnel: ~4.8m

Width: ~7m

Conclusions

- **Continuous 3D muography** was embedded into the shield tunneling cycle for Advanced Geological Prediction (AGP).
- **A joint strata-building correction model** successfully mitigated urban background noise for in-situ measurements.
- **A 736.8 m continuous monitoring** test successfully detected and reconstructed a **27.6 m³** hidden cavity above the TBM.
- **Meter-level spatial resolution** for complex utility networks was empirically calibrated at typical urban burial depths.
- The muography provides a non-destructive, interference-immune way for deep underground risk management.

Cai, Xinyu, et al. "Dynamic Monitoring-While-Tunneling via Muography: Construction-Phase In-Situ Validation during Shield Tunneling in Complex Urban Environments."

Thank you!