Muography in Wigner RCP

Detector development and applications

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13th December 2024

HUN-REN
Magyar Kutatási Hálózat

WIGNER

NATIONAL RESEARCH, DEVELOPMENT
AND INNOVATION OFFICE
HUNGARY

PROJECT
FINANCED FROM
THE NRDI FUND

REGARD
RMKI ELTE Collaboration
on Gaseous Detector
Research and Development

MUOGRAPHY

Outline

I. Introduction

II. Detector Technologies

III. Field measurement examples

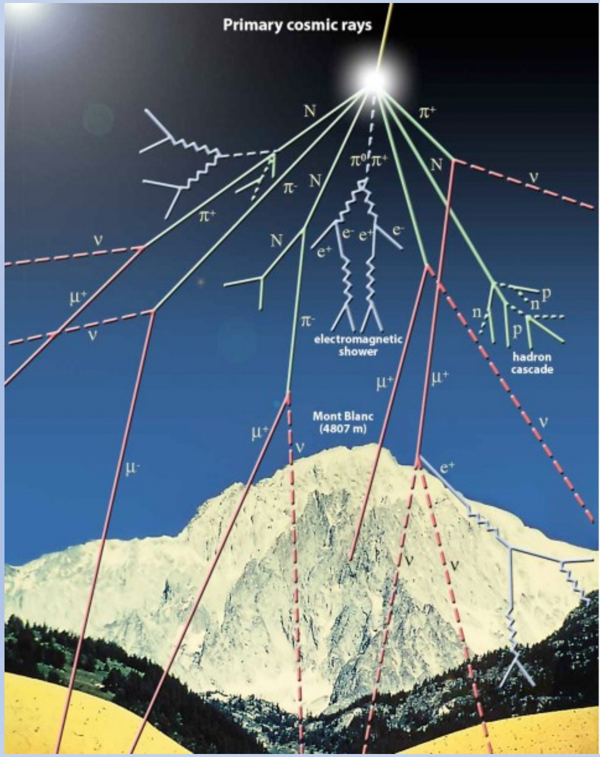
IV. Summary

I. Introduction: Muons and Muography

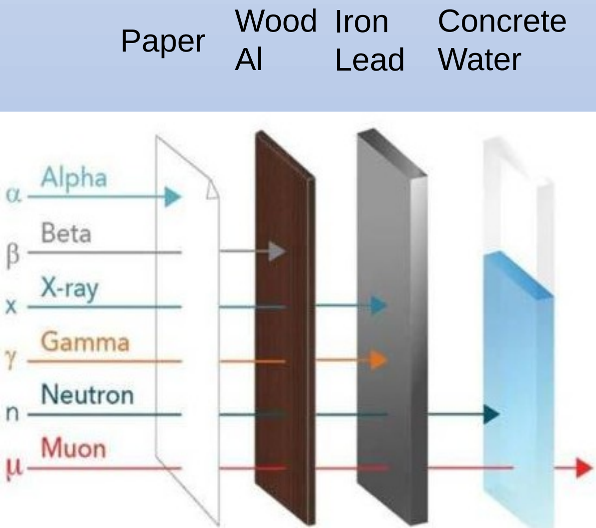
- **Cosmic-ray muons:** continuously produced in the atmosphere and observed everywhere on Earth. Muons are **highly penetrative particles** which can reach even a few km of depth into Earth’s subsurface

- **Muography**: ”X-raying” of large structures (mountains, volcanoes, pyramids, nuclear reactors, etc.) via tracking of cosmic-ray muons → **non-destructive, non-invasive, passive imaging technique**

- Methodology of muography was developed before mid 1960s (E.P. George, L.W. Alvarez et al.) but the imaging of large structures was achieved just in mid 2000s thanks to the development of detector technologies

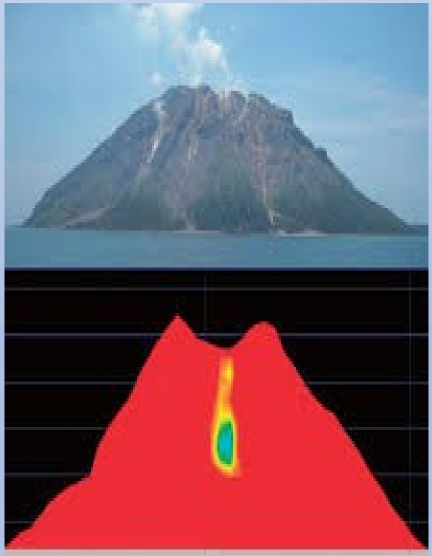


Credit: CERN


Paper
Wood
Al
Iron
Lead
Concrete
Water

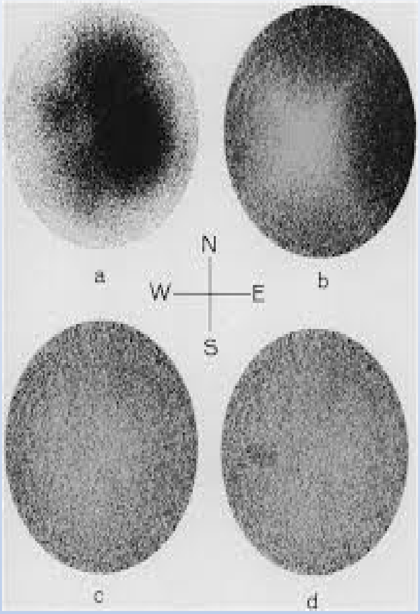
Credit: Decision Sciences

First medical X-ray image by Röntgen (1895)



First muon images of volcanoes by Tanaka et al. (mid 2000s)

“Generations” of muography



1st Generation: George 1955, Alvarez 1970 – demonstration of the principle for underground imaging

2nd Generation: around the 90-ies, Los Alamos, Italy, Japan… expanding the possibilities including scattering, various patents

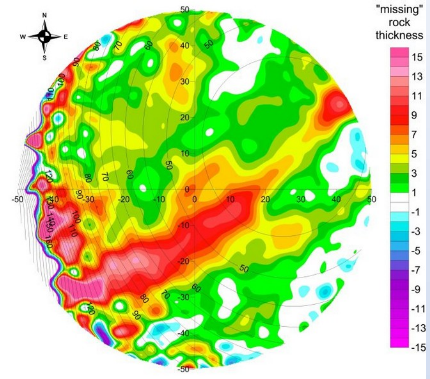
3rd Generation: around 2000, breakthroughs in volcanology (dynamics!), developing industries

4th Generation: dedicated systems, developments driven by the applications, expansion in possible use cases

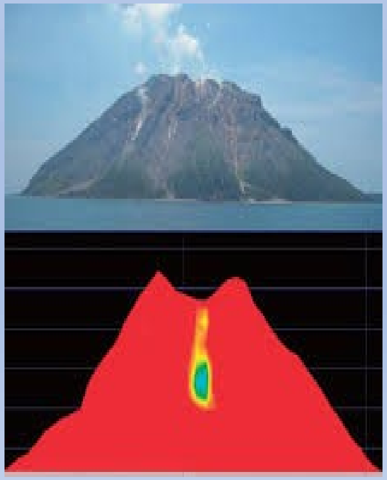
– High efficiency and resolution, high reliability

– Cost efficiency, durability on field, autonomy

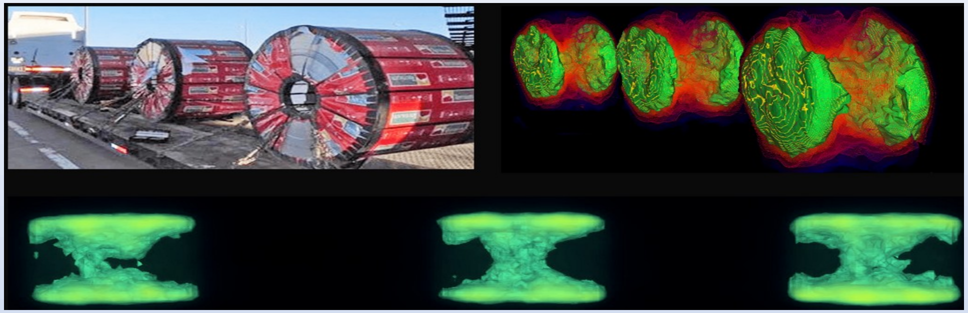
Muon Imaging Techniques



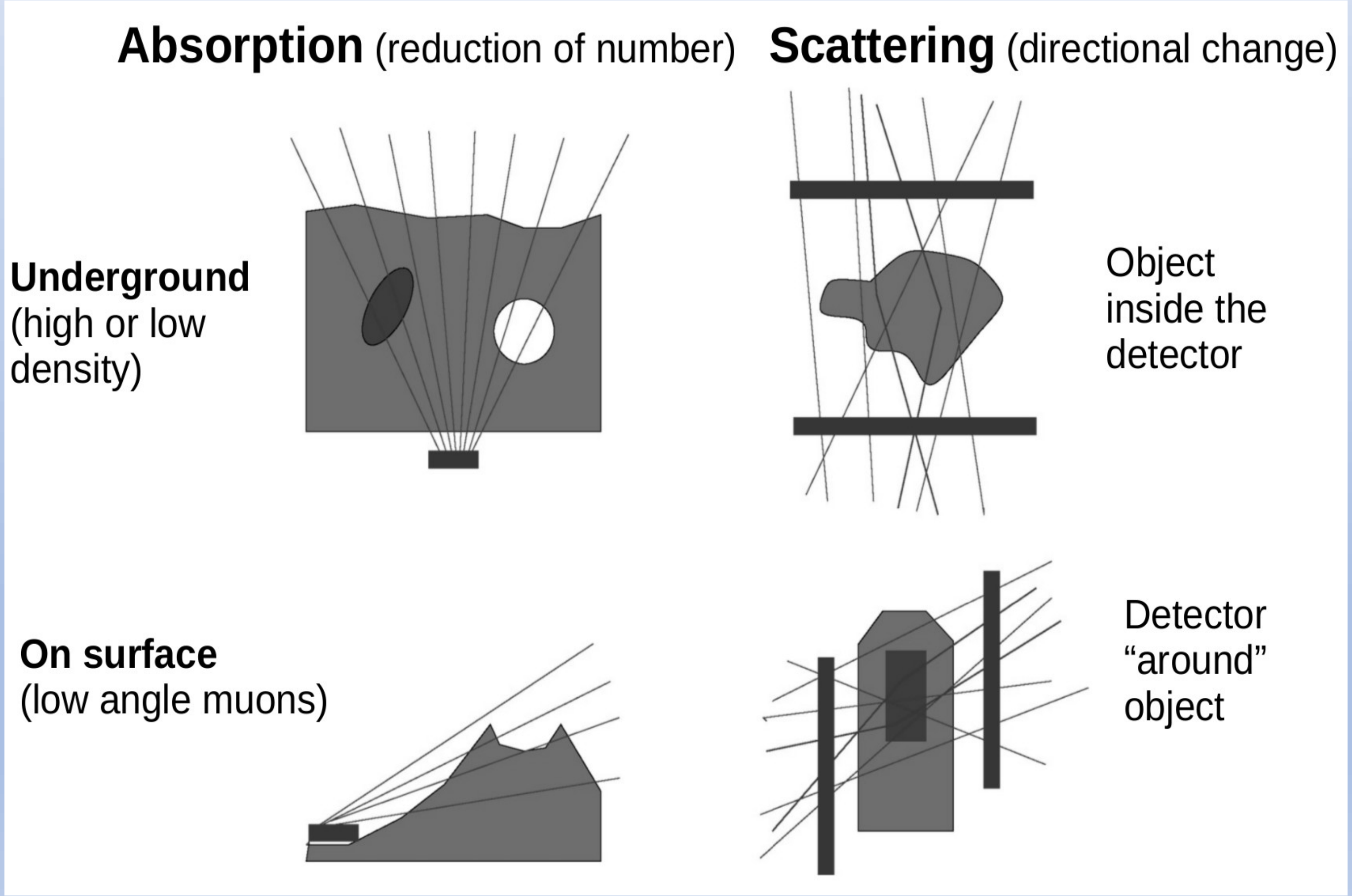
HUN-REN Wigner RCP



The University of Tokyo



Decision Sciences



Absorption (reduction of number)

Scattering (directional change)

Underground
(high or low density)

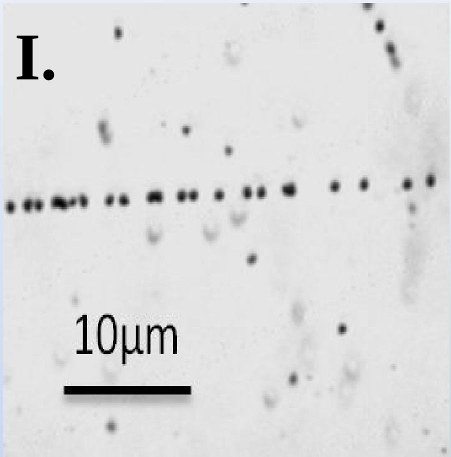
Object inside the detector

On surface
(low angle muons)

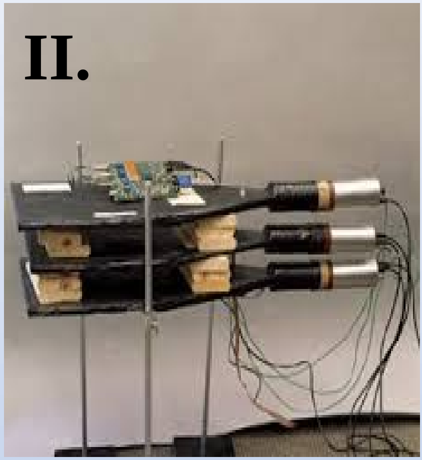
Detector "around" object

II. Muon Detector Technologies

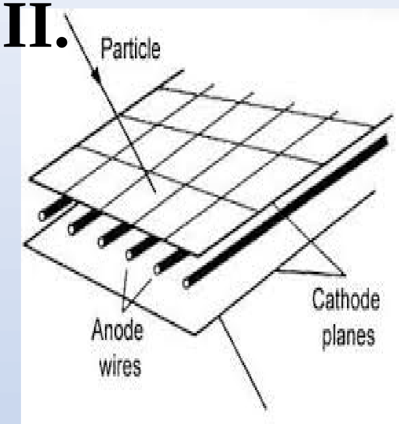
I.



II.



III.



I. Emulsion detector: good positional resolution, but no timing information

II. Scintillator: reliable, but positional resolution is costly

III. Gaseous detector: good positional resolution, but needs optimization to environment

Nagoya University

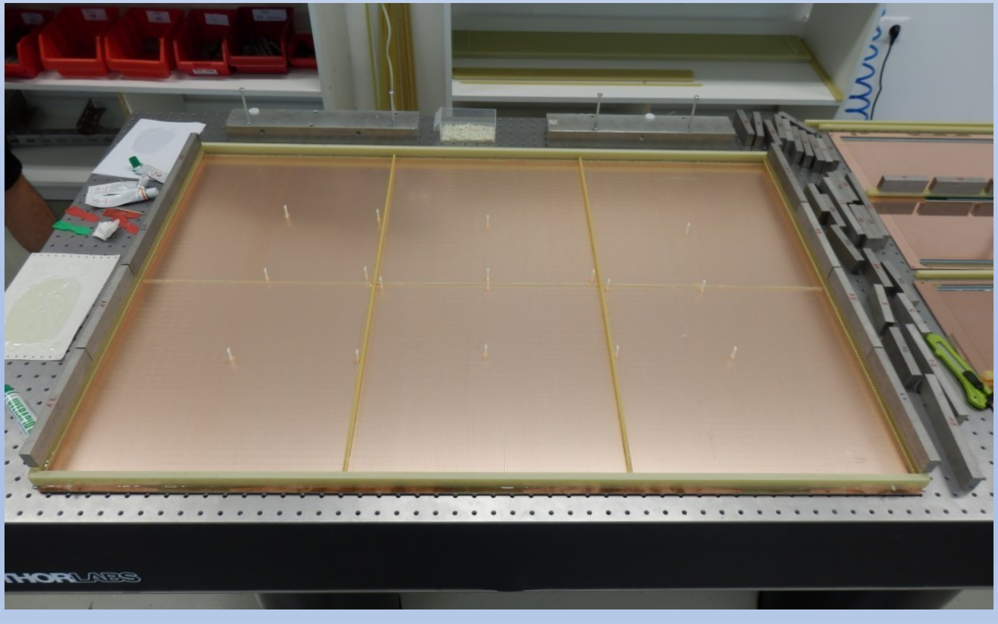
KEK

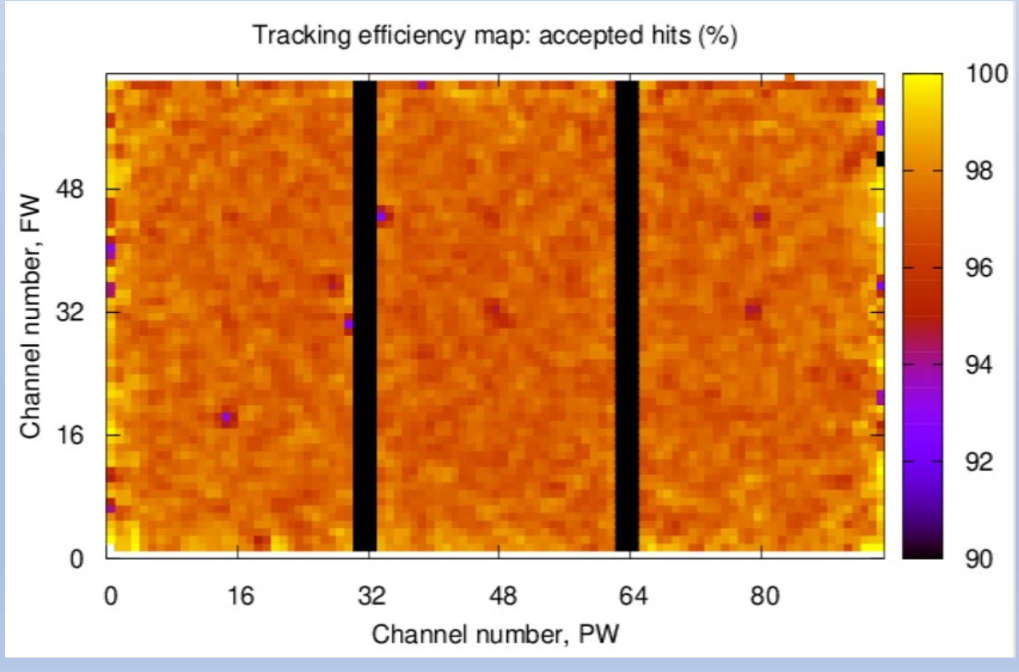
HUN-REN Wigner RCP
The University of Tokyo

II. Muon Detector Technologies: Recent Developments in HUN-REN Wigner RCP

Large area MWPC detector construction

- Reliability, durability, scalability by design
- By now 200+ m^2 produced (70 m^2 at SMO)



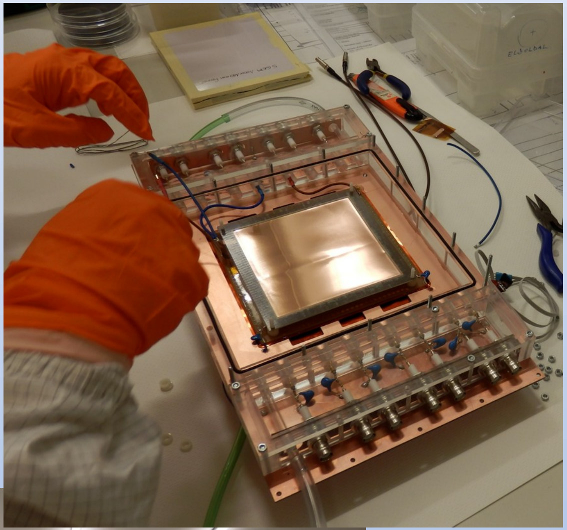


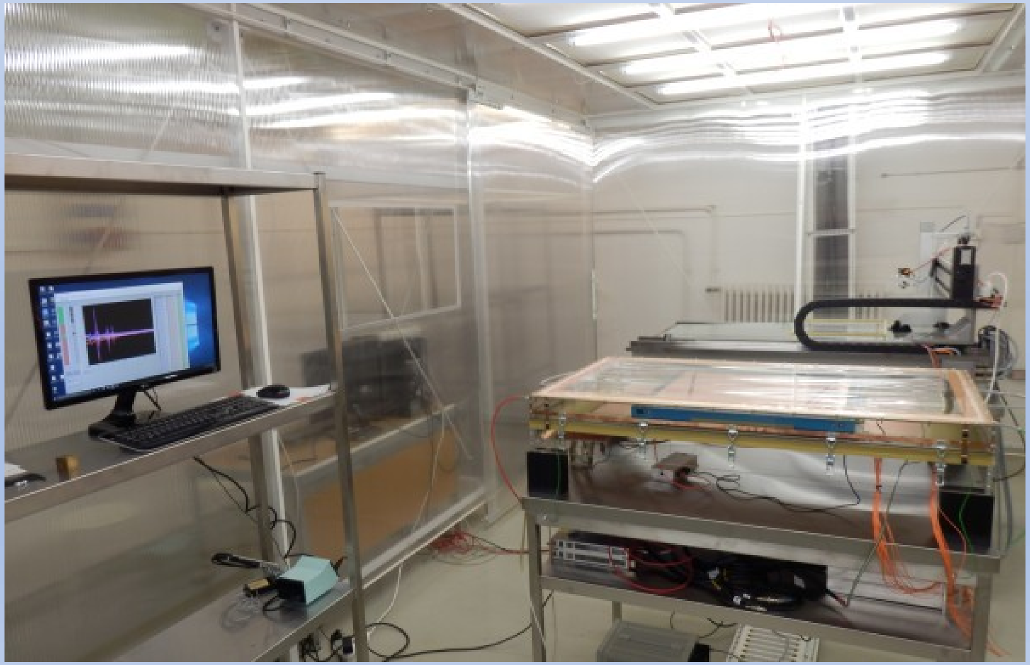
Eur. J. Phys. **36** 065006 (2015), arXiv:1607.08494, AHEP

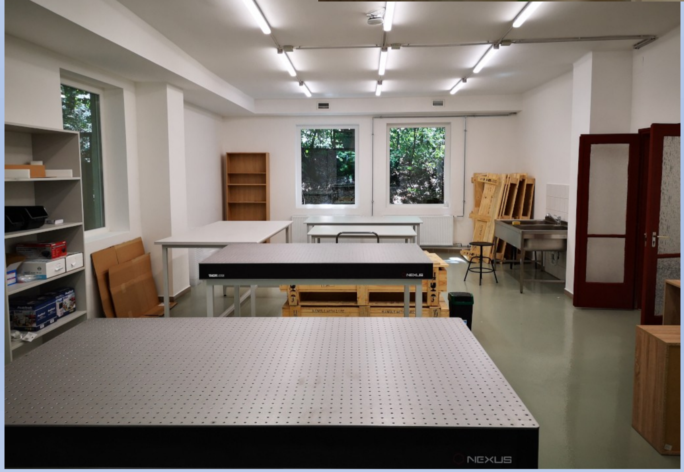
Detector production: “Vesztergombi Laboratory for High Energy Physics”

Dedicated infrastructure, nominated as excellent (Top50) nationally by the NRDI Office

Serves 5+ research groups at RMI

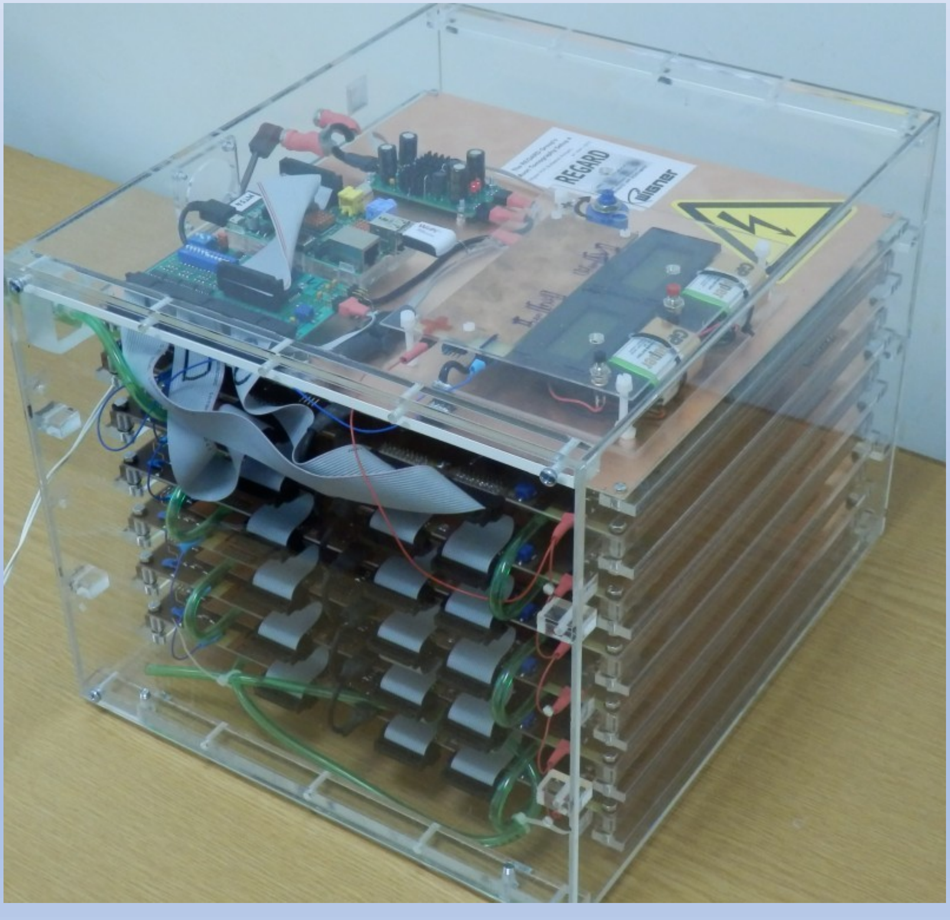






Underground detectors: use what fits!! S to L-size

“Muon Tomograph Large” (MTL1) and “Compact”



Challenge for particle physicists: from lab to field

Hardware development: detector casing for harsh underground conditions

36-38 °C, 100% humidity !!

Hardware development: detector casing for harsh underground conditions

Solution: fully sealed stainless steel casing with long buffer hose on the gas outlet

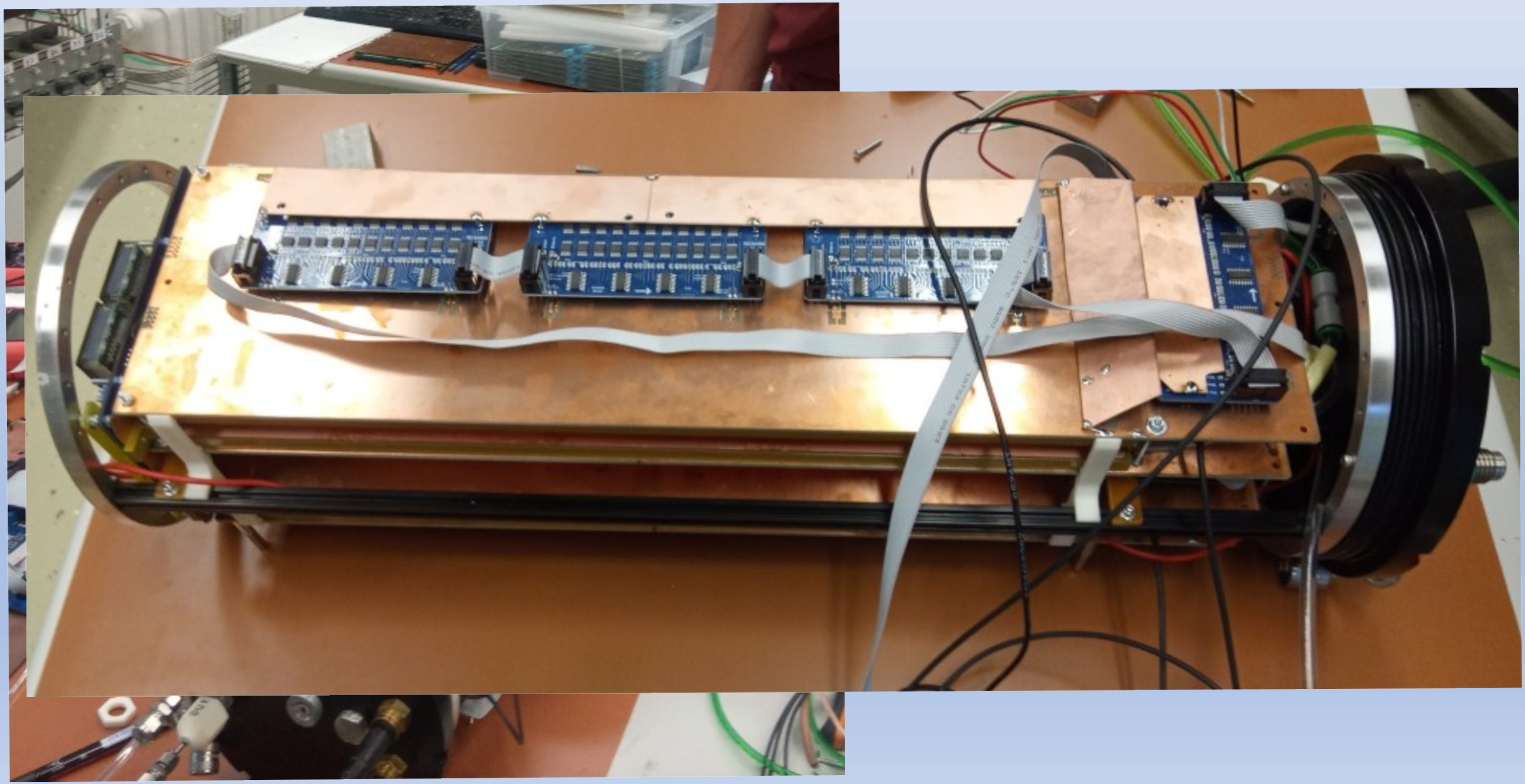
Hardware development: underwater detector (in the frame of the Horizon Europe project „Mine.io”)

Flooded mines up to the depth of 100m
(in collaboration with INESC TEC, Portugal)

Narrow and hard to reach spaces

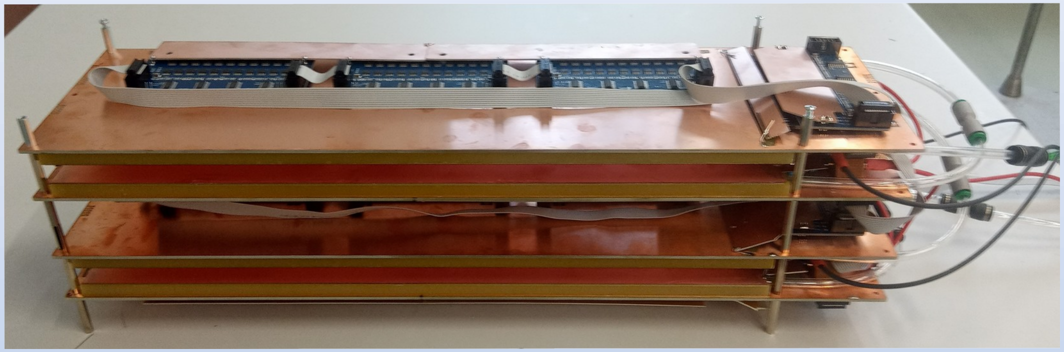
Large diameter **boreholes**
(the diameter of the current version is 20 cm)

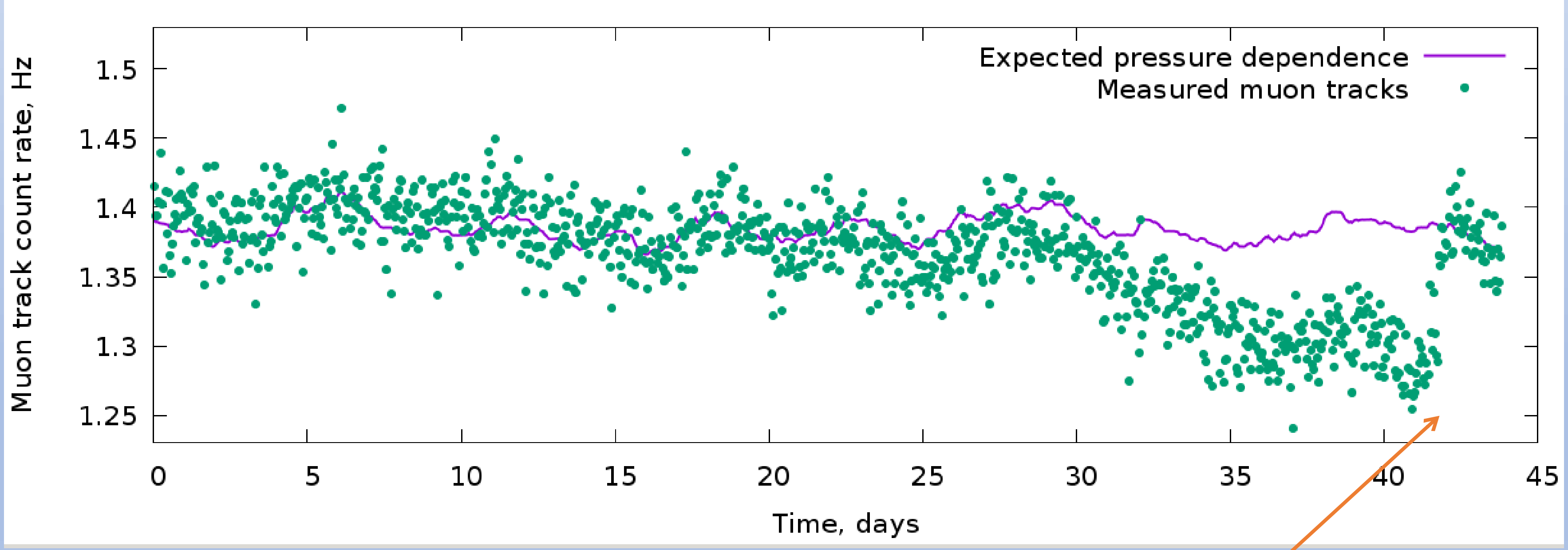
Hardware development: underwater detector (in the frame of the Horizon Europe project „Mine.io”)



Laboratory testing

- 4 layers, 128mm x 384mm, 4mm segmentation
- Detector was running **in sealed mode for 6 weeks**! Track rate drops by less than 10%





Sealed mode run from the beginning of the measurement

Gas flow restored

Software development

- **Framework and database manager for processing muographic measurement data**

The system generates a merged **„muogram”** file containing the binned input data required to perform the inversion.

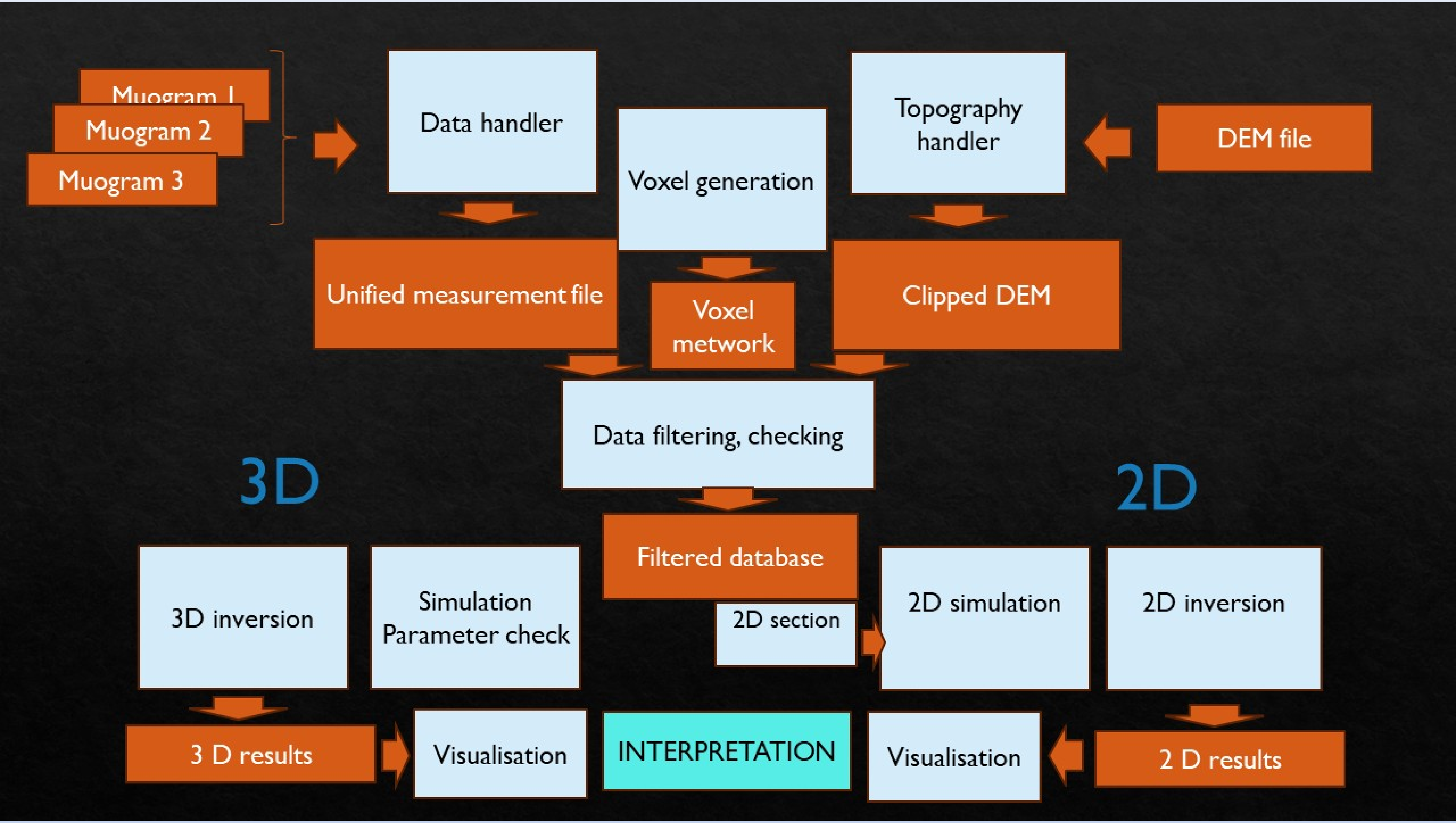
- **Inversion software package**

Bayesian (L2)-type discrete 3D tomographic inversion software (on MATLAB platform) Bayesian inversion can include geological and topographic constraints, with spatial dependencies to compensate for estimation bias. Matrix inversion is performed using LU decomposition with large voxel number. (Optionally, an L1-type Bayes condition can be specified and solved by Lasso-iteration) The package is also capable of performing 2D inversion.

- **Control application on smartphone**

Easy to handle control unit for all the detectors built by Wigner for non professional users.

Software development



Muogram 1
Muogram 2
Muogram 3

Data handler

Voxel generation

Topography handler

DEM file

Unified measurement file

Voxel network

Clipped DEM

Data filtering, checking

3D

2D

Filtered database

2D section

3D inversion

Simulation Parameter check

2D simulation

2D inversion

3 D results

Visualisation

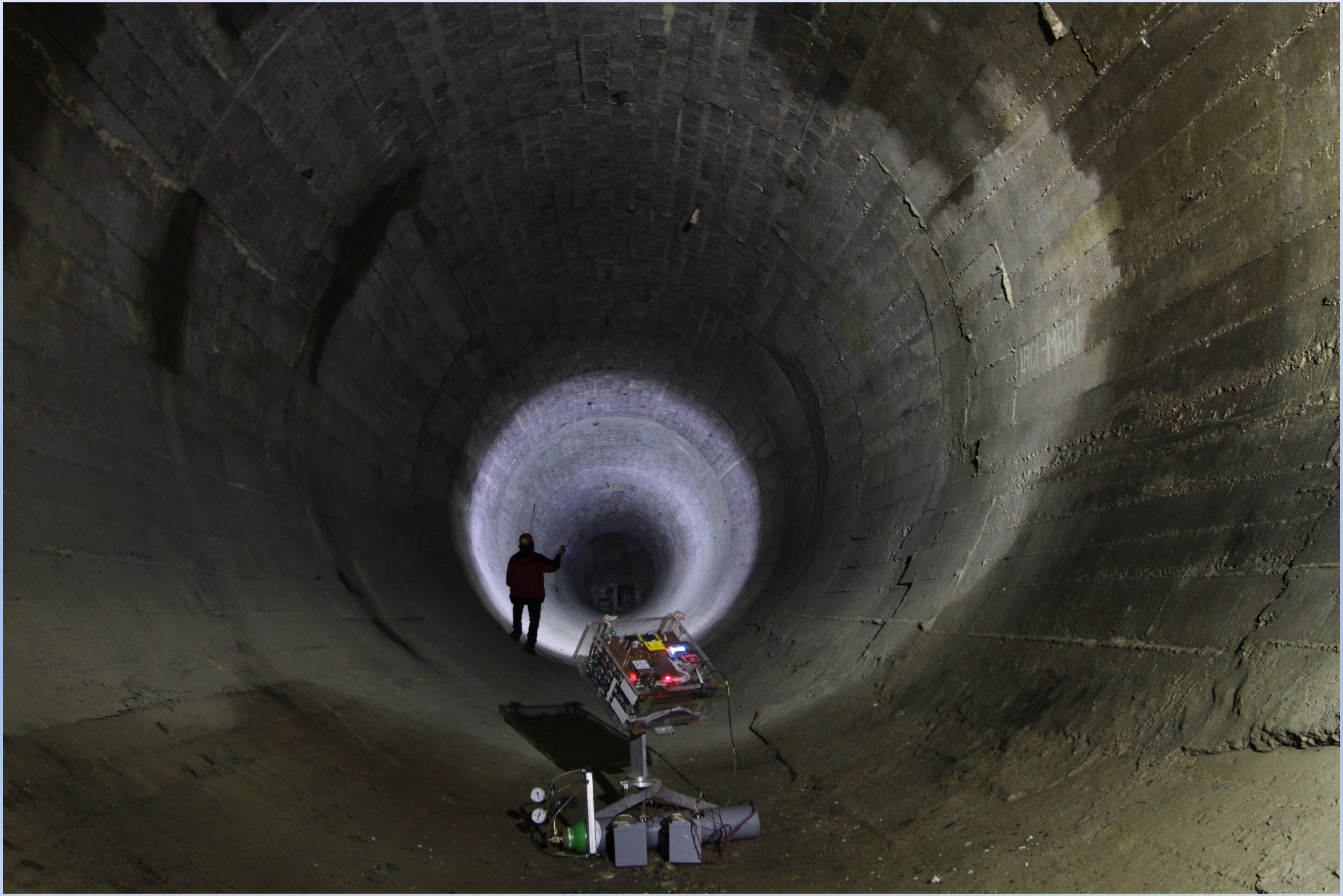
INTERPRETATION

Visualisation

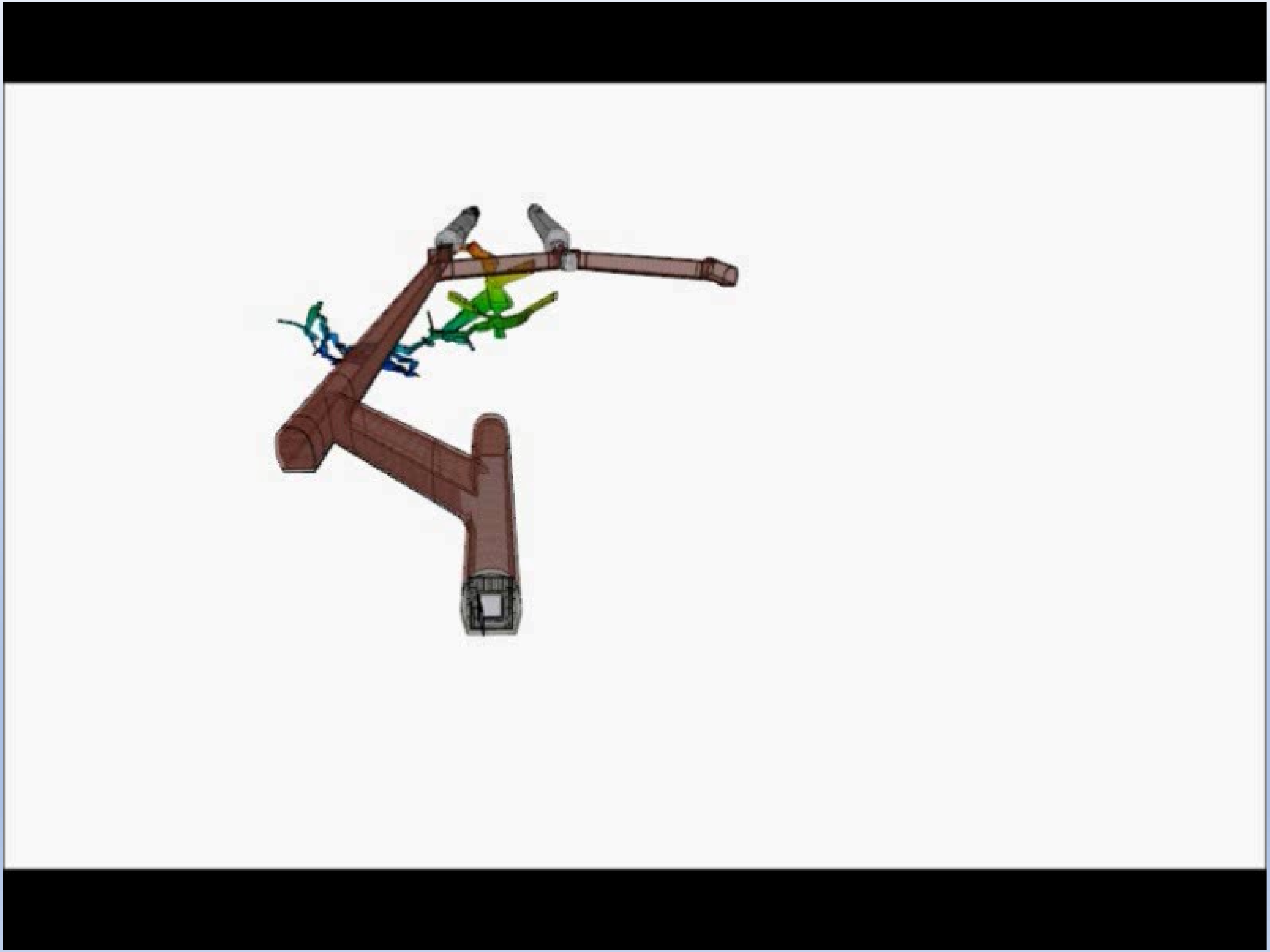
2 D results

III. Field measurement examples

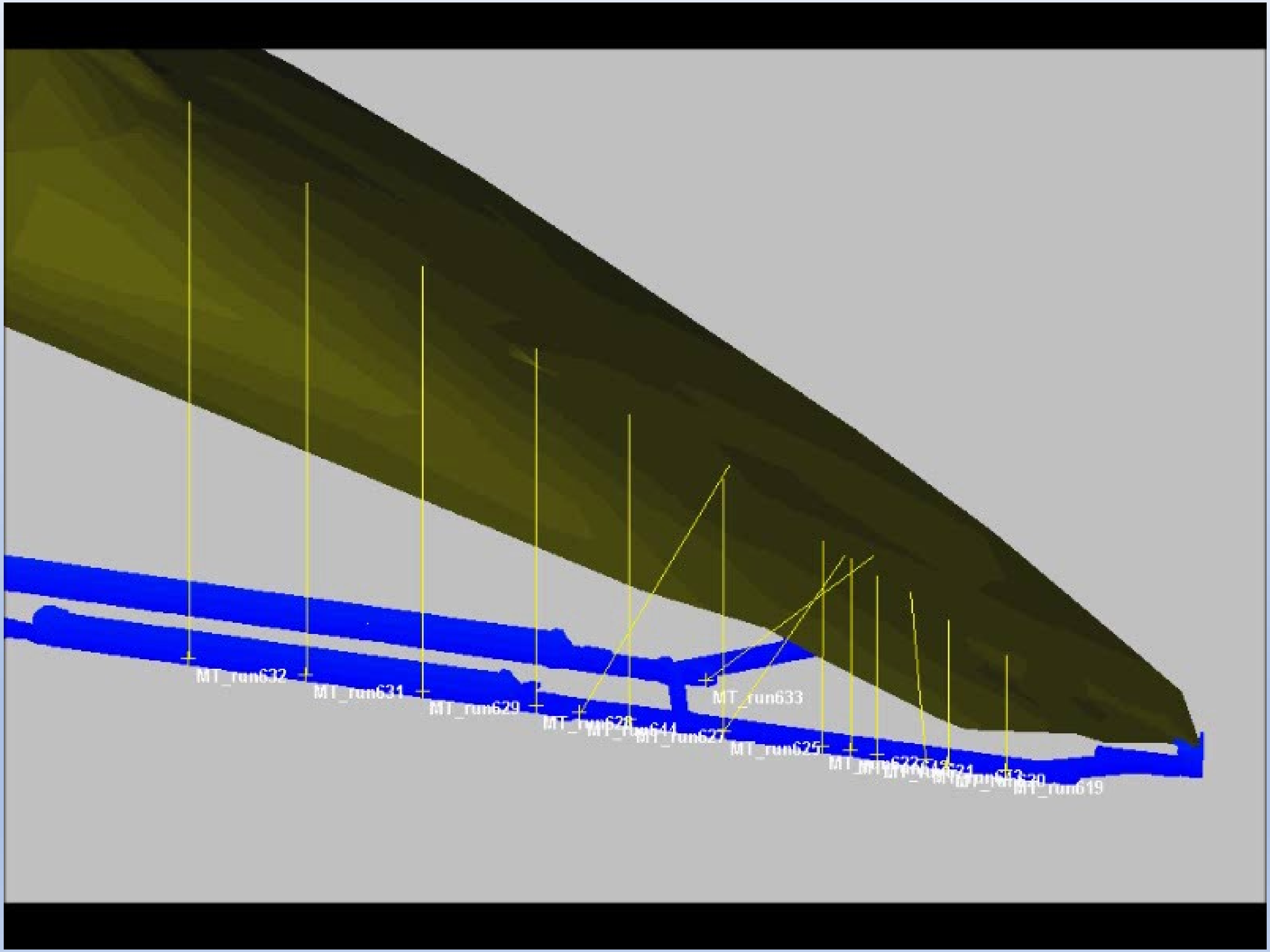
- Undergound measurements



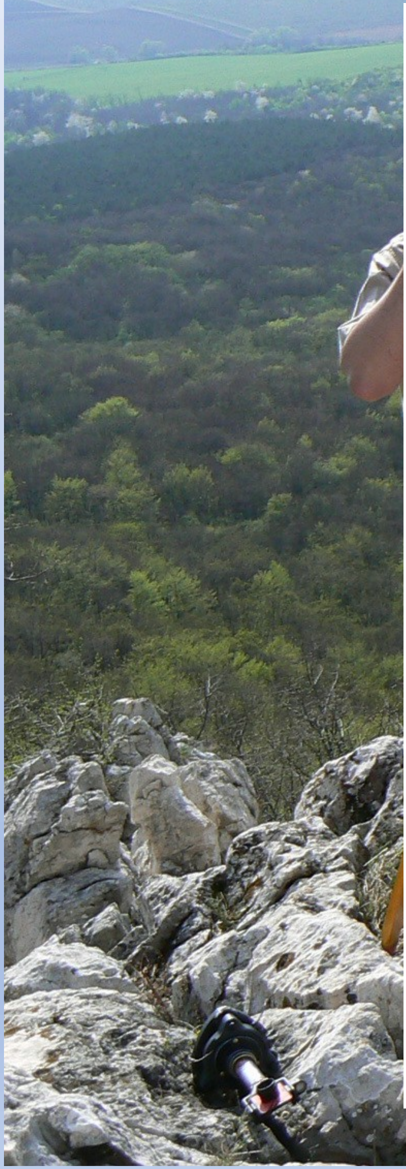
Case study: Királylaki tunnel

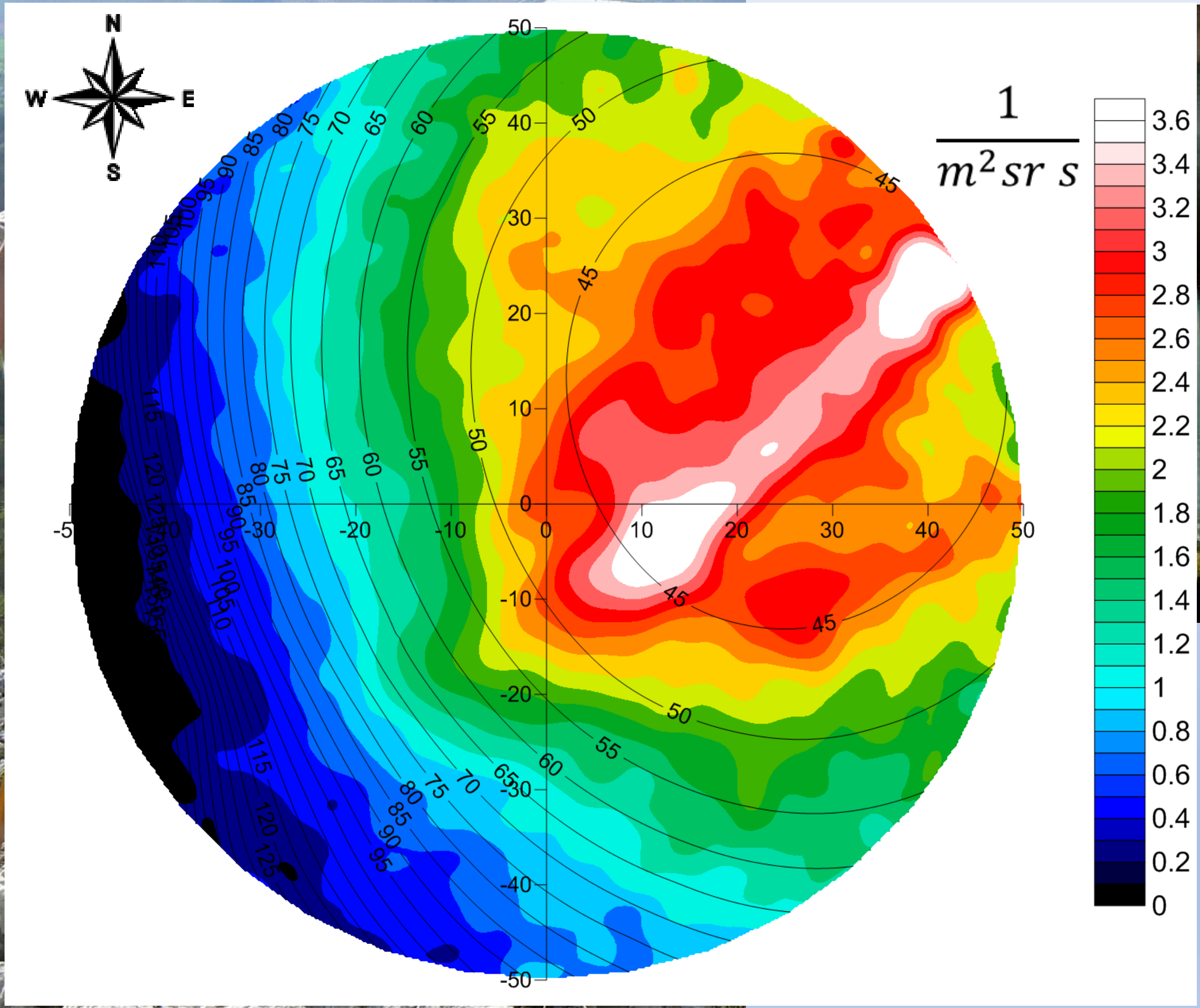


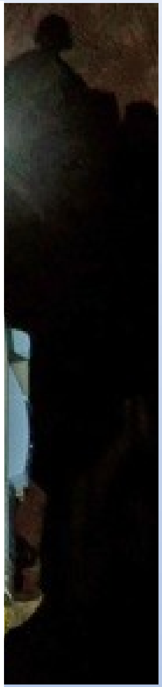
Case study: Királylaki tunnel



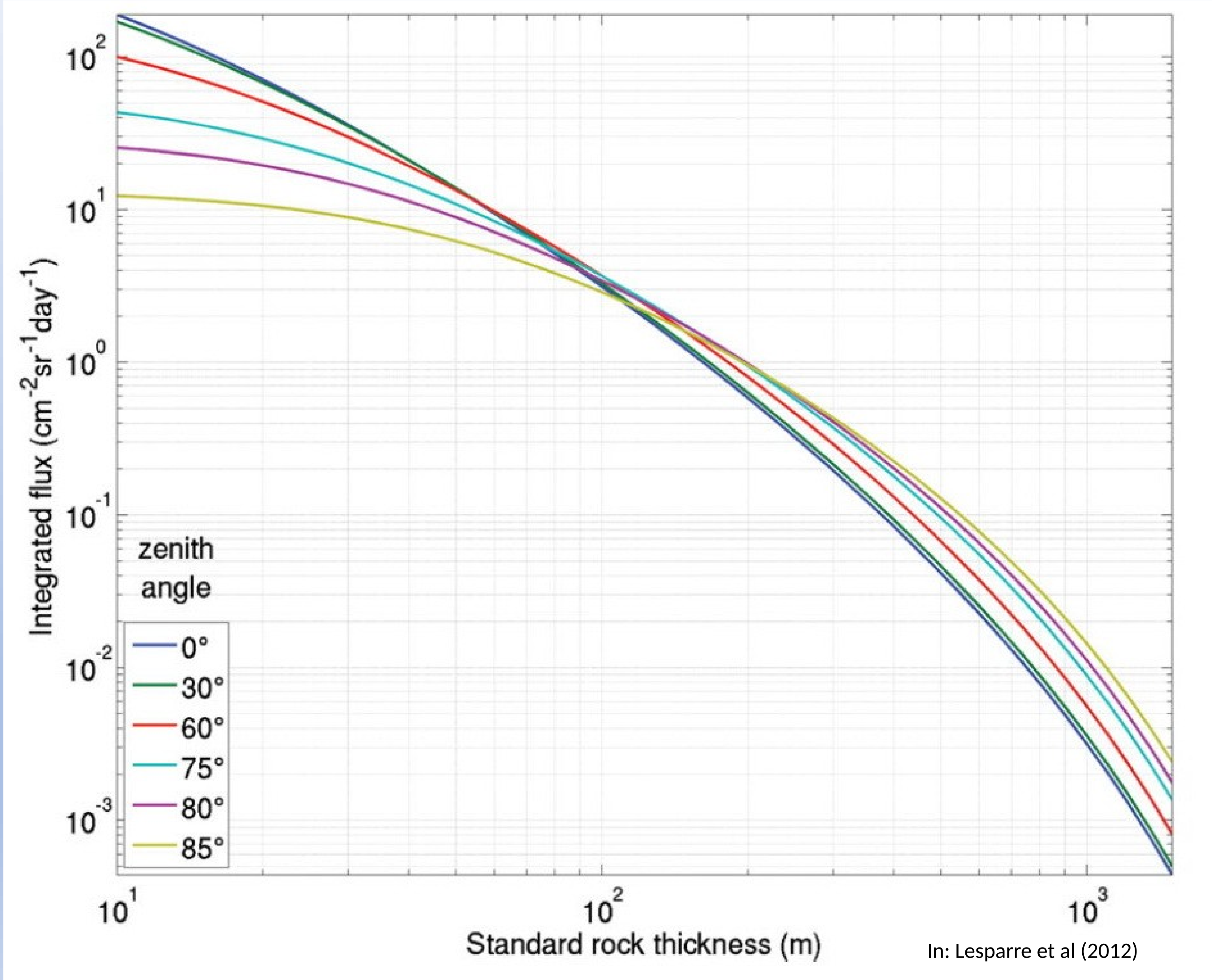
muon flux + rock thickness





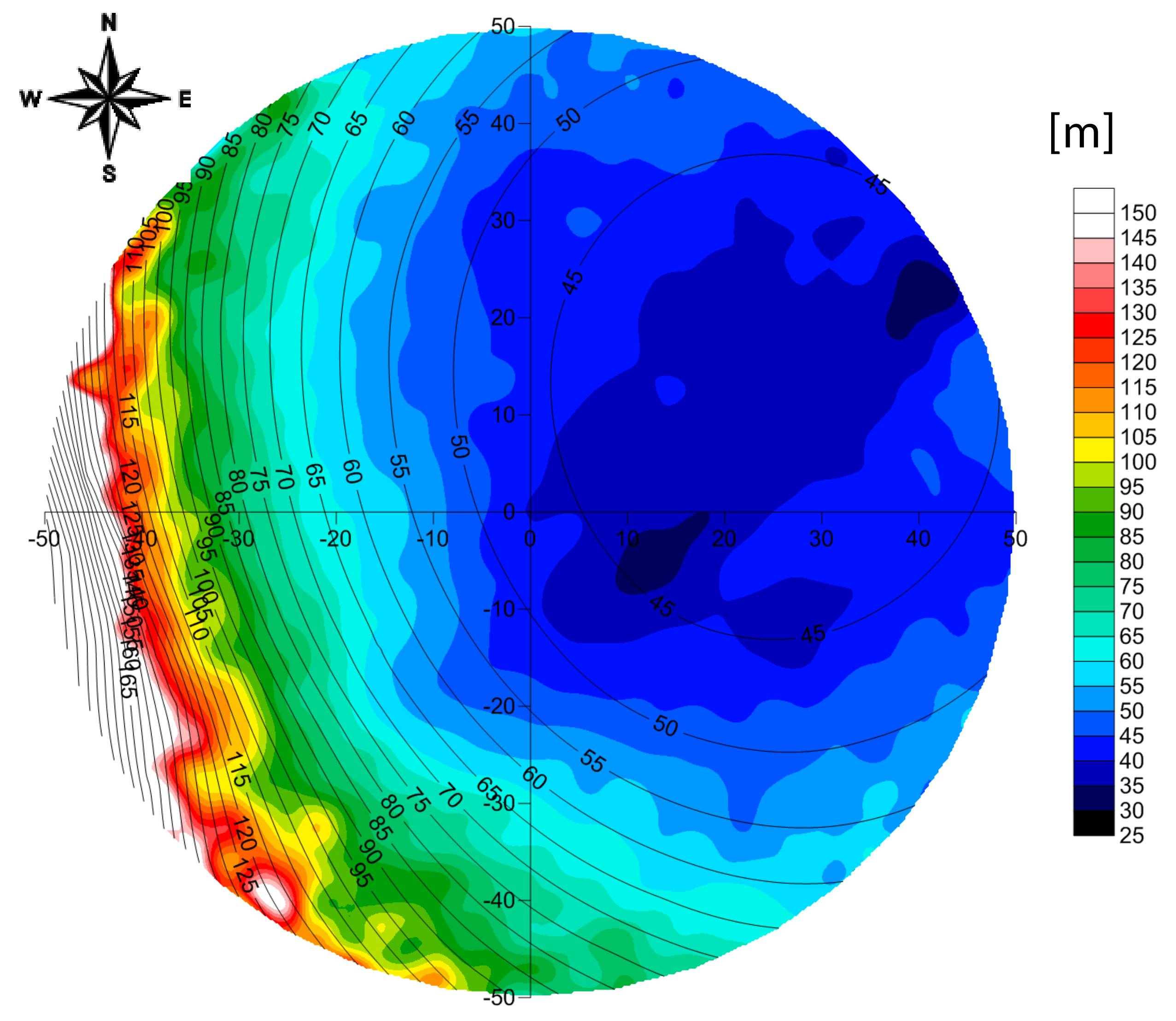


Muon flux of the function of rock thickness at different zenith angle

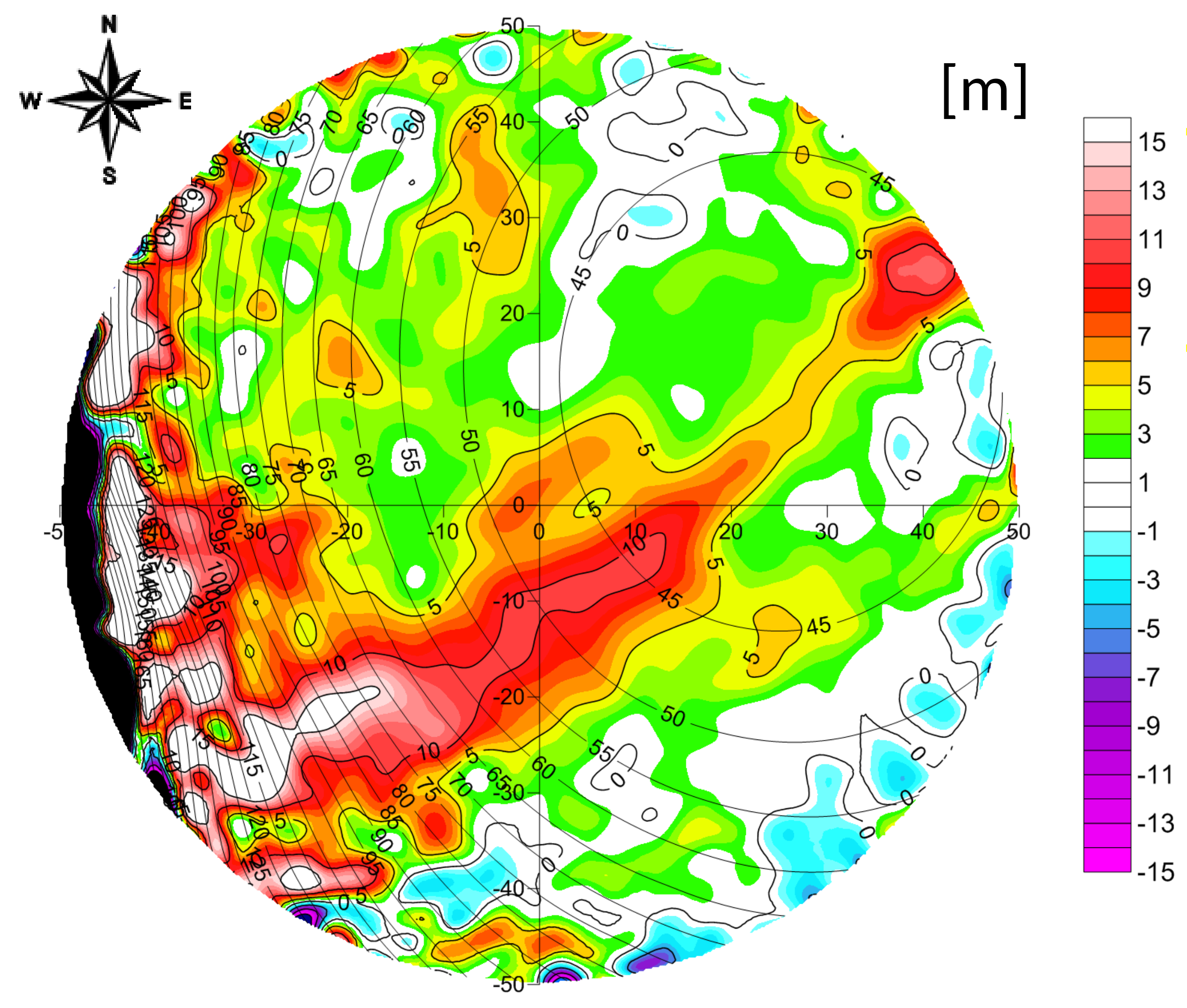


In: Lesparre et al (2012)

Calculated rock thickness based on muon flux



Measured minus calculated rock thickness

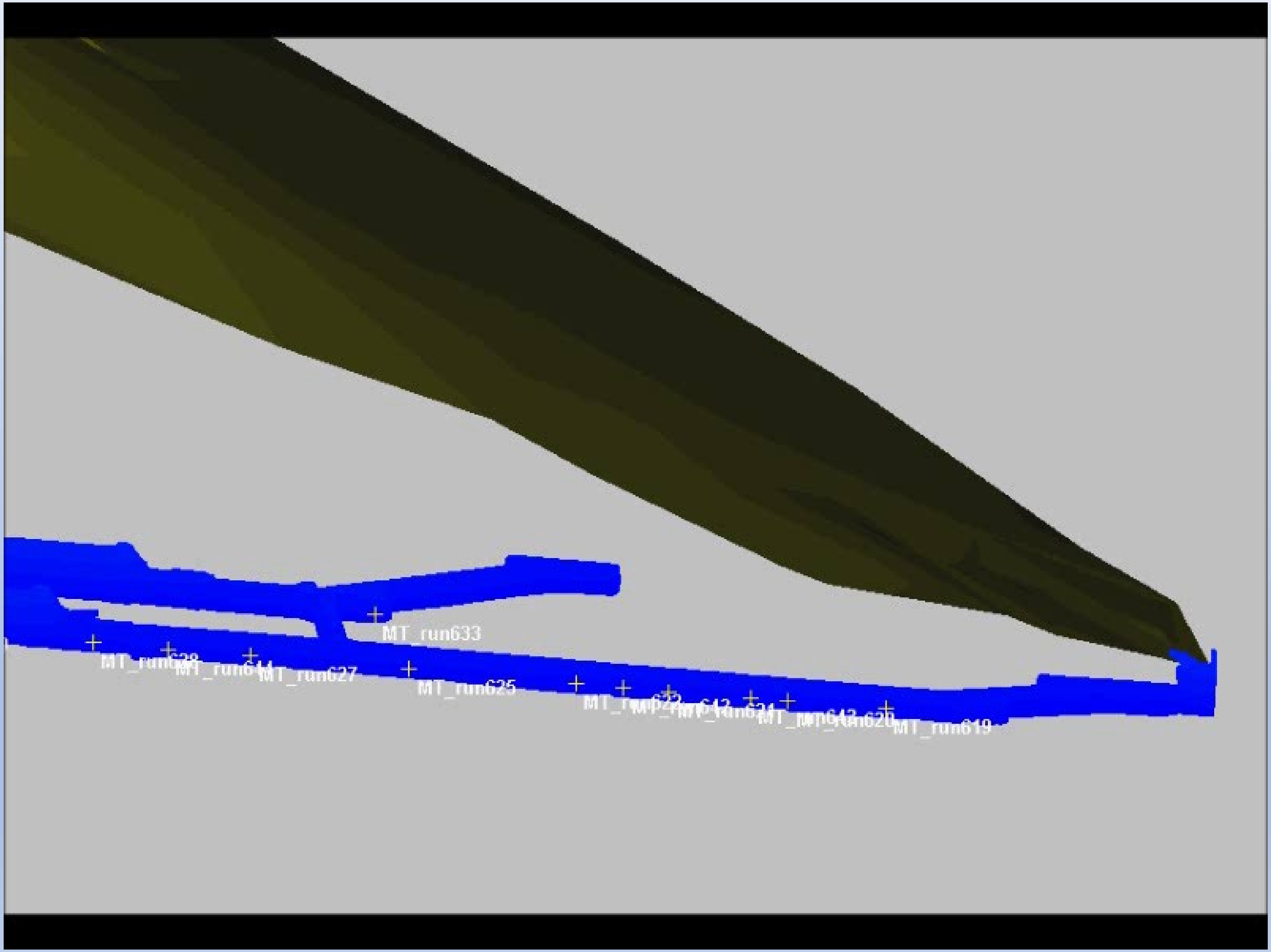


Low density zones or even voids

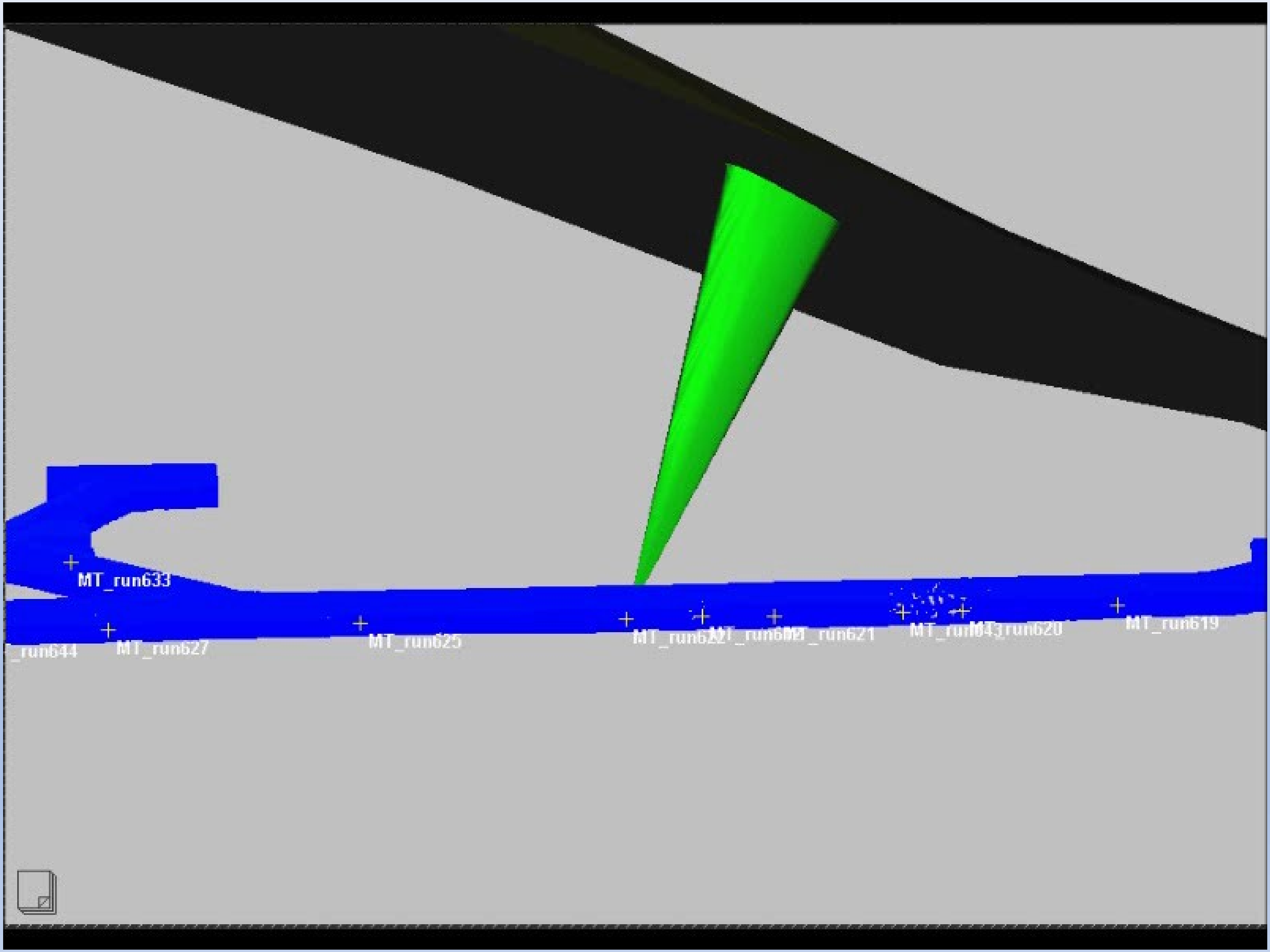
Average rock

Very compact rock, ore, or additional material on the surface

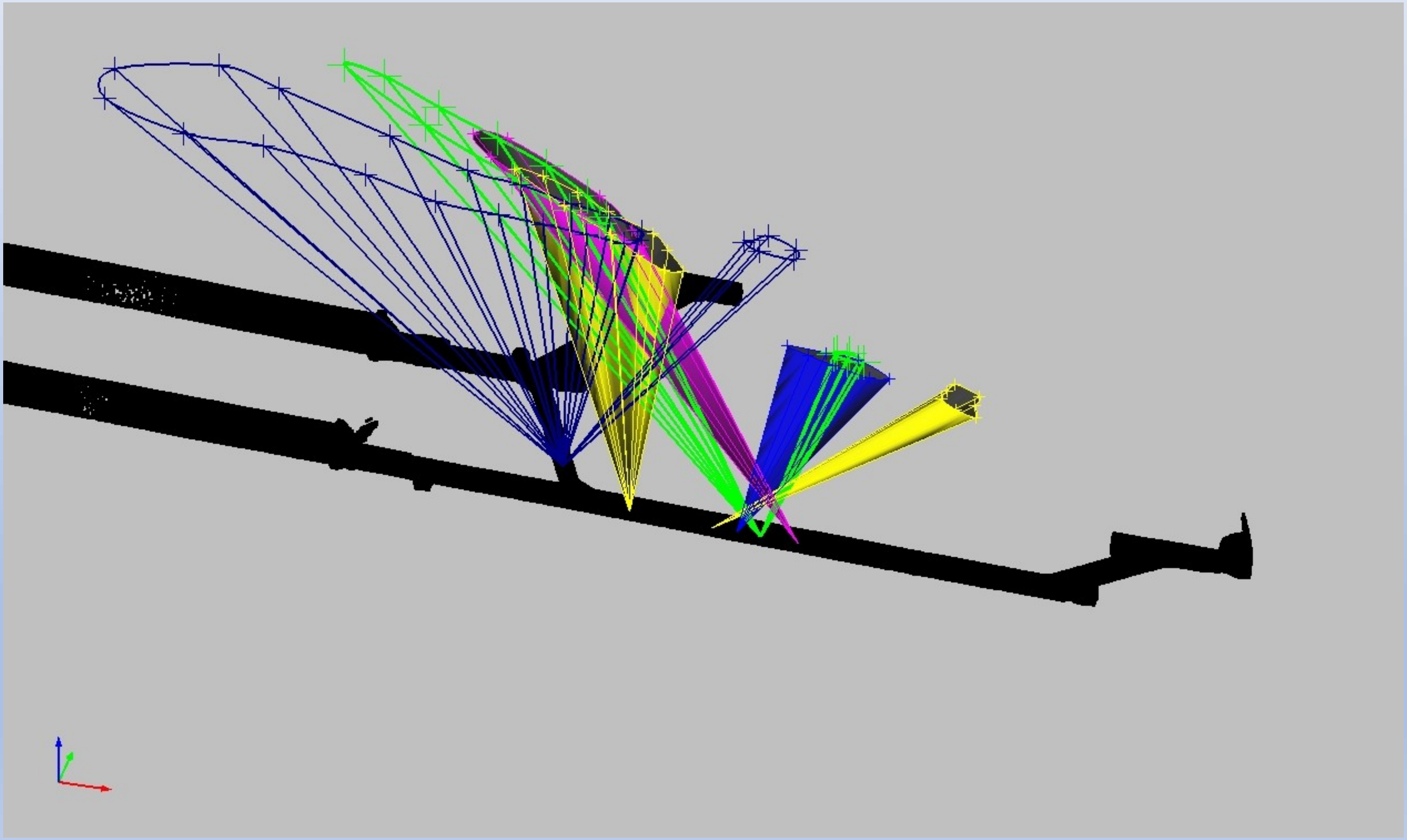
Density anomaly in 3D model



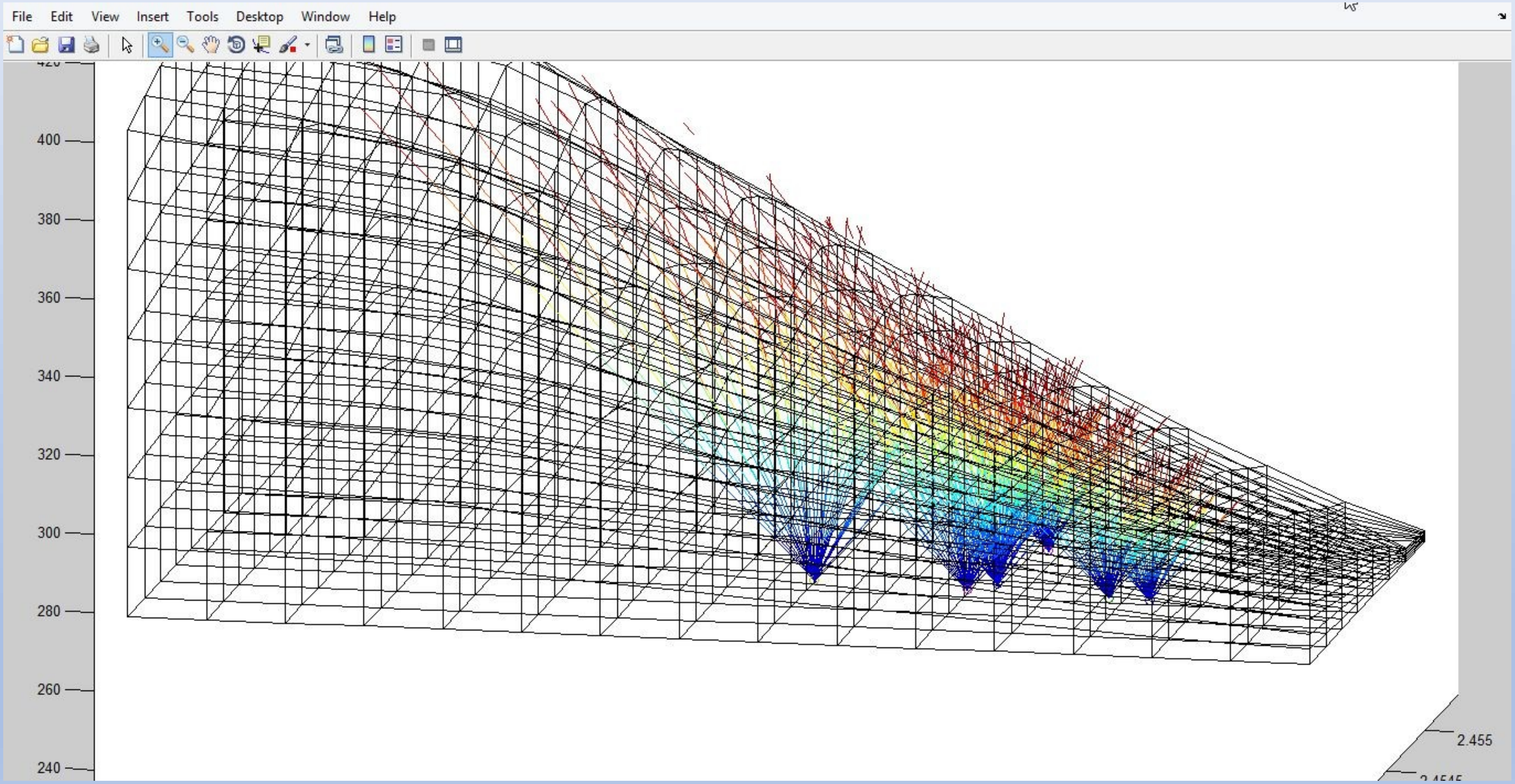
Density anomaly in 3D model



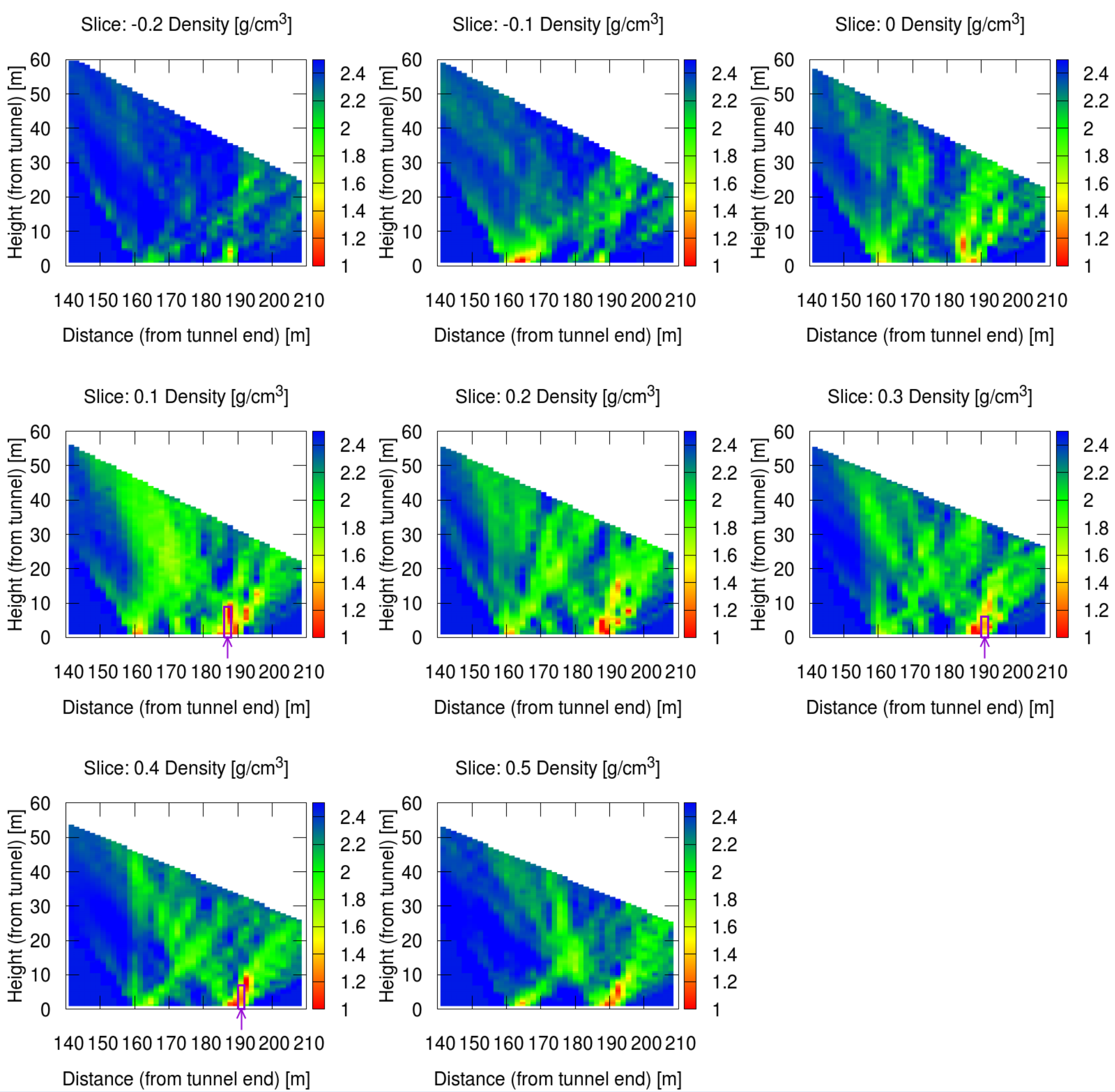
Density anomaly in 3D model



Model for inversion



Result of inversion (vertical slices)



Slice: -0.2 Density [g/cm^3]

Slice: -0.1 Density [g/cm^3]

Slice: 0 Density [g/cm^3]

Slice: 0.1 Density [g/cm^3]

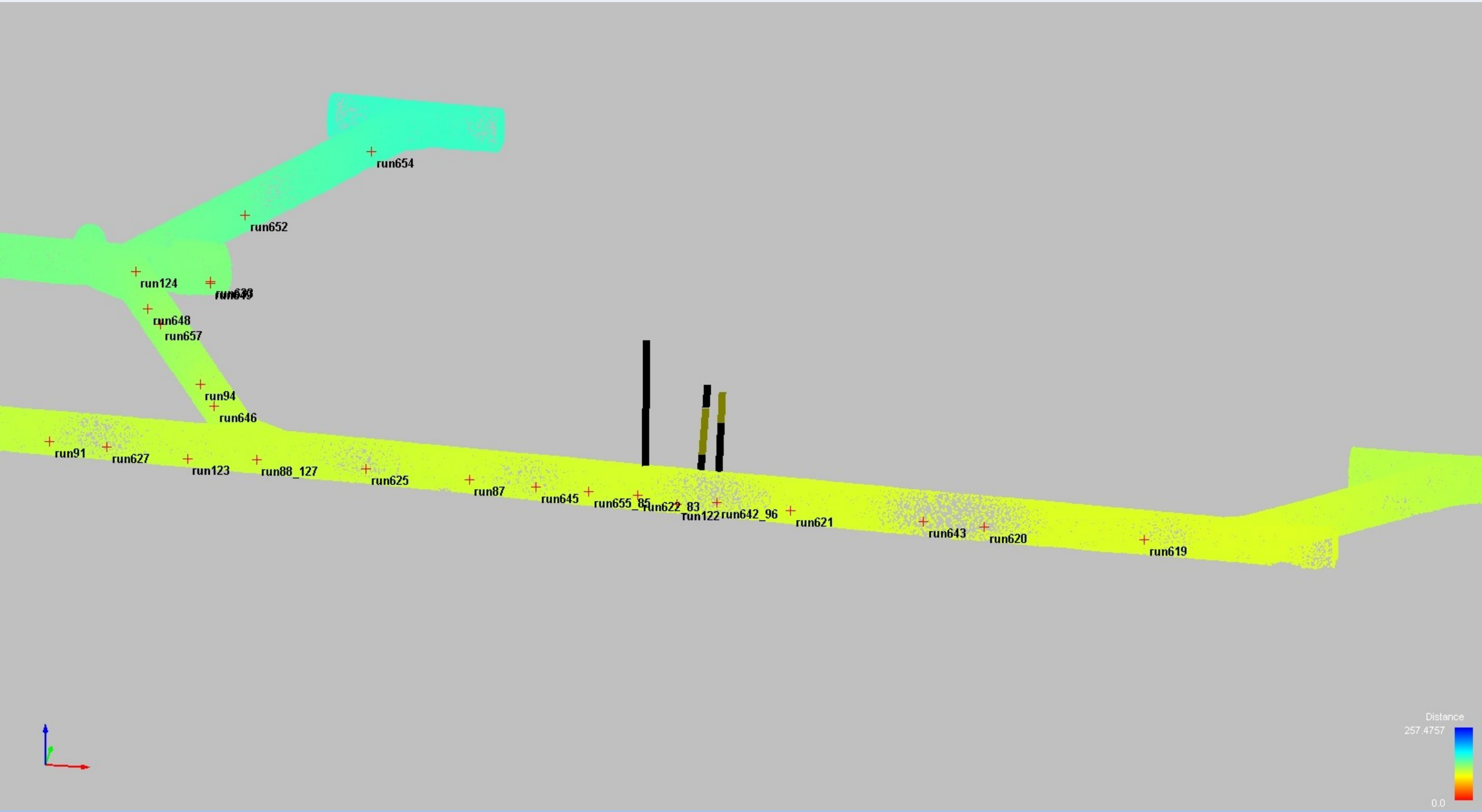
Slice: 0.2 Density [g/cm^3]

Slice: 0.3 Density [g/cm^3]

Slice: 0.4 Density [g/cm^3]

Slice: 0.5 Density [g/cm^3]

Validation by drilling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run652
run124
run638
run649
run648
run657
run94
run646
run91
run627
run123
run88_127
run625
run87
run645
run655_85
run622_83
run122
run642_96
run621
run643
run620
run619
Distance
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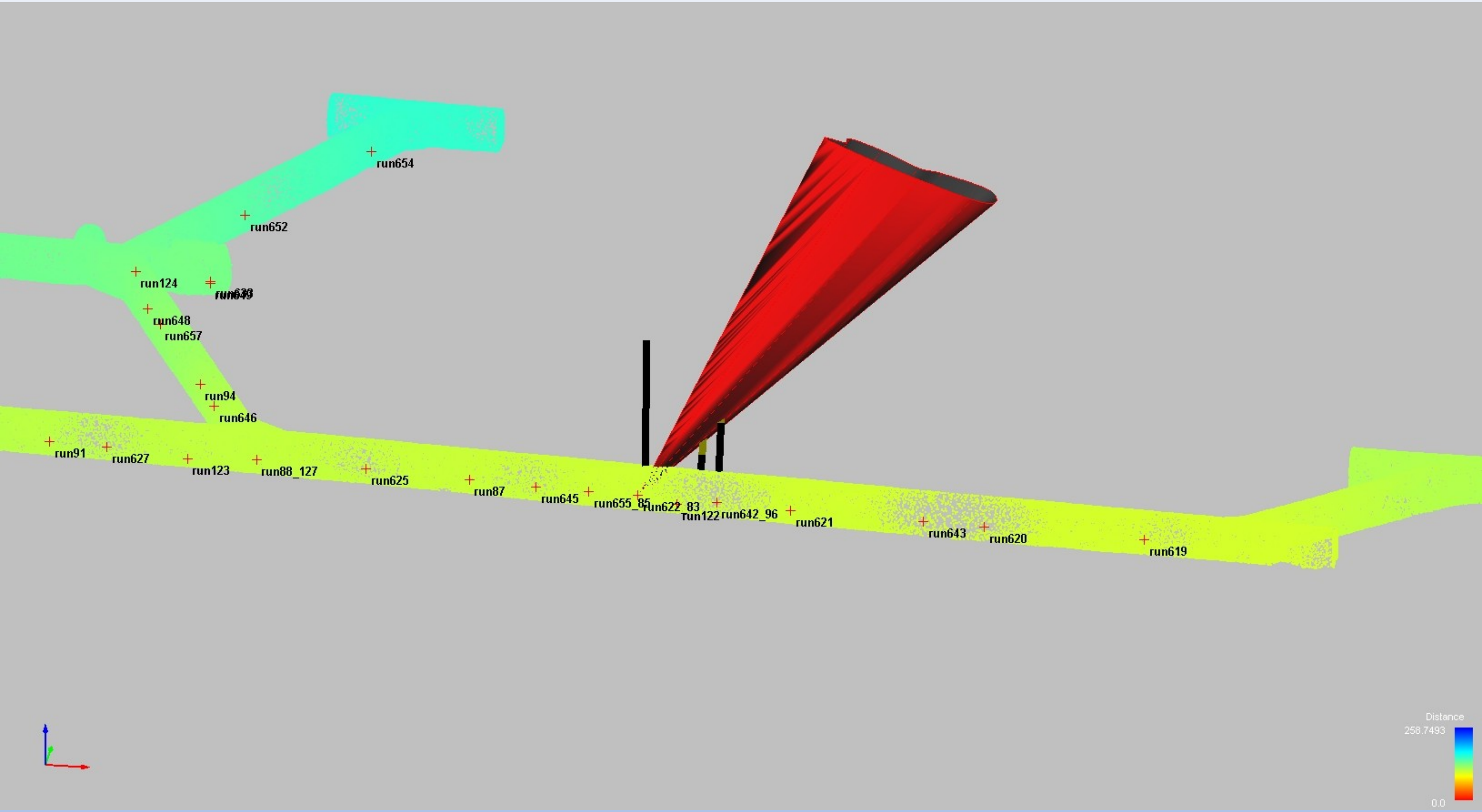
0.0


run654
run652
run124
run648
run657
run94
run646
run91
run627
run123
run88_127
run625
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run622_83
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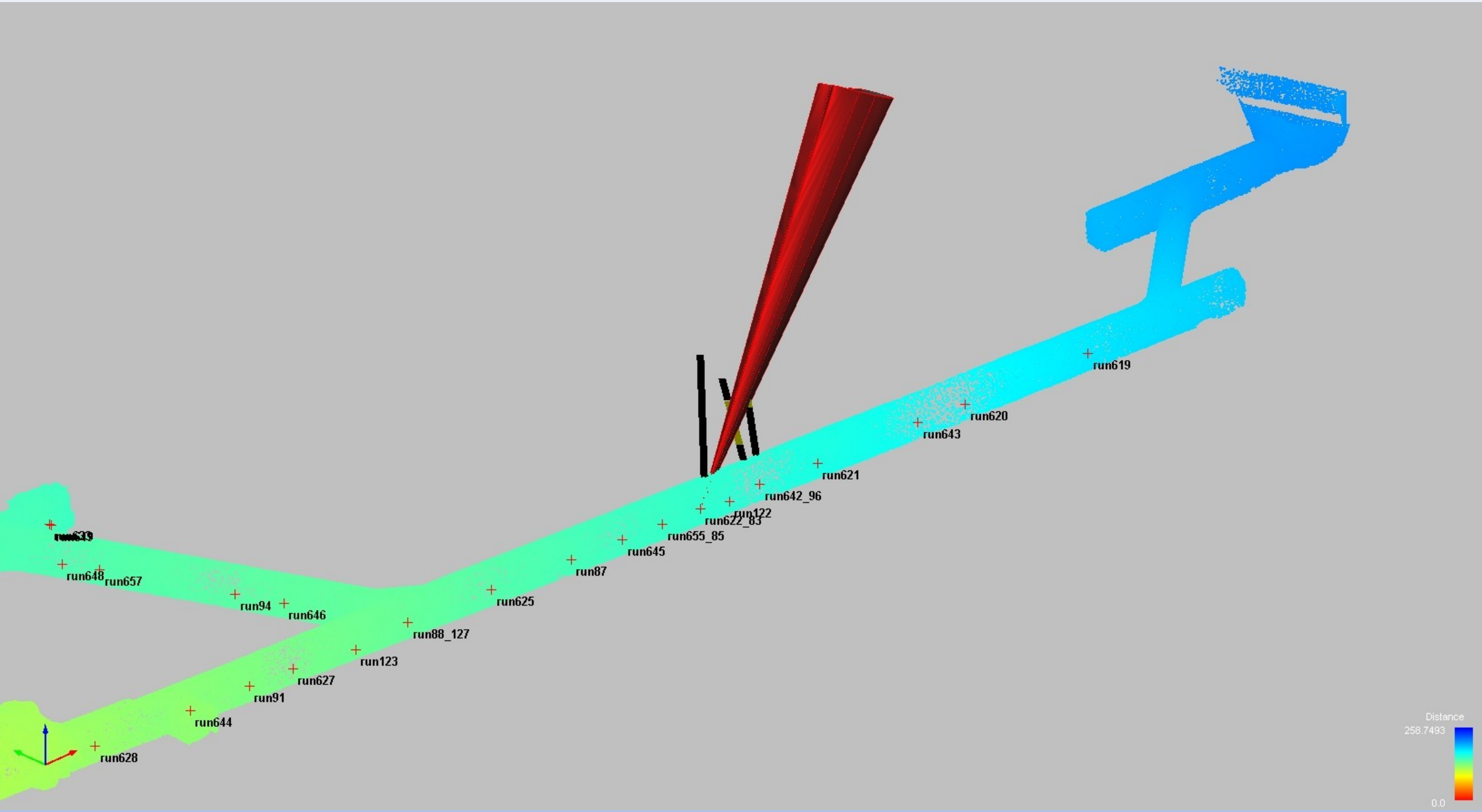
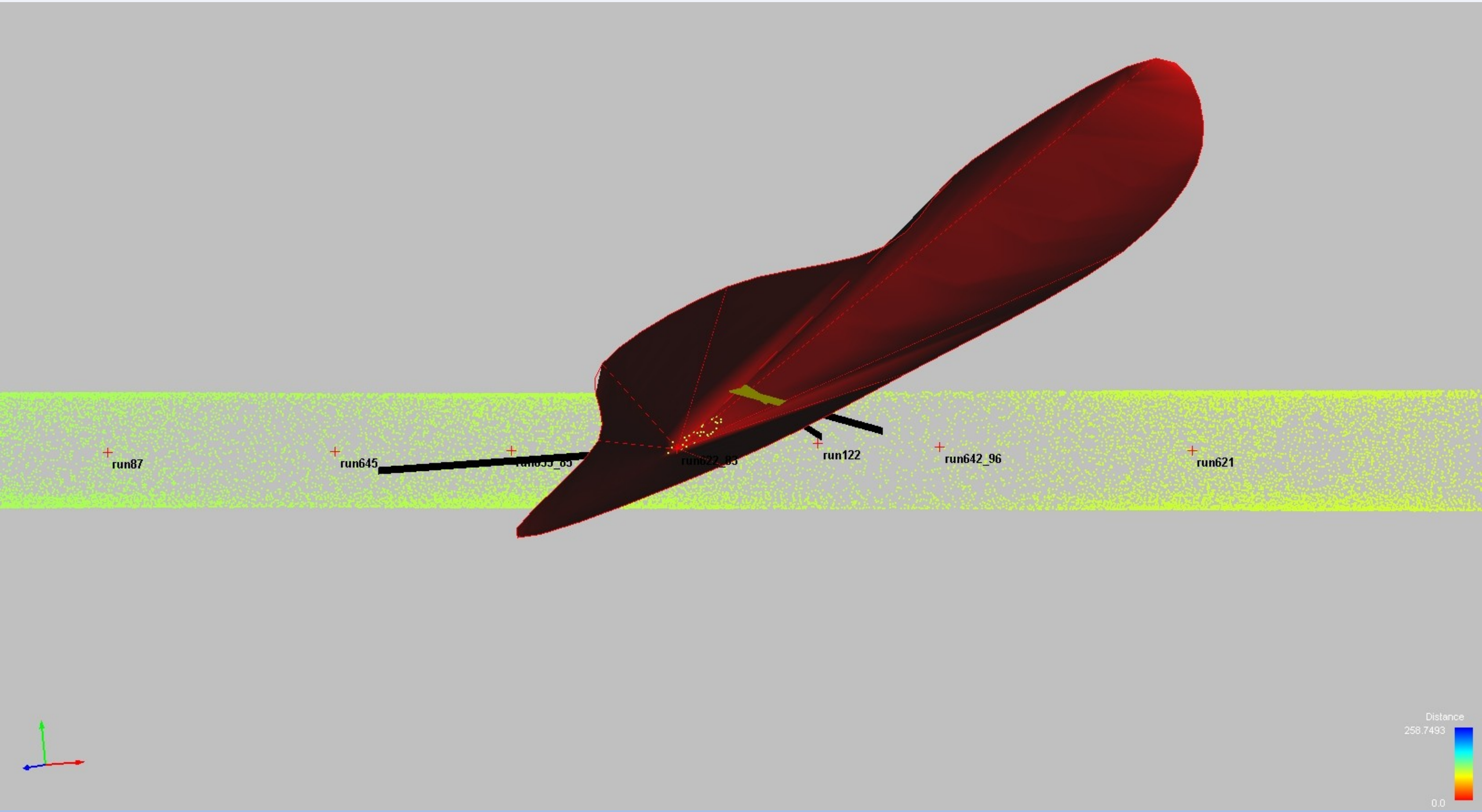
run620
run619
Distance
258.7493
0.0

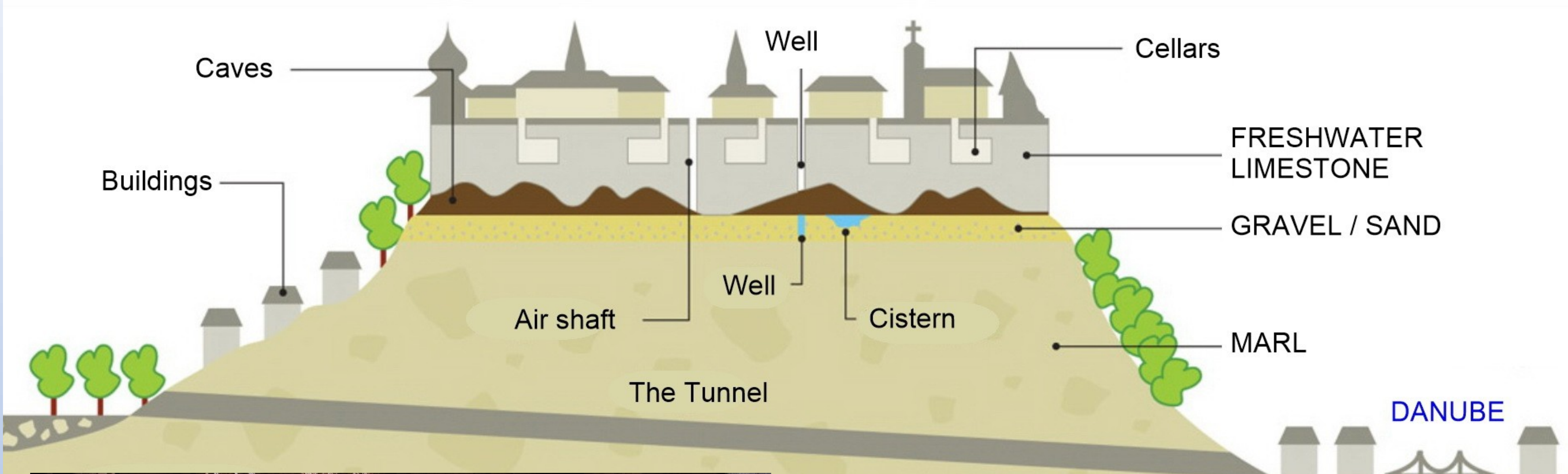

run619
run620
run643
run621
run642_96
run122
run622_83
run655_85
run645
run87
run625
run88_127
run123
run627
run91
run644
run628
run639
run648
run657
run94
run646
Distance
258.7493
0.0



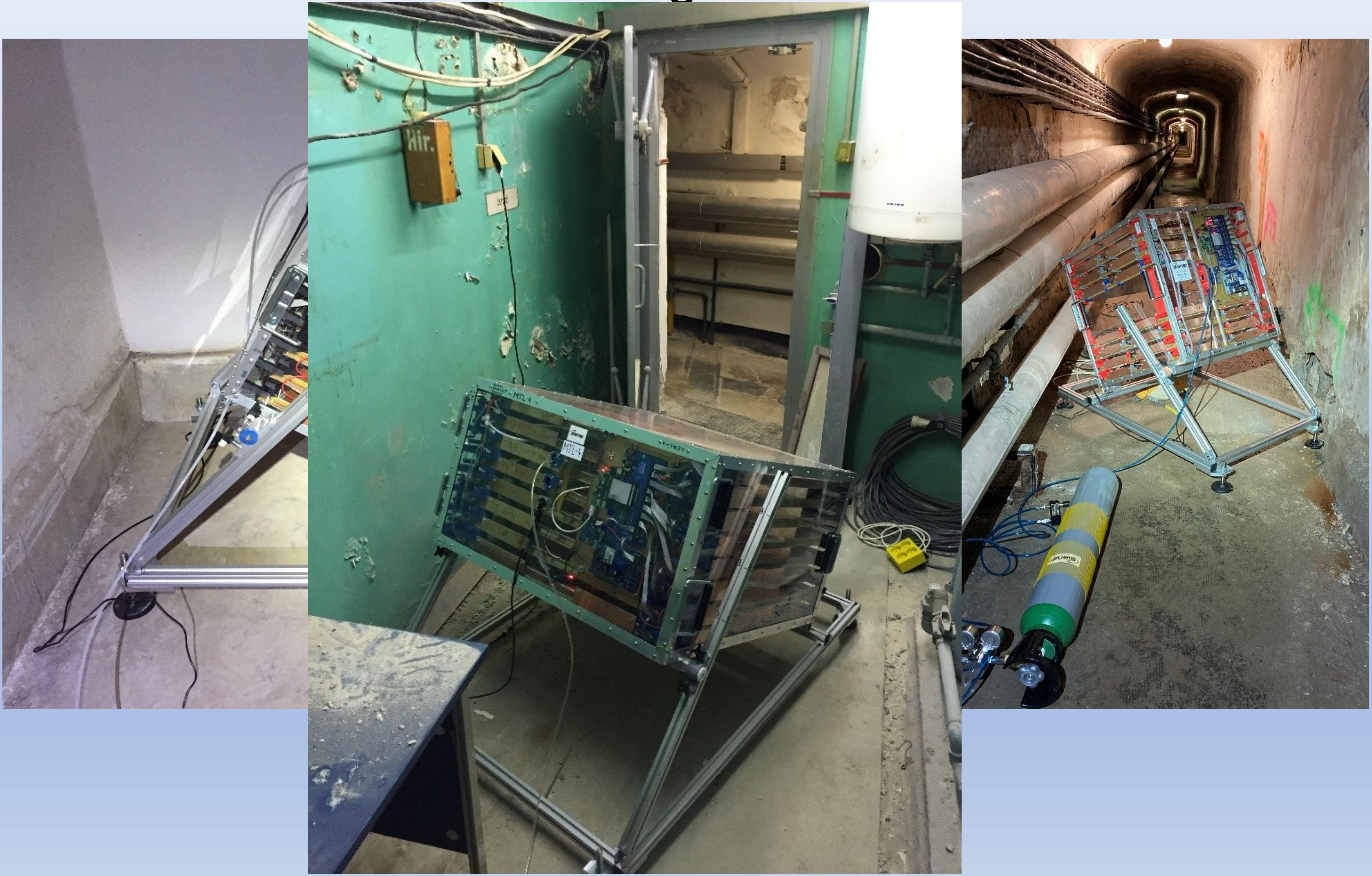
L. Balázs et al. Geophysical Journal International, 236, 700-710 (2024)
,https://doi.org/10.1093/gji/ggad428

Void searching under the Buda Castle

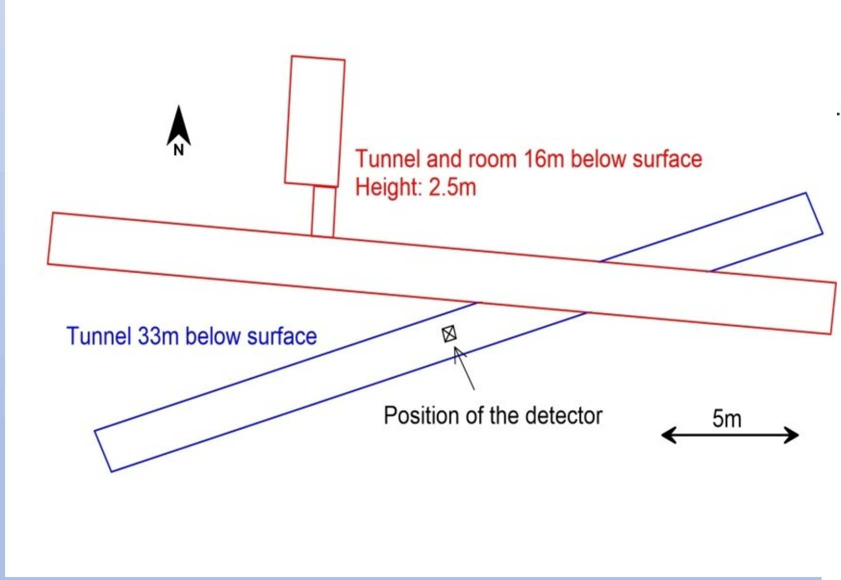
Natural caves and artificial tunnels in the Castle Hill of Buda



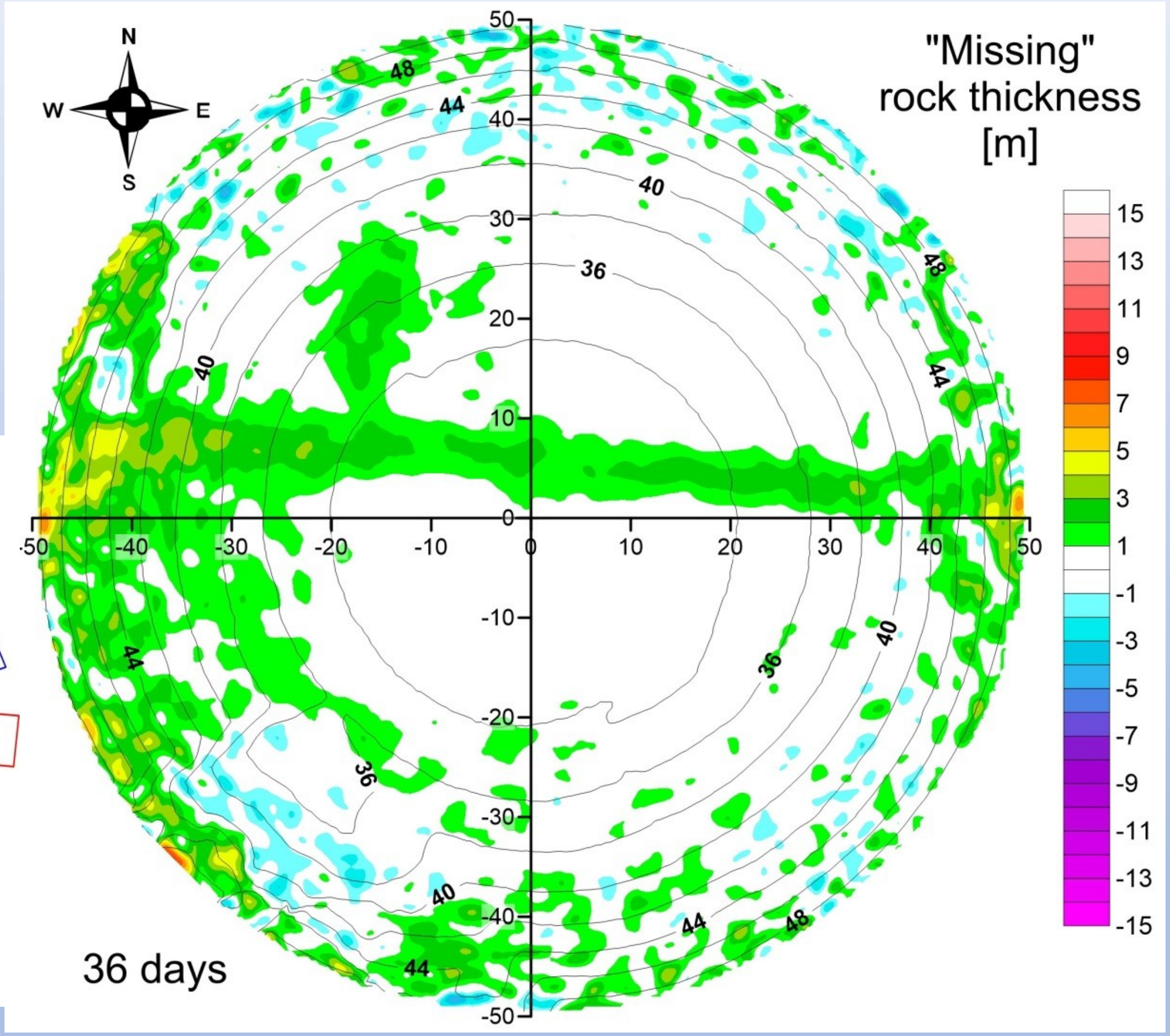
Measurement places: tunnel system 25-50m underground.



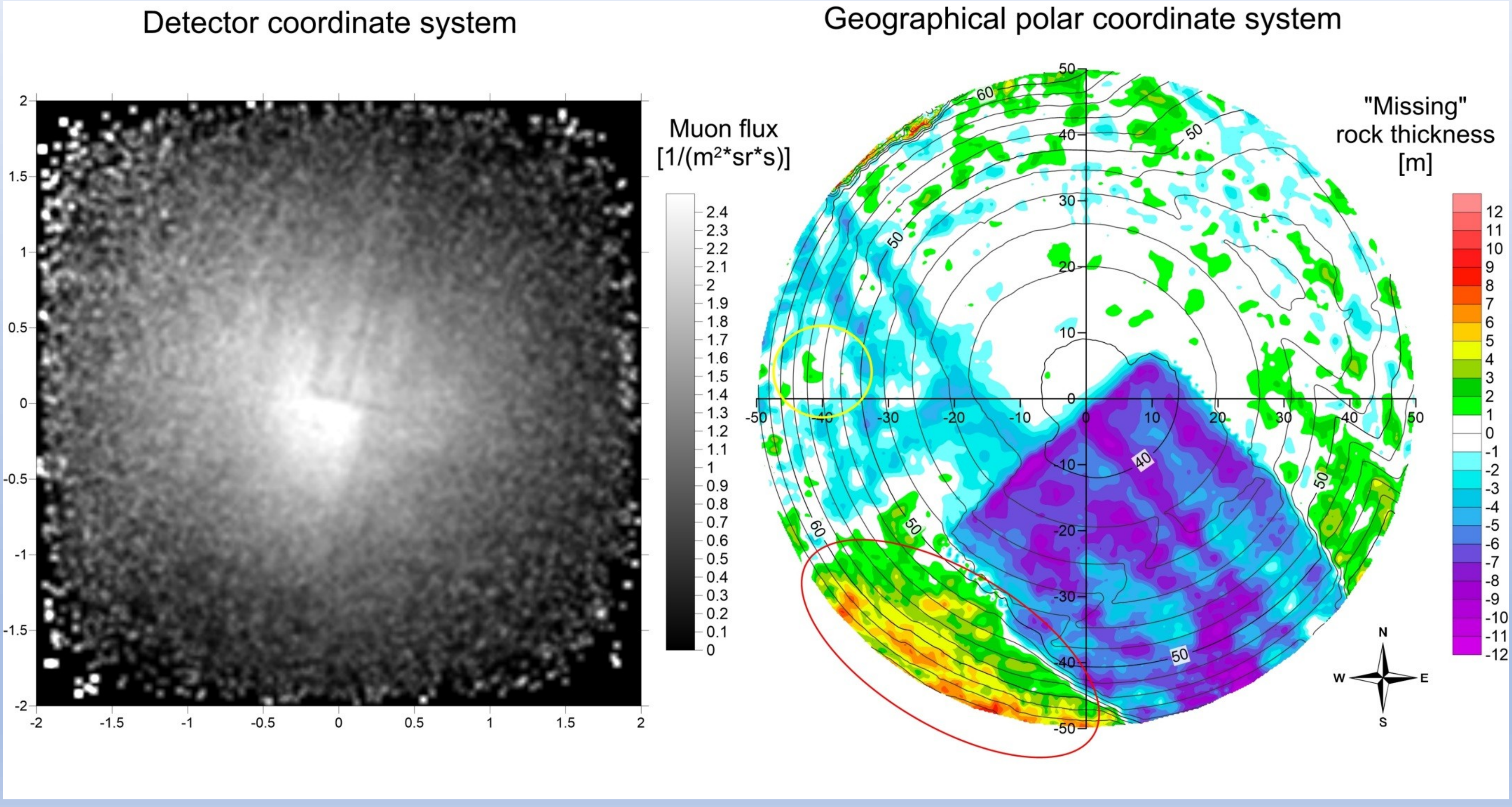
Test measurement under a known void



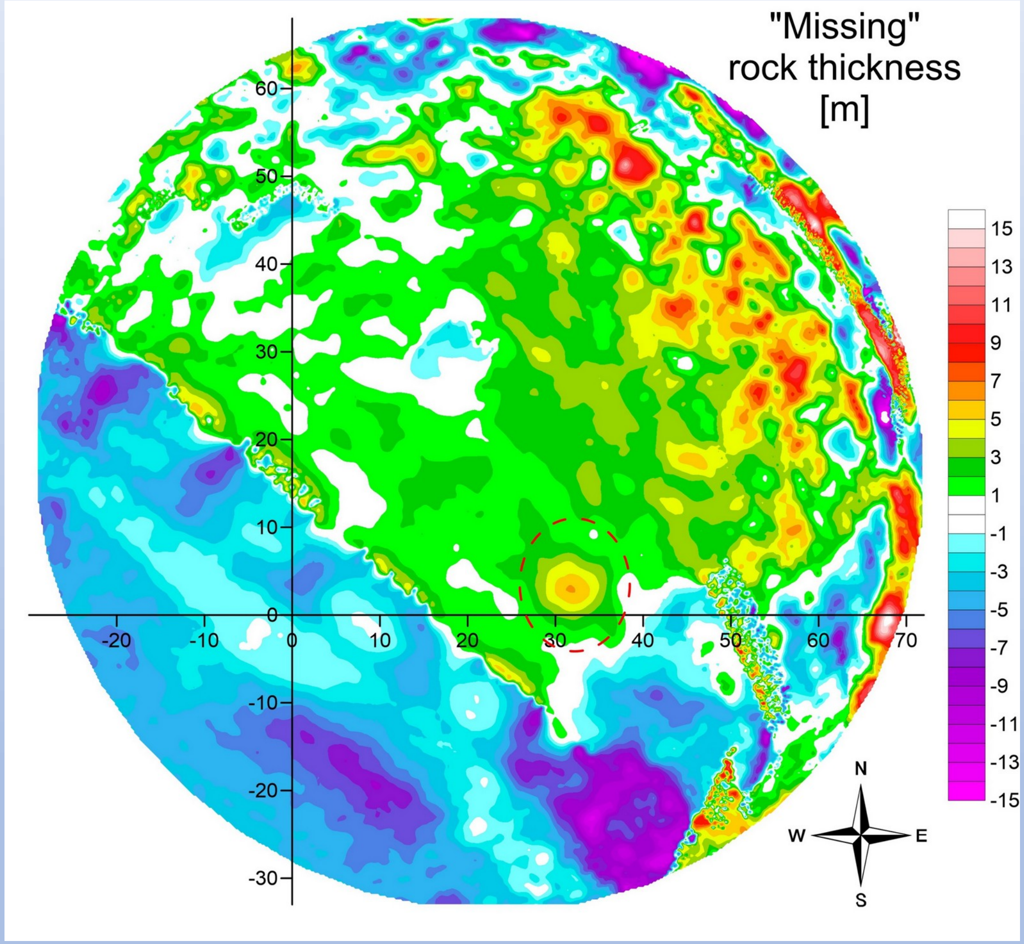
Geographical polar coordinate system

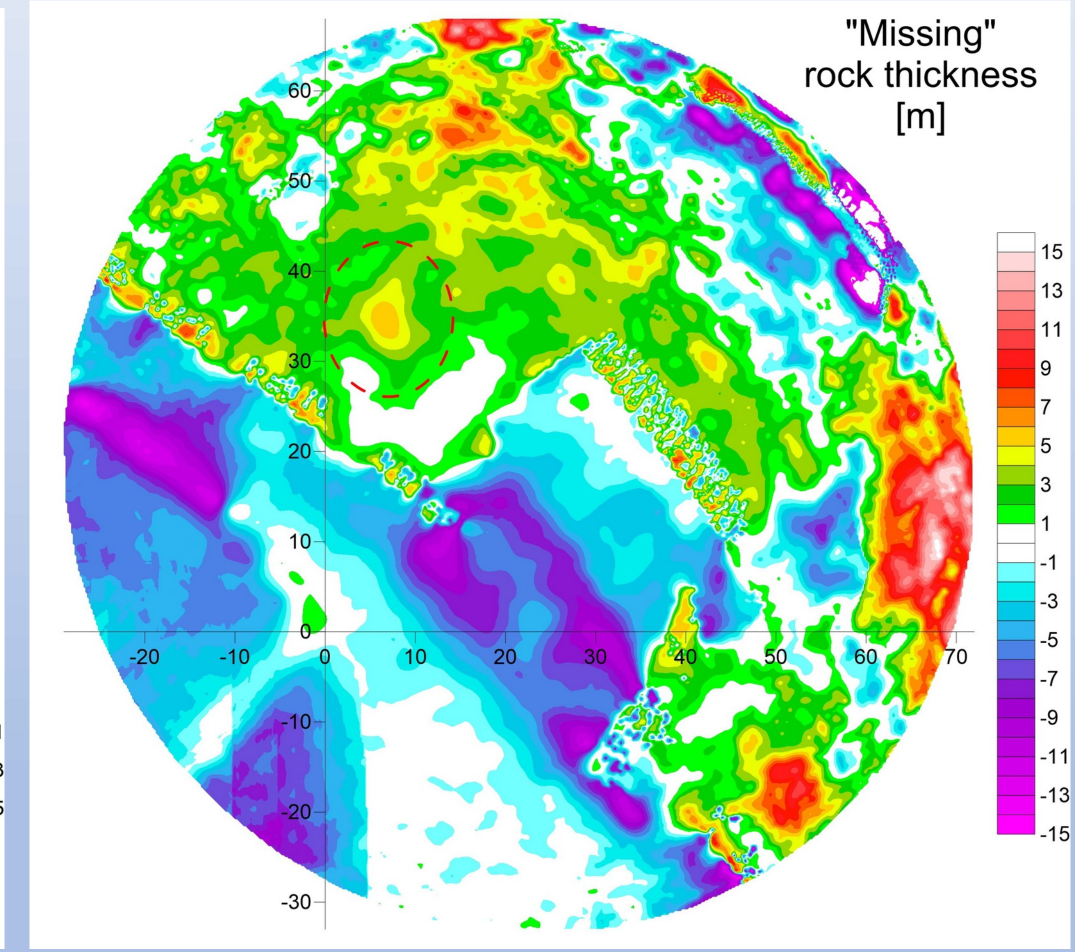


Buda Castle 3

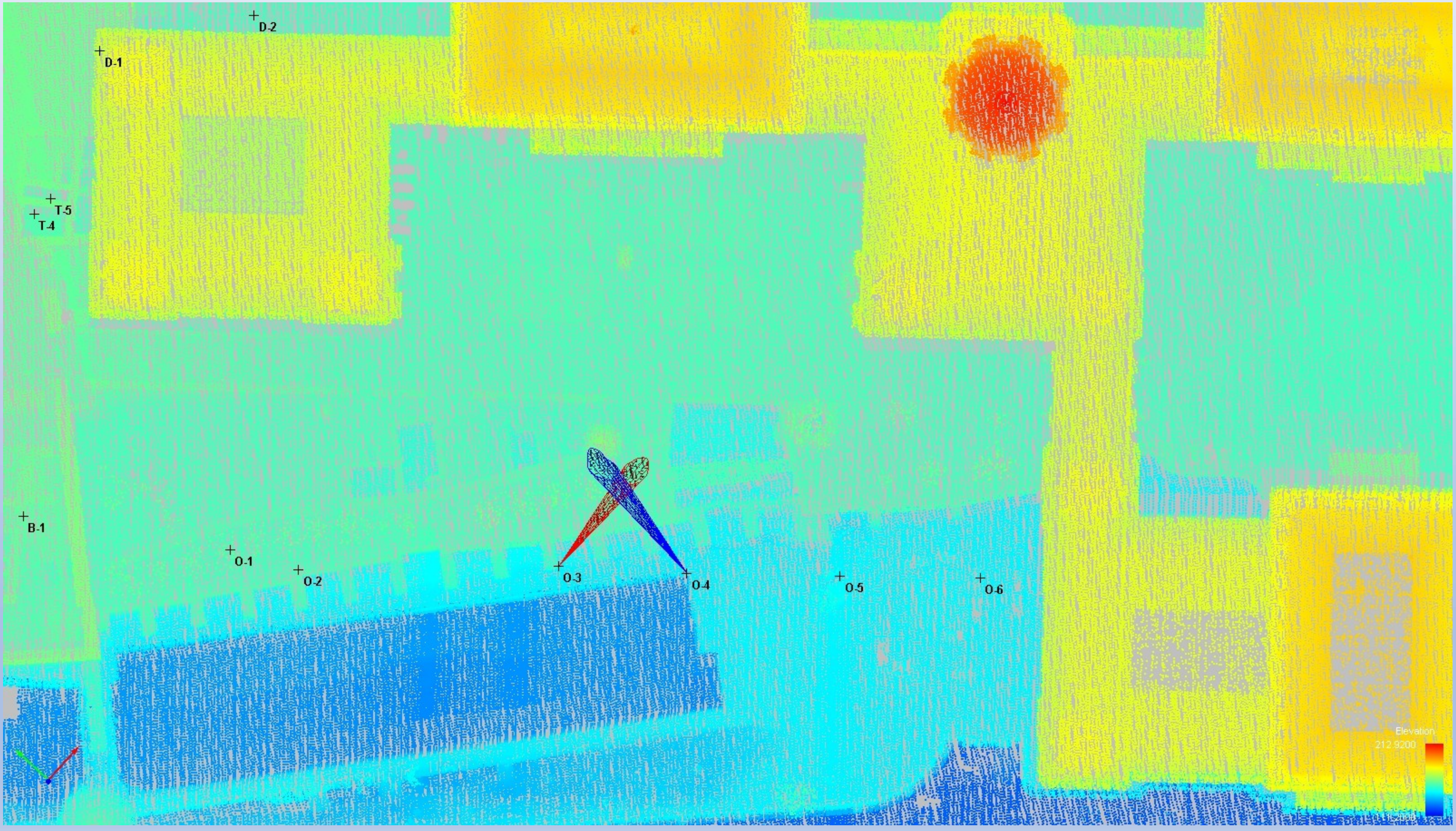


Strong anomaly from two different measurement points

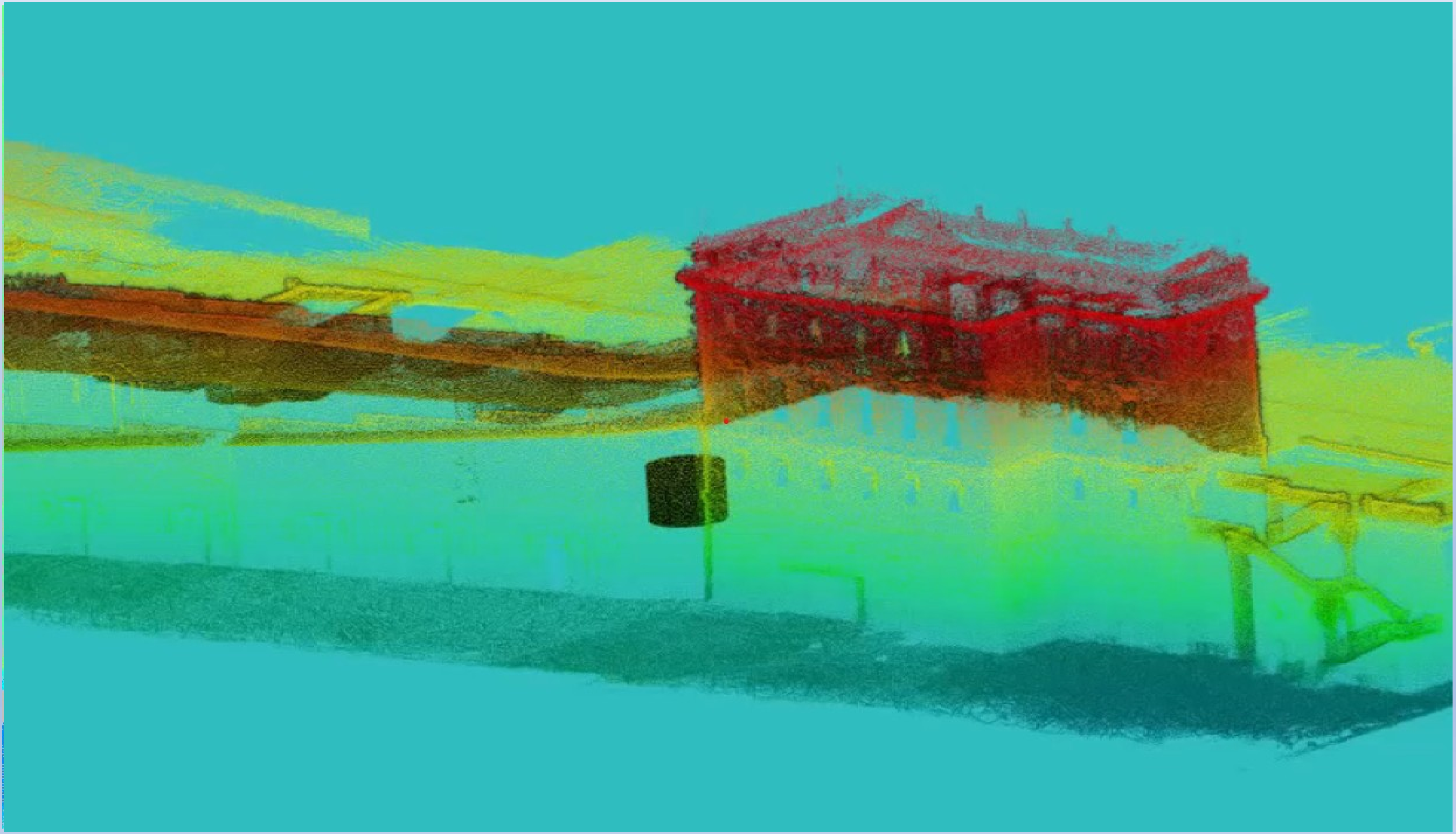




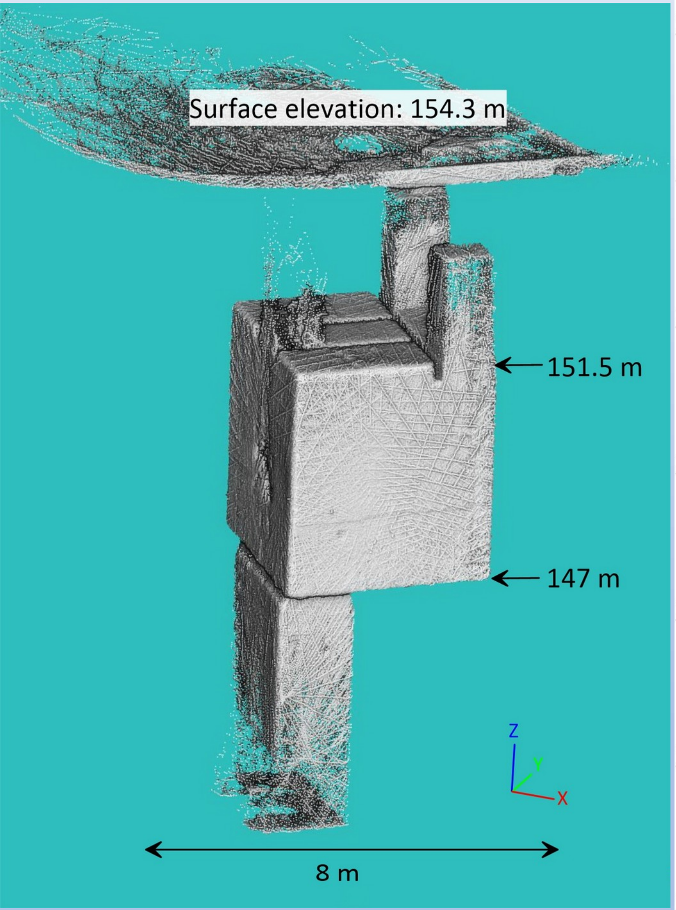
Drawing of anomaly cones

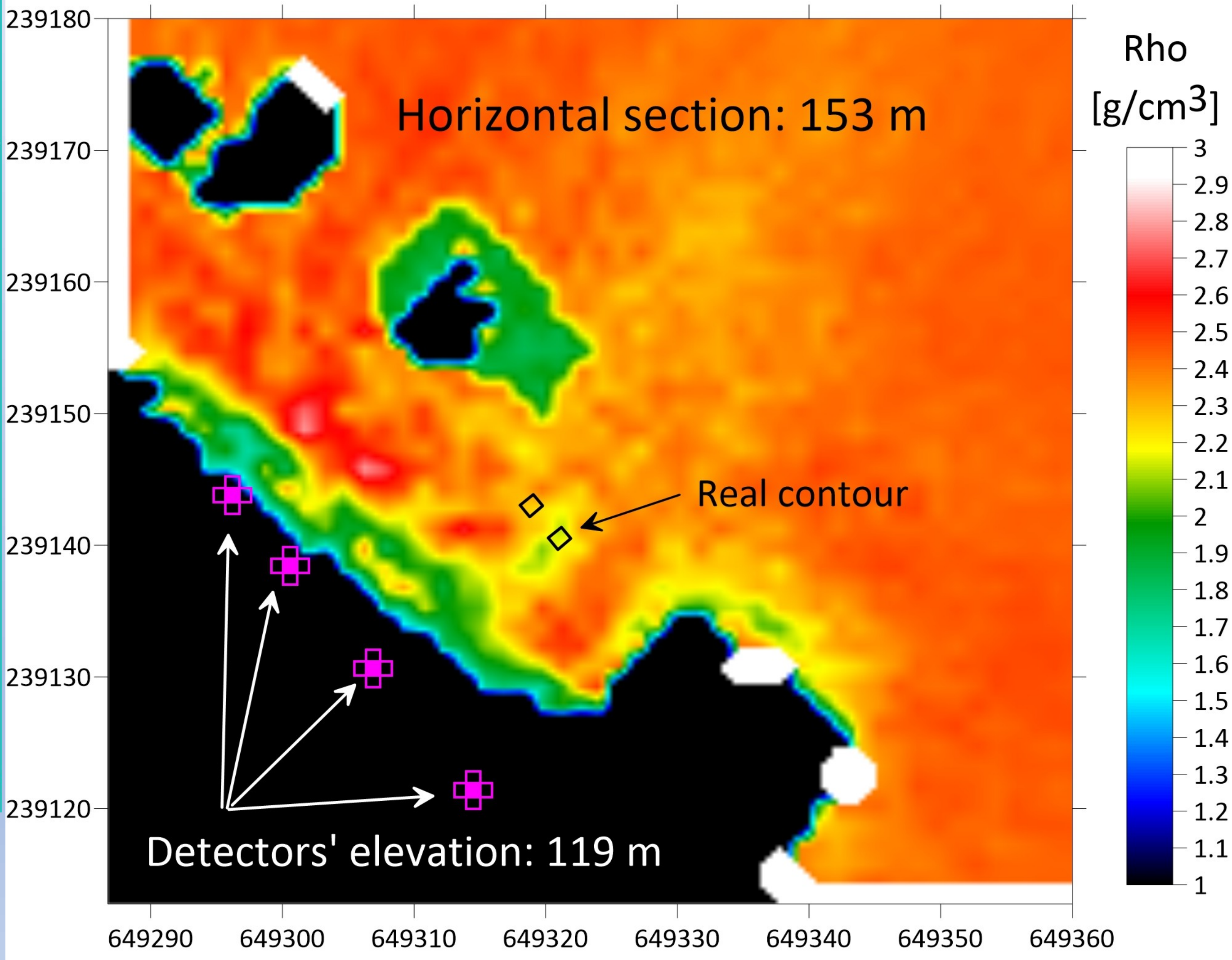


Inversion result of field measurements: Buda Castle



Inversion result of field measurements: Buda Castle

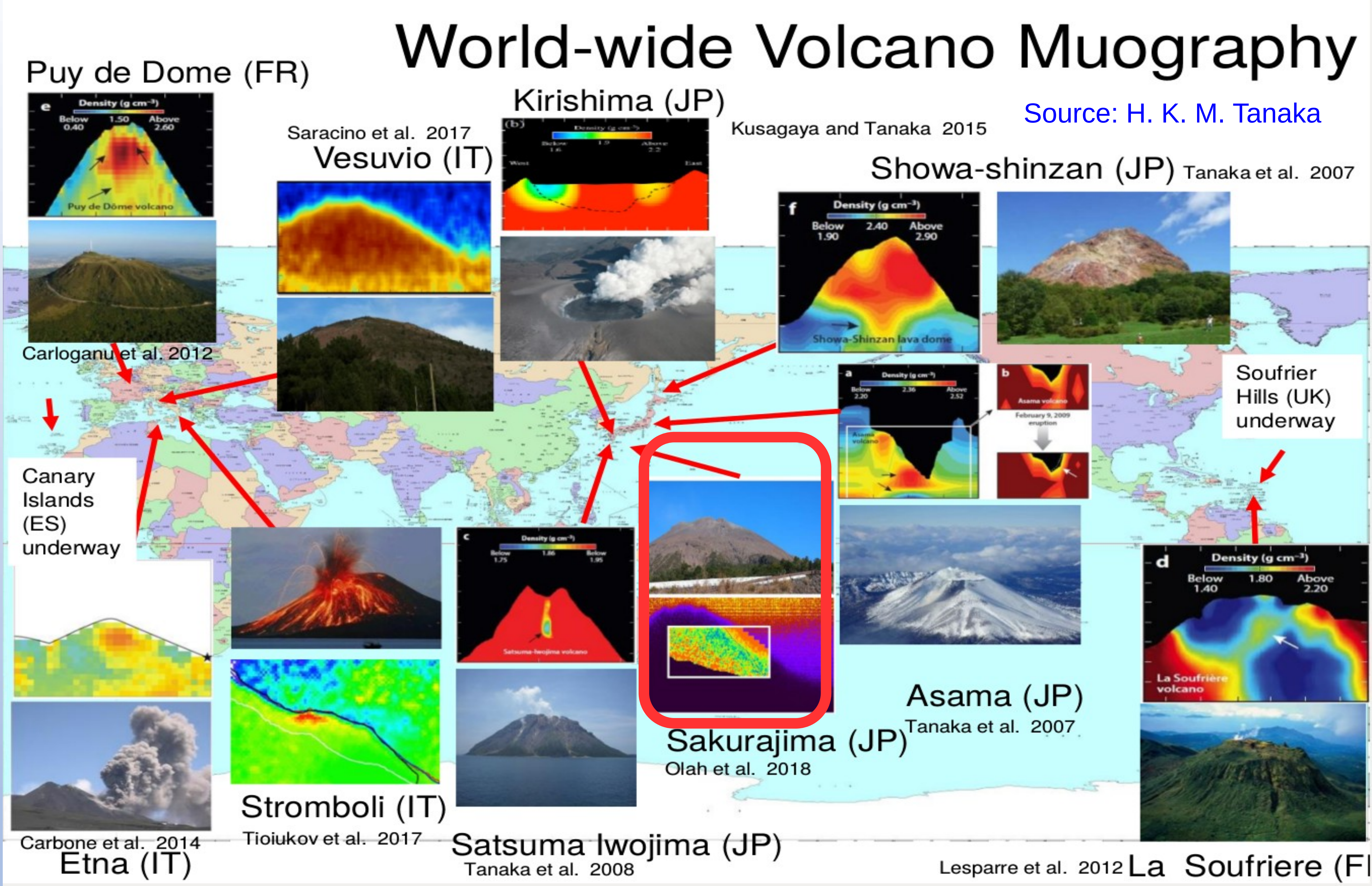




III. Field measurement examples

- Surface measurements

World-wide Volcano Muography



Source: H. K. M. Tanaka

Contributions of Muography to Volcanology: Showa crater

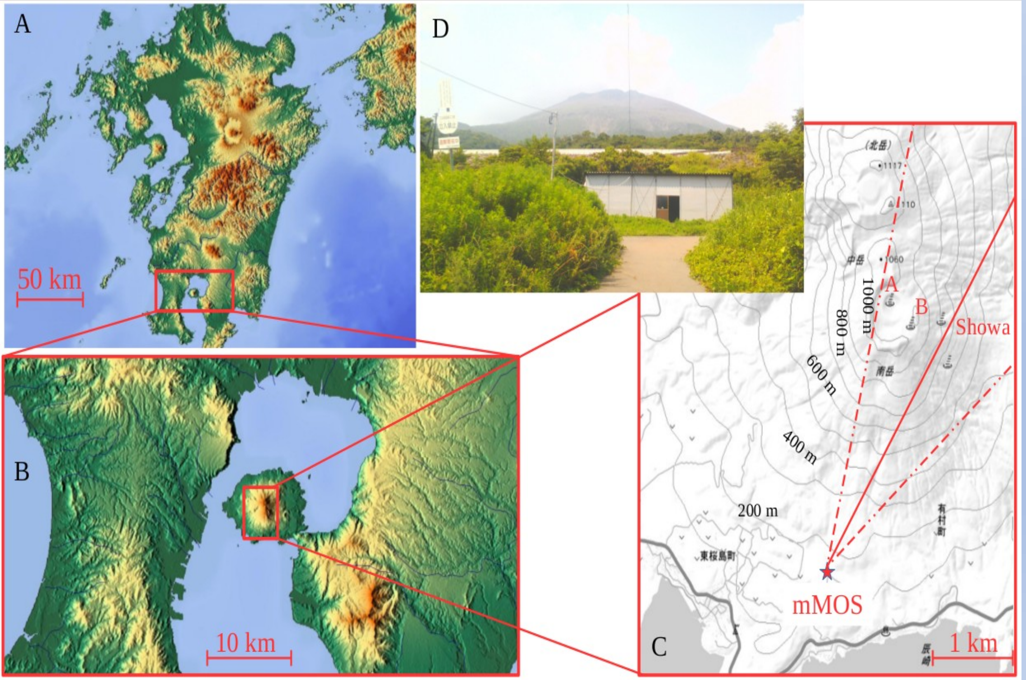
(1) Studying formation and stability of lava domes (Showa-Shinzan, La Soufrière de Guadeloupe),

(2) Exploring conduit structure for eruption modelling (Stromboli),

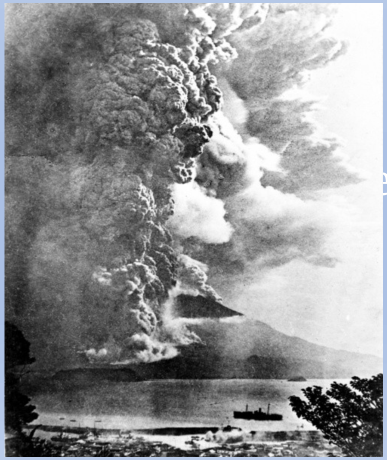
(3) Monitoring magma evolution and movement (Asama, Sakurajima).

Muography of Sakurajima volcano

- **An active stratovolcano** on the "Ring of fire" within the Aira caldera in Kagoshima Bay
- Latest plinian eruption occurred in 1914 → Next plinian eruption is expected in 25 years https://doi.org/10.1038/srep32691
- **Two craters of the southern peak → A few hundreds of (explosive) short-term eruptions per year**
- Short-term eruptions eject aerosols and gas with a bulk volume of ~10^7 m^3 to a height of 1000–5000 meter above the crater rims, throwing fragments of volcanic plug and lava bombs usually within approx. 3000 m radius
  → **Sakurajima pose continuously hazard to the surrounding areas**
- MEXT launched Integrated Program for Next Generation Volcano Research and Human Resource Development https://kazan-pj.bosai.go.jp/next-generation-volcano-pj-2019-jun
- **The University of Tokyo and HUN-REN Wigner RCP conduct muography of Sakurajima since January 2017 to**



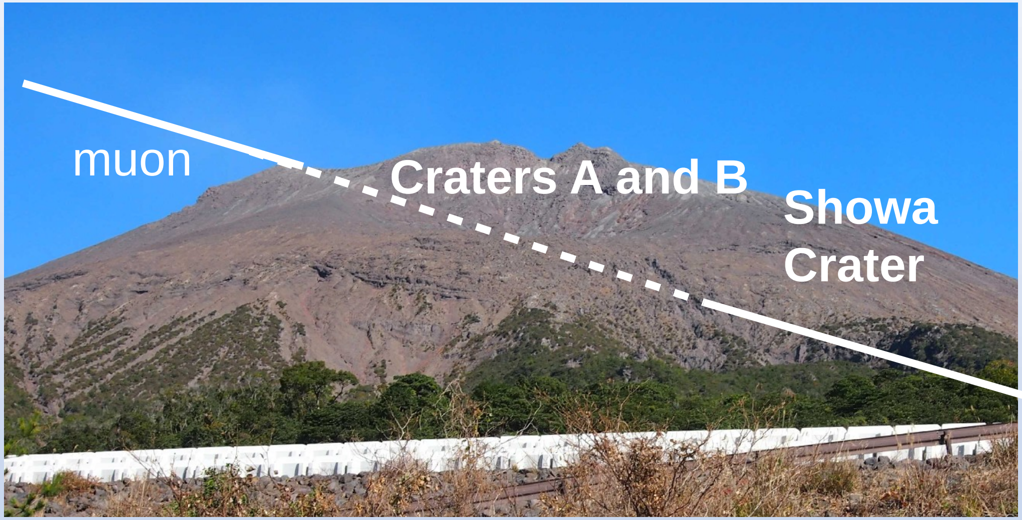
Source: https://doi.org/10.1038/s41598-018-21423-9

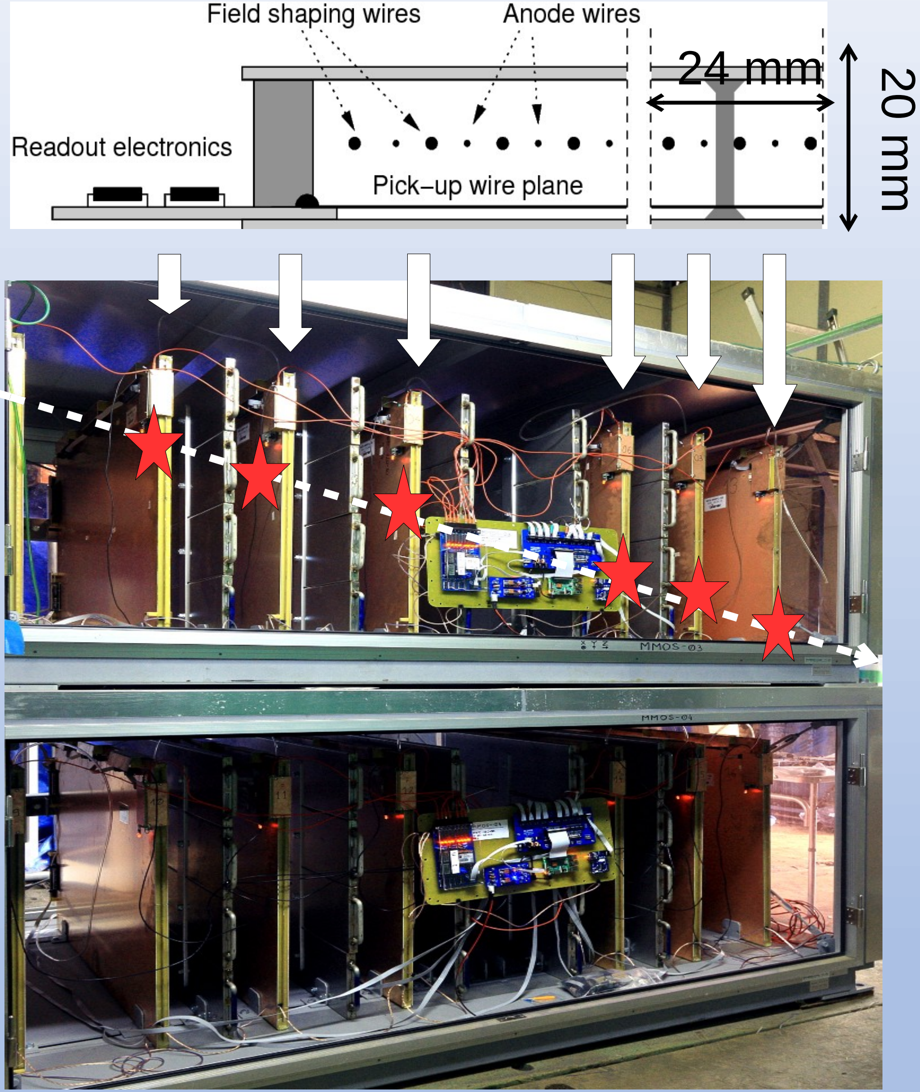


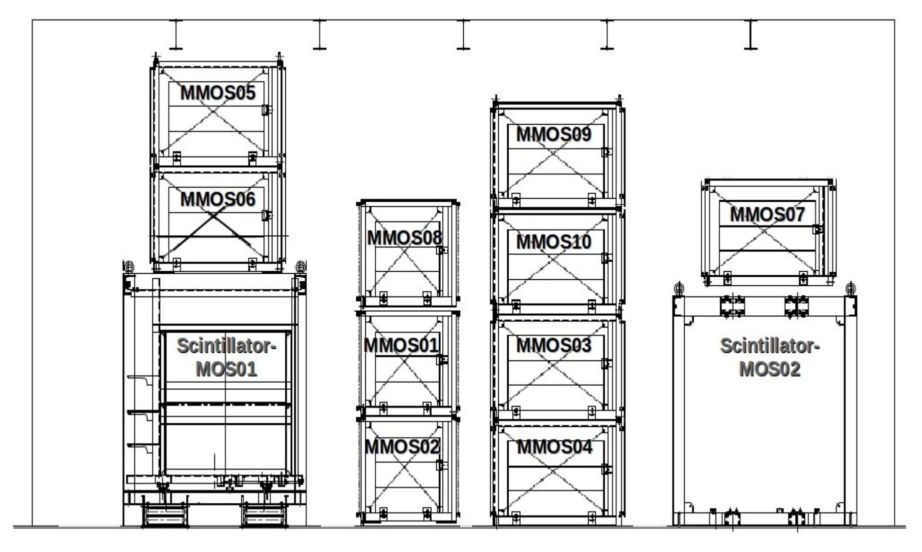
Source: Wikipedia

Source: Kimon Berlin, CC BY-

Muographic Observation Instrument (MOI)







Modular infrastructure for volcano muography
(11 MWPC-based trackers cover10 sqm surface area)

Muograpic Observation Instrument WO2017187308 https://patentscope2.wipo.int/search/en/detail.jsf?docId=WO2017187308

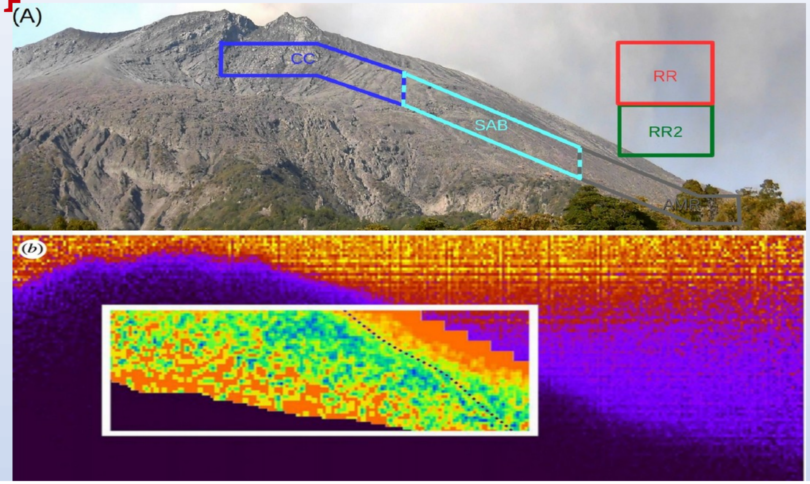
L. Oláh et al. Scientific Reports, 8, 3207, 2018, https://doi.or 1038/s41598-018-21423-9

D. Varga et al. Nucl. Instrum. Meth. A 958, 162236, 2020 htt doi.org/10.1016/j.nima.2019.05.077

The First Observations: Plug Formation, Tephra Deposition and Erosion

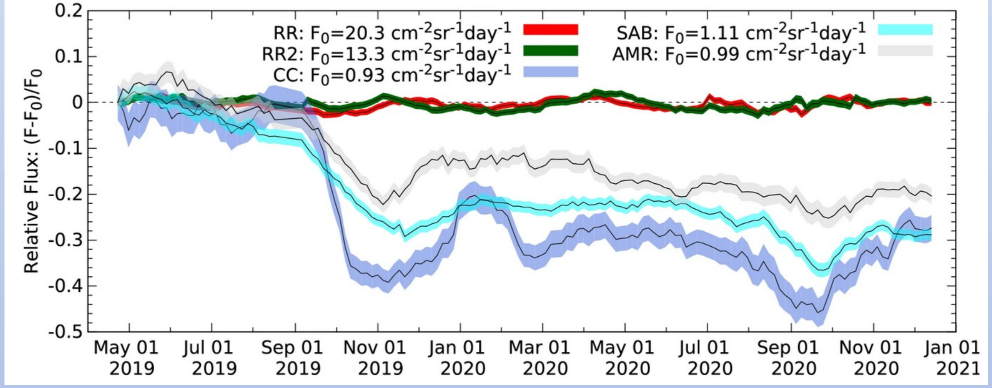
- Resolving the internal structure of the volcano with a spatial resolution of below 10 metres that is challenging to other techniques

L. Oláh et al. Scientific Reports, 8, 3207, 2018, https://doi.org/10.1038/s41598-018-21423-9



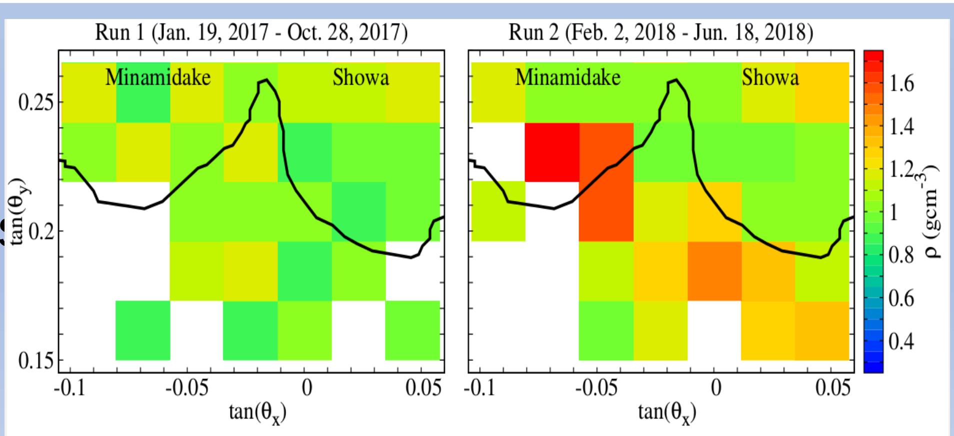
- Monitoring changes in the amount of materials on the volcanic edifice due to volcanic ejecta deposition, erosion and mudflows (lahars)

L. Oláh et al. Scientific Reports 11, 17729, 2021, https://doi.org/10.1038/s41598-021-96947-8



- Imaging of a magmatic plug beneath Showa crater with the cease of eruptions

L. Oláh et al. Geophys. Res. Lett. 46, 10417, 2019, https://doi.org/10.1029/2019GL084784



IV. Summary

- Muography is an imaging method, based on either transmission or scattering, allows non-destructive, remote and passive inspection of large-sized structures.
- Muography is made real by contemporary technology and detector construction methods. Need reliable production and performance.
- HUN-REN Wigner Research Centre for Physics, Detector Development group: extensive collaborations (Finland, Japan, Italy, …), VLAB infrastructure, multiple H2020 / HEU / national projects
- At the heart of that: HEP science and technology!

Thank you for your attention !

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