Muography, aka Muon Imaging

29.06.2021
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Imaging Nowadays

Muography :: based on naturally present atmospheric muons

Medical

Security

Geophysical
The precursors

1. Alvarez 1970

2. George 1955
Muons from Atmospheric Showers

At sea level:
~1 muon/cm²/min i.e. ~1 muon/s crosses one’s hand
Two Interactions Useful for Imaging

**Transmission**

\[ I = I_0 f(\rho) \]

**Scattering**

\[ \delta = f(Z) \]

- **2D image**
- applicable to very large targets
- relies on incident flux knowledge

- **3D image**
- necessary to measure each individual track before and after the target
- small to medium targets
- high position resolution, large area detectors
Scattering muography


Muon data confirms fuel melt at Fukushima Daiichi 1

23 March 2015

Initial results from using a muon detection system at the damaged Fukushima Daiichi unit 1 in Japan appear to confirm that most of the fuel has melted and dropped from its original position within the core, Tokyo Electric Power Company (Tepco) announced.

Results obtained from the muon detector on the northwest side of the reactor building (Image: Tepco)

The company completed installation of the muon detection system on 12 February. Two detectors were installed: one on the northwest side of the reactor building and the other on the north side. Since then, data collection continued until 10 March (a period of 26 days). The initial results have now been analysed.

The detector system was developed by Japan's High Energy Accelerator Research Organization (KEK). The system uses the so-called permeation method to measure the muon data.
Transmission muography

Very broad radiation source

Very penetrant radiation

\[
< R_\mu(E_\mu) > = \int_0^{E_\mu} dE_\mu / < \Delta E/dx > \sim \beta^{-1} \ln(1+\beta/\alpha E_\mu)
\]

standard rock:
A=22, Z=11, ρ=2.65 g cm⁻³

<table>
<thead>
<tr>
<th>E_\mu (GeV)</th>
<th>R_\mu (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>19</td>
</tr>
<tr>
<td>100</td>
<td>155</td>
</tr>
<tr>
<td>1 TeV</td>
<td>0.9</td>
</tr>
<tr>
<td>10 TeV</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Transmittance:

\[
\int \rho(\alpha,\beta) dr = F(T(\alpha,r(\alpha,\beta))) = F\left(\frac{N(\alpha,\beta)}{N_0(\alpha,\beta)}\right)
\]

Relative error on integrated density

- when assuming propagation in standard rock and ignoring the chemical composition
- when assuming propagation in dry rock

K Vernet

~400 m standard rock
~2 km

V Niess, 2017
Transmission muography from “inside”: mining

Bay 19
Deposit
Chamber G
Chamber F
Chamber 2

McArthur River Uranium Mine, 500 m underground
First measurement of ice-bedrock interface of alpine glaciers by cosmic muon radiography

Obvious industrial & Military Applications

Using Muon Tomography

High-energy cosmic rays create showers of particles (Muons) in the upper atmosphere.

Using the Lynkeos Muon Imaging System we are able to non-invasively scan objects and differentiate between different materials.

The system is ideal for scanning intermediate Level Nuclear Waste.

More
11,000 years old composite dome in the Chaîne des Puys

Dome characteristics:
- ~400m high,
- 1.8 km wide at its base

Two distinct units:
- two lava pulses
- partial destruction of the first construction

Important hydrothermal alteration
Volcano Imaging with Ballistic Muons

Exposure = time needed to reach a certain precision on the density measurement for a given angular resolution and detector size

- 10 days (10m² detector, 3°x3°)
- 10 days (1m² detector, 3°x3°)

Infinite ways of statistically optimising the measurements and the model testing

Synthetic model for Puy de Dome and 1 year data with TOMUVOL detector (~0.5 m²)

Valentin Niess EGU2018-18110
One particular choice of inversion with three muographic viewpoints

Synthetic model of Puy de Dôme
0.5 x 0.5 x 0.5 m³ voxels
Gaussian random field for densities:
σρ = 100 kg/m³
Λ = 200 m

Volcano Imaging with Atmospheric Muons

\[ \frac{N}{N_0}(\alpha, \beta) \rightarrow \int \rho(r, \alpha, \beta) dr \]

calculated from an measured number of muons in a given direction

**Measurement** = Signal + Background

<table>
<thead>
<tr>
<th>Integrated Density (True, mwe)</th>
<th>Elevation Angle (deg)</th>
<th>Transmitted Flux (m(^{-2}) d(^{-1}) deg(^{-2}))</th>
<th>Integrated Density (measured, mwe)</th>
<th>Bias (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>18</td>
<td>3.18</td>
<td>389.7</td>
<td>-22</td>
</tr>
<tr>
<td>1000</td>
<td>11</td>
<td>0.83</td>
<td>539.6</td>
<td>-46</td>
</tr>
<tr>
<td>2000</td>
<td>3</td>
<td>0.19</td>
<td>498.3</td>
<td>-75</td>
</tr>
</tbody>
</table>

Ambrosino, F., et al. (2015), Joint measurement of the atmospheric muon flux through the Puy de Dôme volcano with plastic scintillators and Resistive Plate Chambers detectors, J. Geophys. Res. Solid Earth, 120

Solution: sample the muons backwards in time, from the detector to the atmosphere

CPU time needed to simulate the transmitted flux with 1% accuracy

https://arxiv.org/abs/1705.05636
TOMUVOL project (2012-2018)

- 4 layers of 6 Glass Resistive Plate Chambers (GRPC)
- GRPC: gaseous detector with glass electrodes
- Applied voltage: 7.5 kV
- 1.2 mm gap filled by a gas mixture chosen for its ionisation properties
- 1 layer: ~1 m²
- Readout cells of 1 cm² (~40000 cells in total)
- Using a 5 MHz clock and auto-triggered
- Remotely monitored from web interface
TOMUVOL :: Impact of the muon detection threshold

rock depth (km)

azimuth $\in [25, 35]$  

TDF 2013, $P_\mu > 0.1$ GeV/c

$1.8 \text{ g/cm}^3 \pm 0.6 \text{ g/cm}^3$

0 - 5 cm - 10 cm Pb

PRELIMINARY
Different Types of Telescopes for Vulcano Imaging

energy threshold $\sim$ GeV
resolution: $\sim 0.28^\circ$

$R$ = $10\mu m$ - $0.1 mm$ - $1 mm$ - $1 cm$

$d = cm - m$

$d = 1 km$

energy threshold $\sim 20 GeV$
resolution: $\sim 0.14^\circ$

Osvaldo Catalano, Melania Del Santo, Teresa Mineo, Giancarlo Cusumano, Maria Concetta Maccarone, Giovanni Pareschi,
arXiv:1511.01761
Muography Vs Traditional Geophysical Methods for Volcano Imaging: Gravimetry

Ellipsoidal Earth

Geoid (equipotential surface following the averaged sea level)

Gravity field variations due to density variations

Δg = 0.004 m/s² = 400 mGal

Δg = 1 mGal

GPS and Scintrex CG5 gravimeter

Gravity stations location for the total survey

Summit area gravity stations

C. Cârloganu, 29.06.2021

Gravity disturbance (EGM2008, xmax=500)
Simulated model of the volcano

Gravimetric inversion

Muographic inversion

Muography Vs Traditional Geophysical Methods for Volcano Imaging: Gravimetry

Gravimetry = static imaging method: it cannot be used for survey of active volcanoes!

Increase the detection surface of muon telescopes

Muography = best way of imaging kilometre scale volcanoes

Saltus & Blakely 2011

Control the detection threshold

1  3,5 g/cm³

2  2.7 g/cm³

3
Conclusion

Muography - is a fast developing field with a lot of potential and a broad spectrum of applications:

- inland security
- archeology
- mining
- volcanology
- ....

Further development will depend on the availability of

- robust
- low cost
- large area
- high segmentation

detectors and (in some cases) successful transfer of rather complex reconstruction algorithms towards the user community.