The Integrated Program for Next Generation Volcanic Research
and Human Resource Development (INeVRH) Workshop 2024, Tokyo, Japan

Development of the technique to visualize the internal structure of a volcano, and its extension to monitor undeground position

László Oláh[1,2], Gergő Hamar[1,2], Takao Ohminato[3], József Szűcs[2], Hiroyuki K. M. Tanaka[1,3], László Tercsi[2], Soshi Tsuno[4], Dezső Varga[1,2]

1 International Virtual Muography Institute, Global
2 HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
3 Earthquake Research Institute, The University of Tokyo, Tokyo, Japan
4 National Institute of Technology, Kagoshima College, Kagoshima, Japan

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Outline

I. Introduction

II. Research Infrastructures and Instrumentation

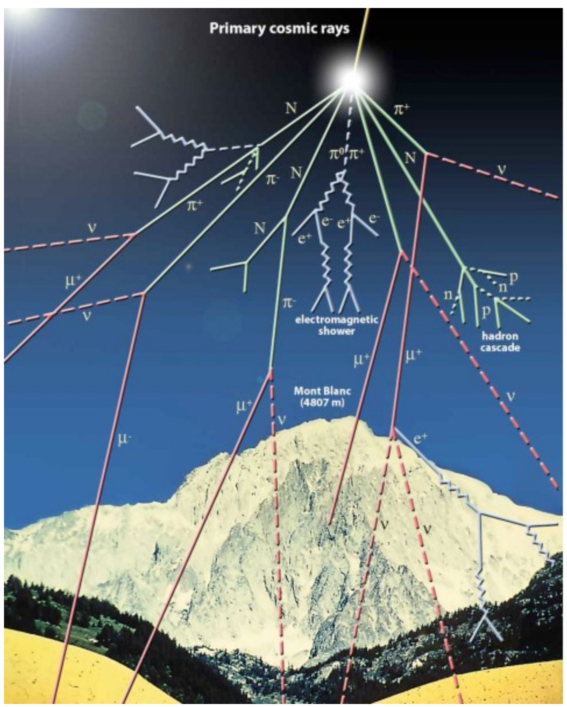
III. Muography of Sakurajima Volcano

IV. Monitoring of underground position with Muometric Positioning (muPS)

V. Summary

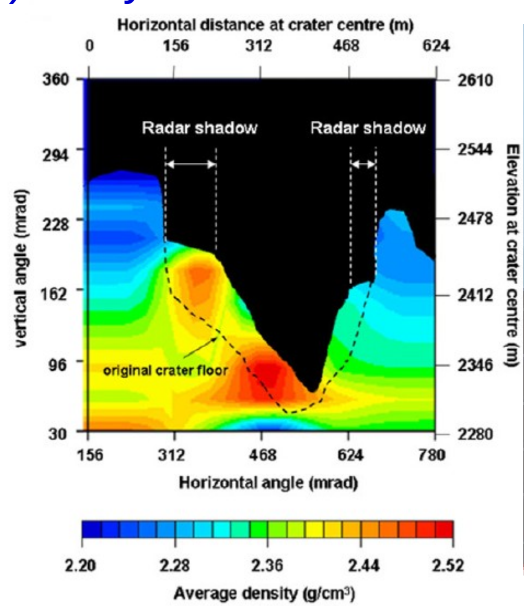
I. Introduction: Cosmic-ray Muon Imaging

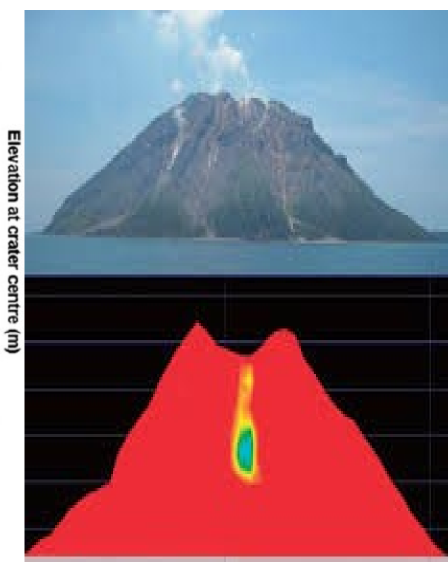
- **Cosmic-ray muons** continuously produced in the atmosphere and observed everywhere on Earth
- Muons are **highly penetrative particles** which reach down even a few km into Earth's subsurface.
- **Muography**: ”X-raying” of large structures (mountains, volcanoes, pyramids, nuclear reactors, etc.) via tracking of cosmic-ray muons → **non-destructive, passive, remote imaging technique**
- Methodology of muography has been 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

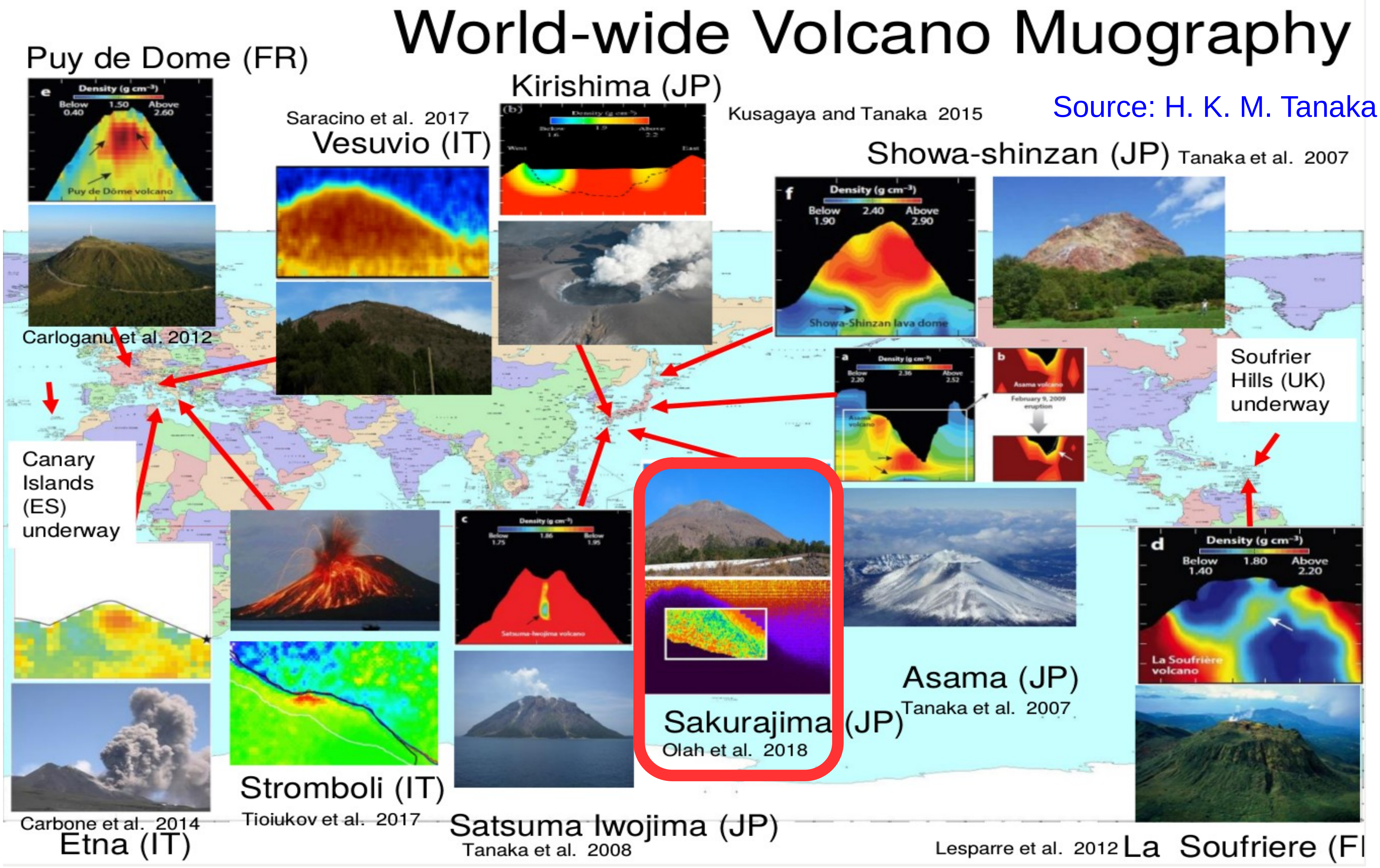


First medical X-ray image by F. C. Röntgen (1895)

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





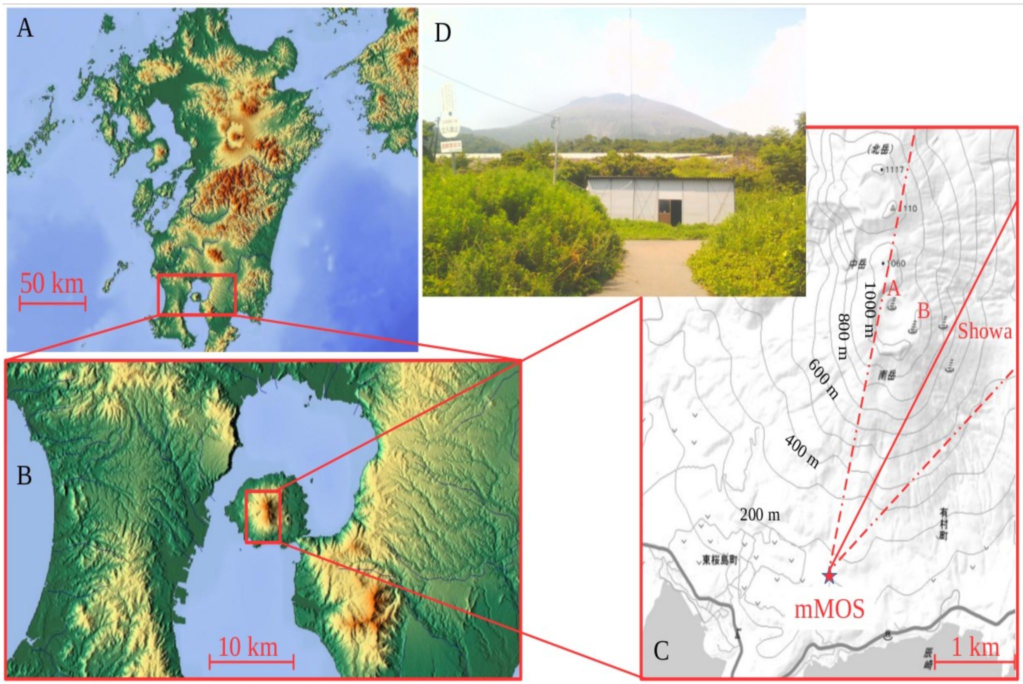


Contributions of Muography to Volcanology:
(1) Studying formation and stability of lava domes (Showa-Shinzan, La Soufrière de Guadeloupe),
(2) Exploring conduit structure for eruption modelling (Stromboli, Etna),
(3) Monitoring magma evolution and movement (Asama, Sakurajima, Vesuvius).

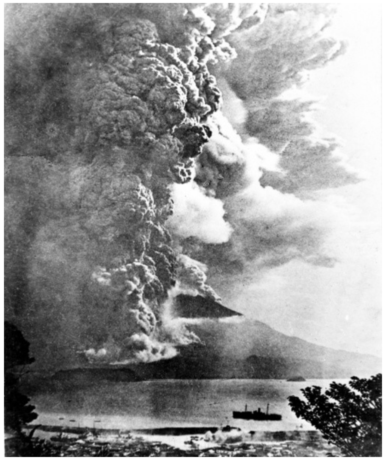
II. Research Infrastructures and Instrumentation

Sakurajima Muography Observatory

- **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** (the connected Vents A and B, as well as Showa crater) erupted consecutively in the recent years
  → **A few hundreds of (explosive) short-term eruptions per year**
- Short-term eruptions eject aerosols and gas with a bulk volume of below 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 study active volcanism**



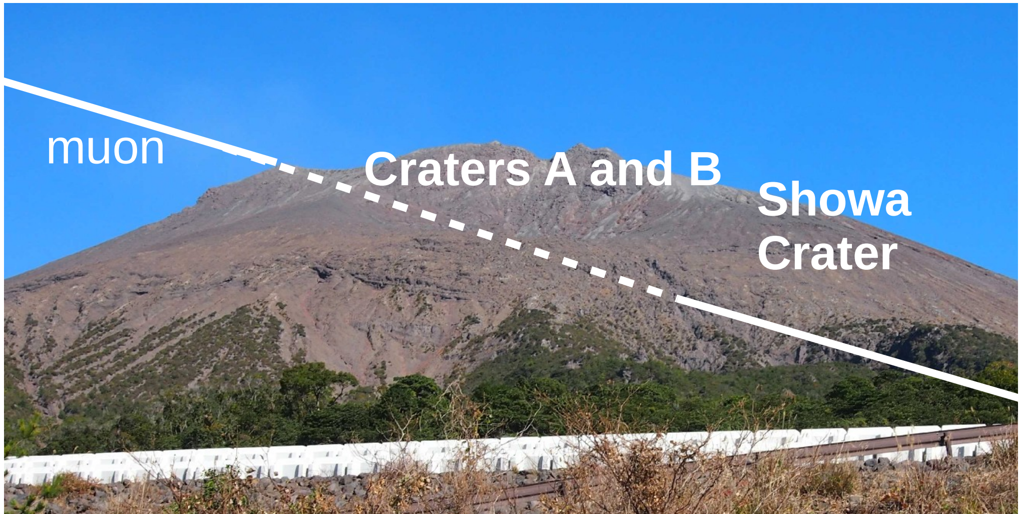
Source: https://doi.org/10.1038/s41598-018-21423-9

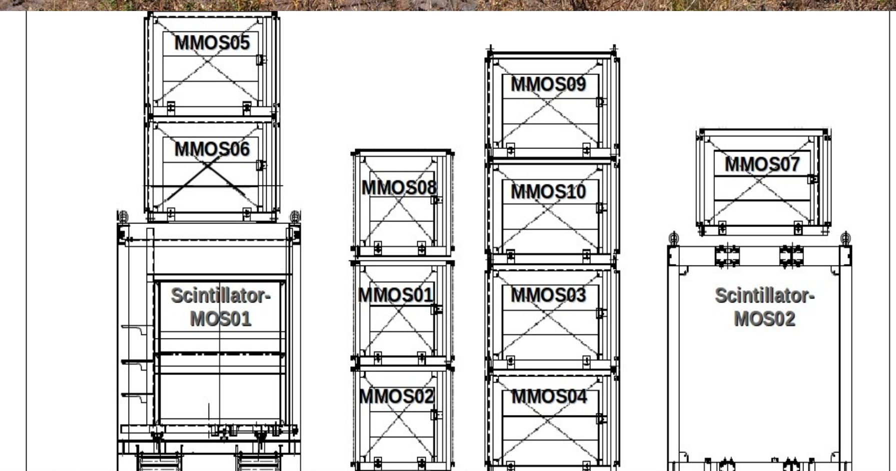


Source: Wikipedia

Source: Kimon Berlin, CC BY-SA 2.0

Muographic Observation Instrument (MOI)



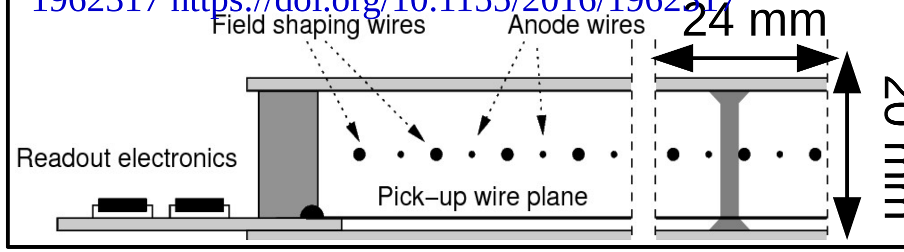


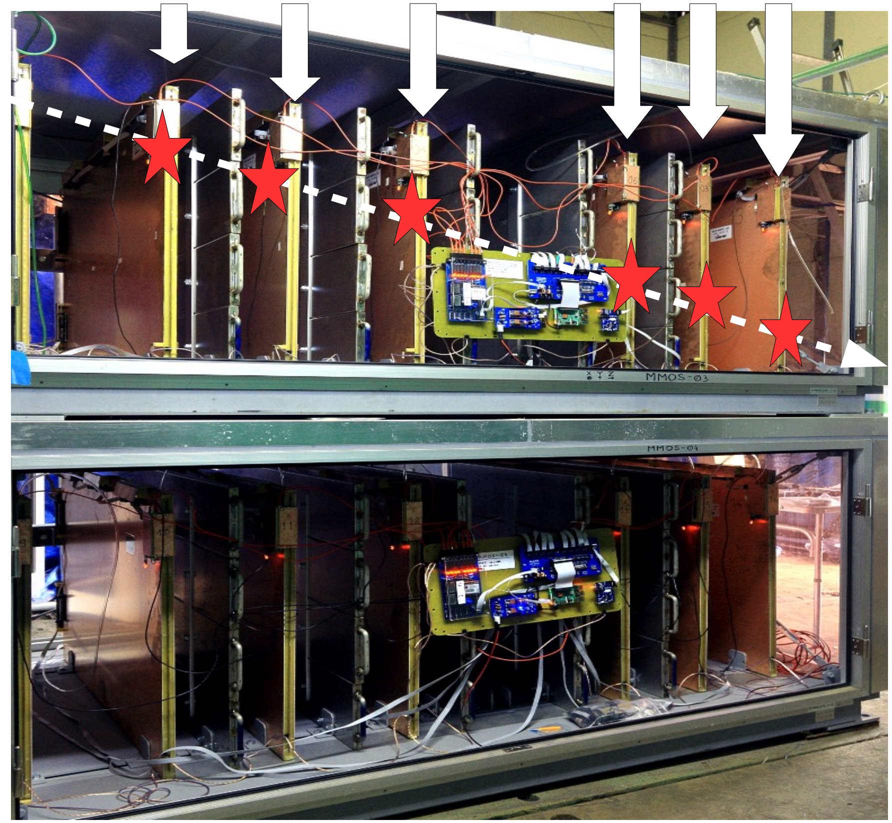
- Custom-designed electronics
- Micro-computer controlled → real-time DAQ & analysis
- Power consumption: ~ 6 W per MMOS

- **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

D. Varga et al. Advances in High Energy Physics, 2016, 1962317 https://doi.org/10.1155/2016/1962317

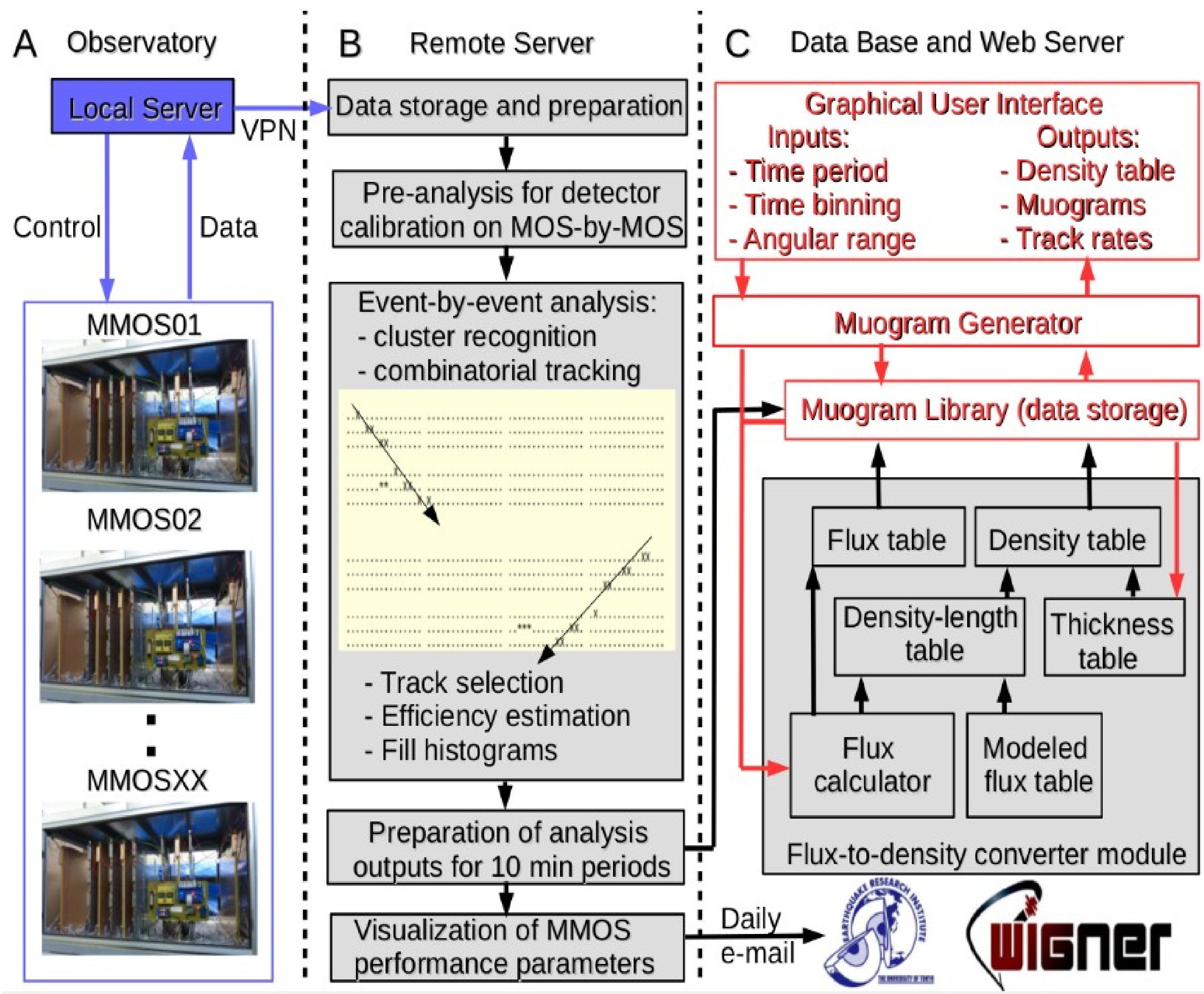


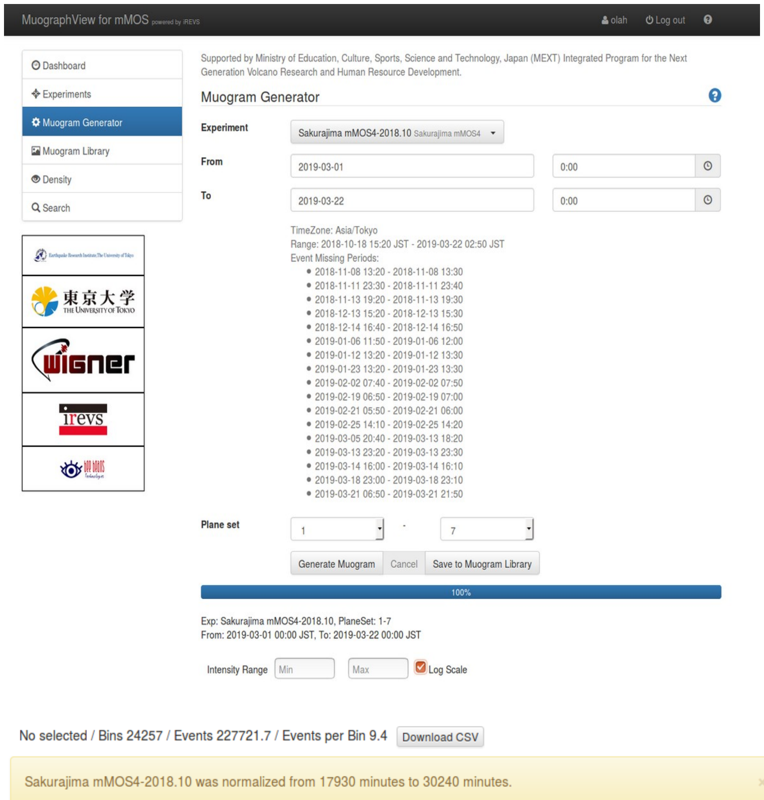


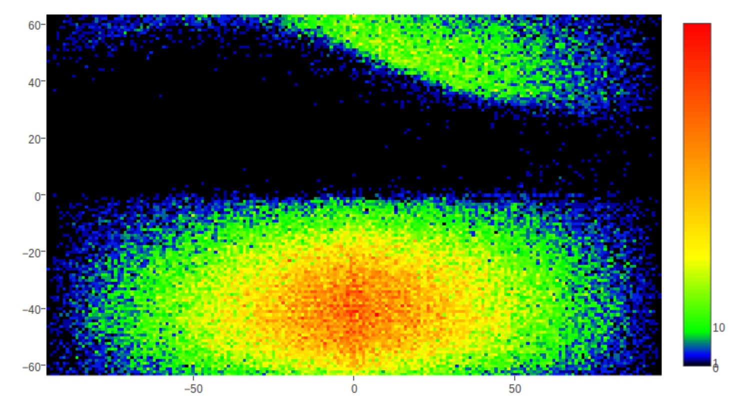
L. Oláh et al. Scientific Reports, 8, 3207, 2018, https://doi.org/10.1038/s41598-018-21423-9

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

Data Processing







https://mmos.muographers.org

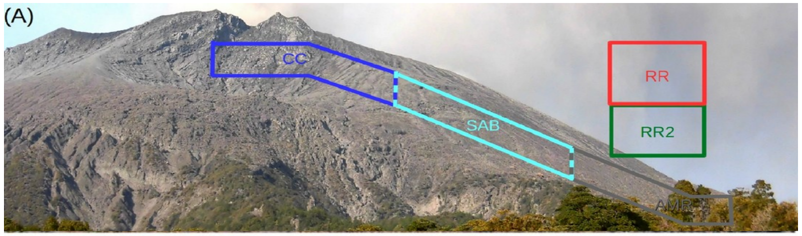
Oláh INeVRH WS 2024

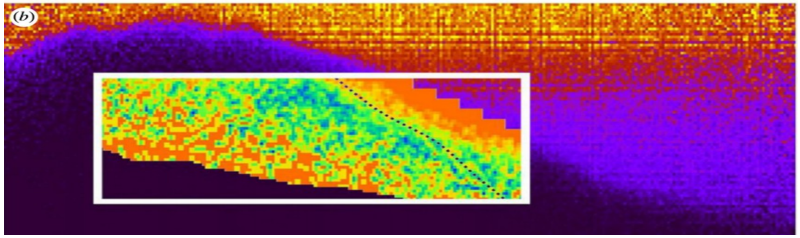
III. Muography of Sakurajima Volcano

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

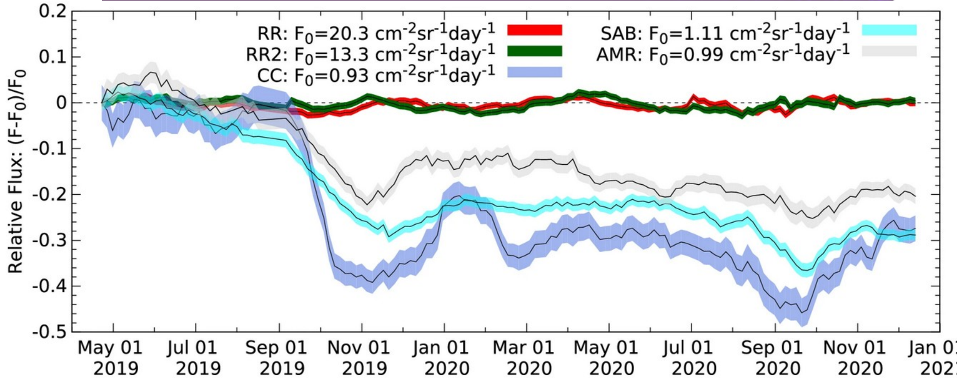
  L. Oláh et al. Scientific Reports, 8, 3207, 2018 https://doi.org/10.1038/s41598-018-21423-9





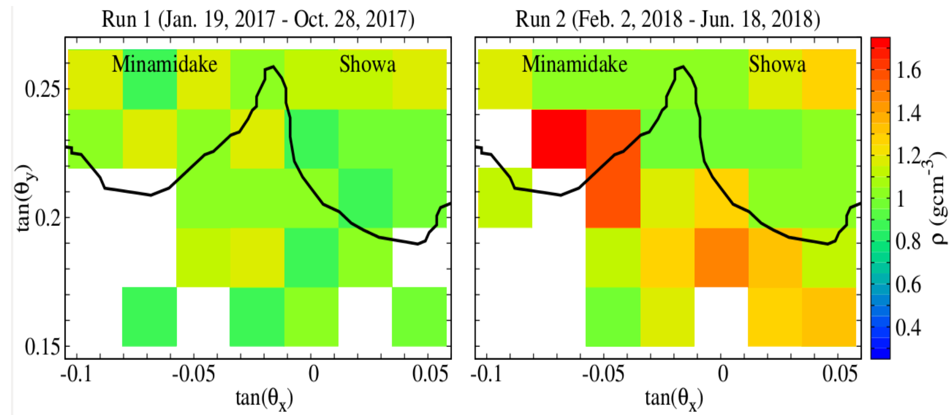
- Monitoring changes in the amount of materials on the volcanic edifice due to volcanic ejecta deposition, erosion and mudflows (lahars)

  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



Link between ground deformation and eruptions

- **Active volcanism** is driven by the subsurface evolution and movement of magmatic materials, which **may induce seismicity, ground deformation, gas emission, and fumarolic activity**

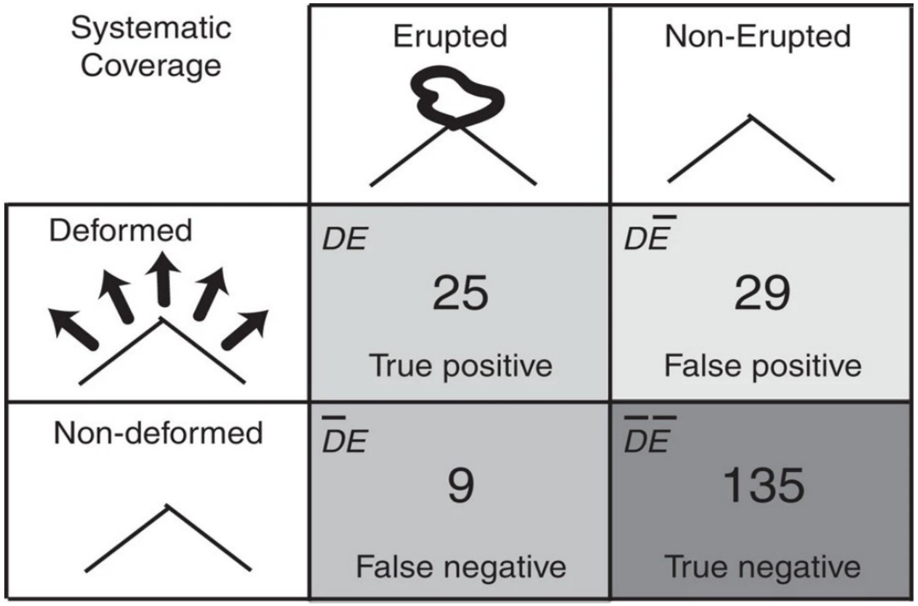
- Monitoring of the signals induced by these phenomena is indirect and interpretation of the origin of the signals is challenging because a wide variety of factors influence the behaviour of magma and host rock in the run-up towards eruption

- 198 volcanoes with a full 18-year observation history showed that **46 % of deformed volcanoes erupted**

- **Understanding the causal physical mechanism by which ground deformation and volcanic activity are linked is required for robust forecasting**

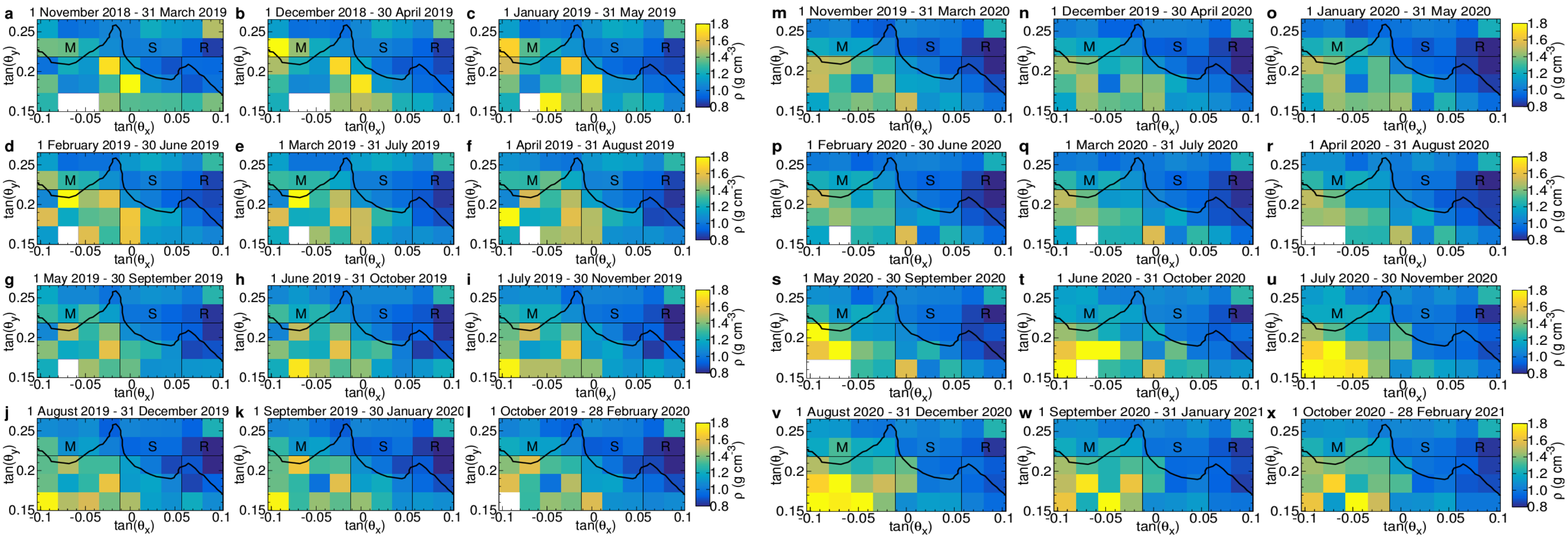
- **Aim: Revealing the causal physical mechanism of ground deformations (changing in the state of magma) via density monitoring with muography**

J. Biggs et al. Global link between deformation and volcanic eruption quantified by satellite imagery. Nat Commun 5, 3471 (2014).https://doi.org/10.1038/ncomms4471

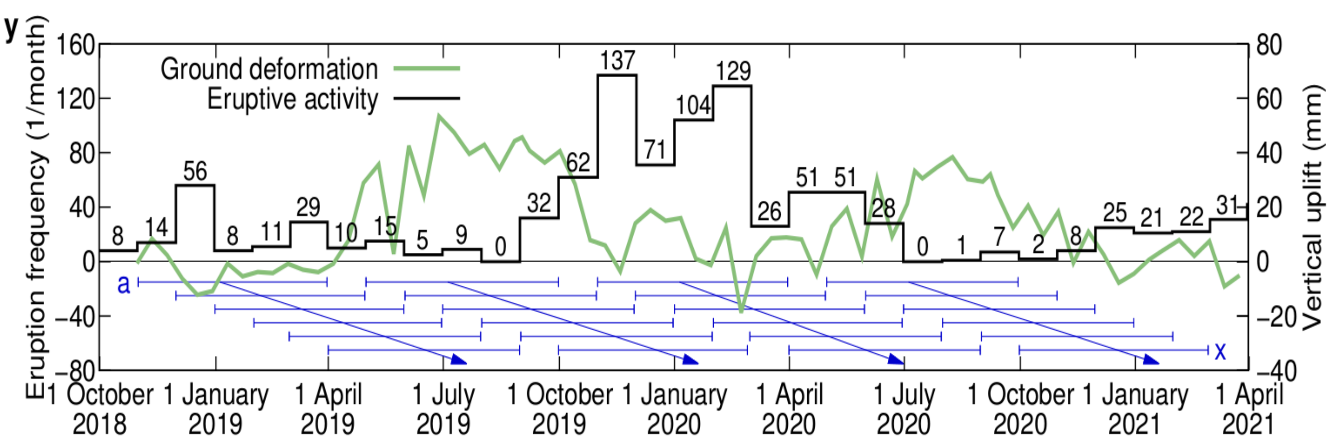


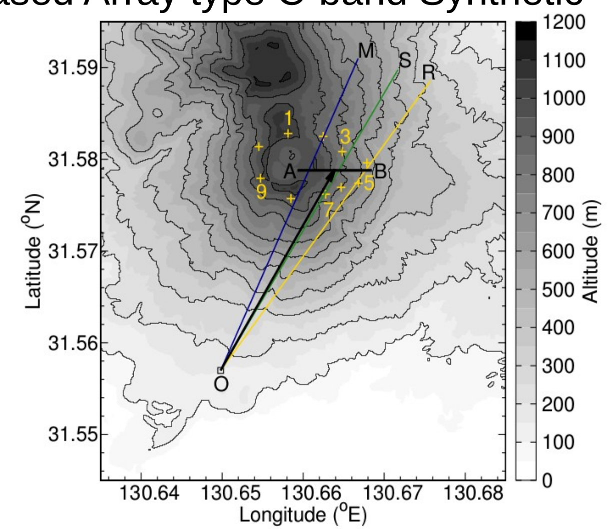
Muography and InSAR Observations of Sakurajima

Muographic images were captured for the crater region with 9 × 5 angular bins **for time sequences of 5 months between November 2018 and March 2021.**



Vertical displacement around the active crater of Sakurajima was determined relative to the ground level measured on 31 October 2018 at ten locations (yellow-coloured crosses) by NEC using the Phased Array type C-band Synthetic Aperture Radar images acquired by Sentinel-1 **with a periodic time of 12 days.**

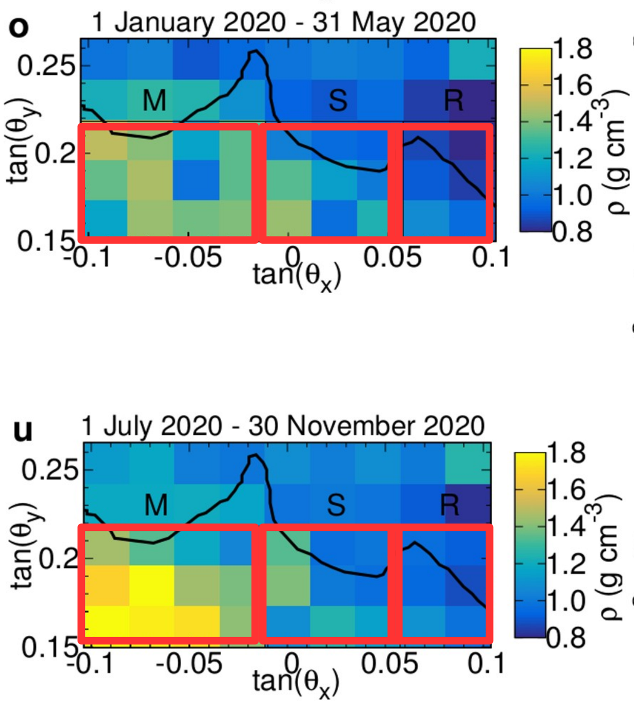




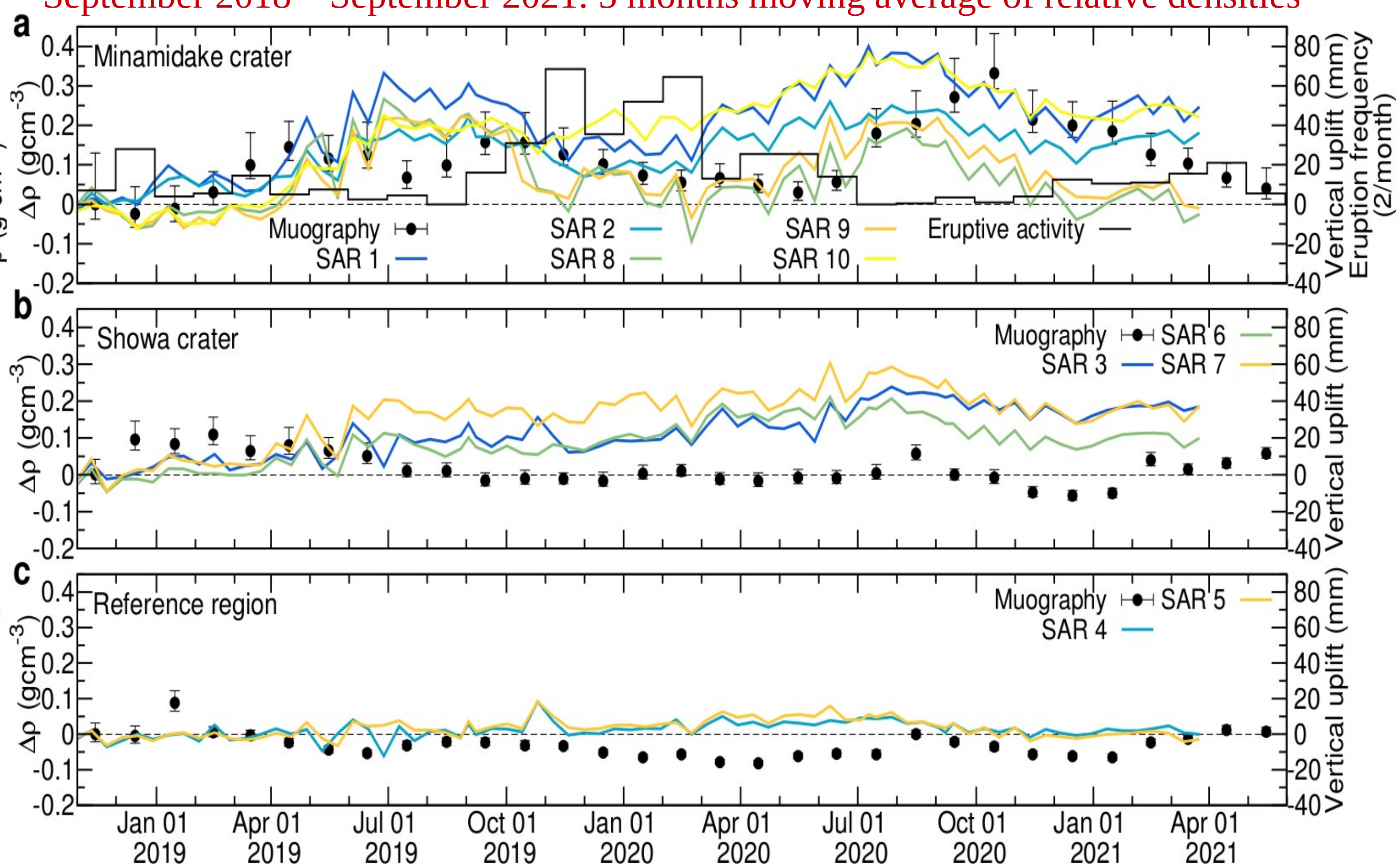
Muography explains link between eruption frequency and ground deformation

- Mass density increased during inflation, when eruption frequency was low, and decreased during deflation, when eruption frequency was high.
- Periods of low eruption frequency are associated with the formation of a dense plug in the conduit, which we infer caused inflation of the edifice by trapping pressurized magmatic gas.
- **Muography reveals the in-conduit physical mechanism for the observed correlation.**

Minamidake Showa Reference



September 2018 – September 2021: 5 months moving average of relative densities



L. Oláh, et al. (2023) Geophys. Res. Lett. 50, e2022GL101170 https://doi.org/10.1029/2022GL101170

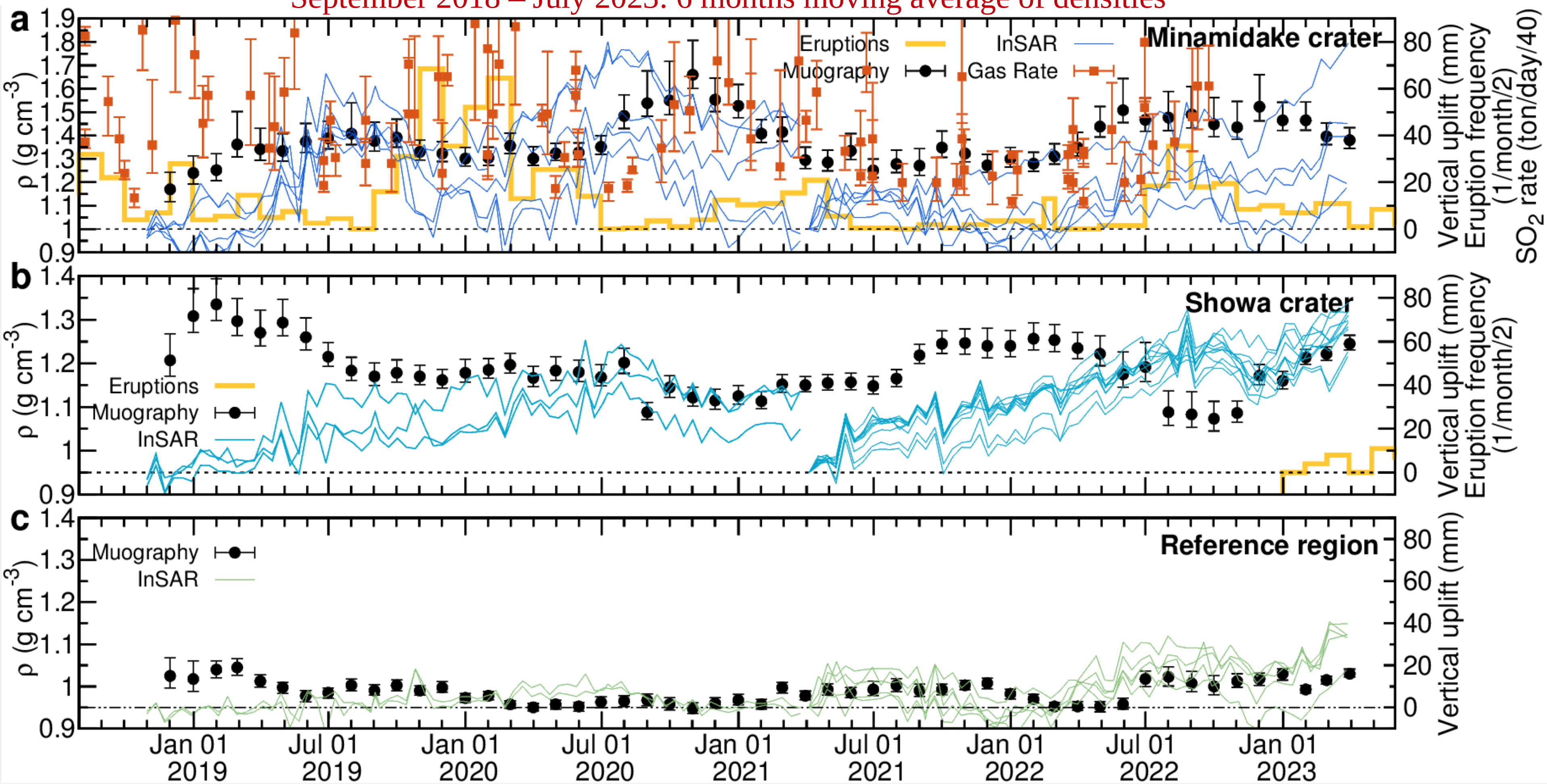
Plug Formation and Magma Drain-back Process

- **Minamidake crater:** The increasing trend in density is interpreted as plug formation due to magma rising. The decreasing trend is interpreted as plug reduction due to recurrent eruptions.

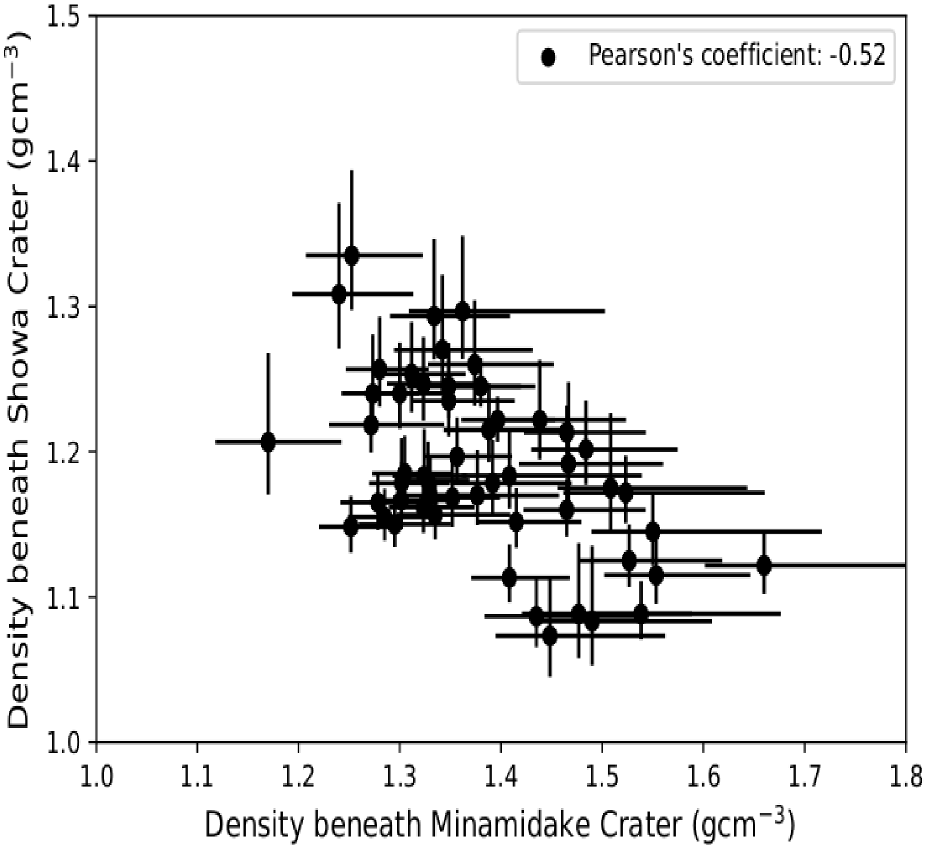
- **Showa crater:** eruptions did not follow the density increase observed beneath Showa crater in January 2019 and in August 2021; however, later the mass density decreased. It was interpreted that the uprising magma generated the plug underneath Showa crater. However, the gas pressure mightn't be enough to trigger eruptions and non-solidified part of the plug drained-back

- **The InSAR and sulfur dioxide emission rate data** support our current picture.

September 2018 – July 2023: 6 months moving average of densities



Branched Conduit Structure Inferred From Muography



- An anti-correlation was found between the densities beneath Minamidake and Showa craters: The Pearson's coefficient was quantified to -0.52 for these mass density values.
- Infrasonic monitoring data showed a similar anti-correlation between the regions beneath the adjacent craters of Mount Etna. Marchetti et al (2009) observed the switching of infrasonic source locations (that correlated with gas pressure) and change of activity between the and Bocca Nouva and the South East Crater (SEC). A branched conduit structure was inferred.
- Inverse correlation between mass densities observed for the entire period, suggesting that magma degassing occurs either in Minamidake crater and in Showa crater, acting as a similar preferential pathway to the one observed in Etna

→ **a branched connection between the conduits of the two active craters**

Oláh, L., Hamar, G., Ohminato, T., Tanaka, H. K. M., & Varga, D. (2024).
Branched conduit structure beneath the active craters of Sakurajima volcano inferred from muography.
Journal of Geophysical Research: Solid Earth, 129, e2023JB028514.
https://doi.org/10.1029/2023JB028514

Towards Short-term Eruption Forecasting via Machine Learning of Muon Images

- Machine learning of consecutive daily muon images for predicting eruption on the next day
  Y. Nomura et al. Scientific reports, 10, 5272, 2020, https://doi.org/10.1038/s41598-020-62342-y

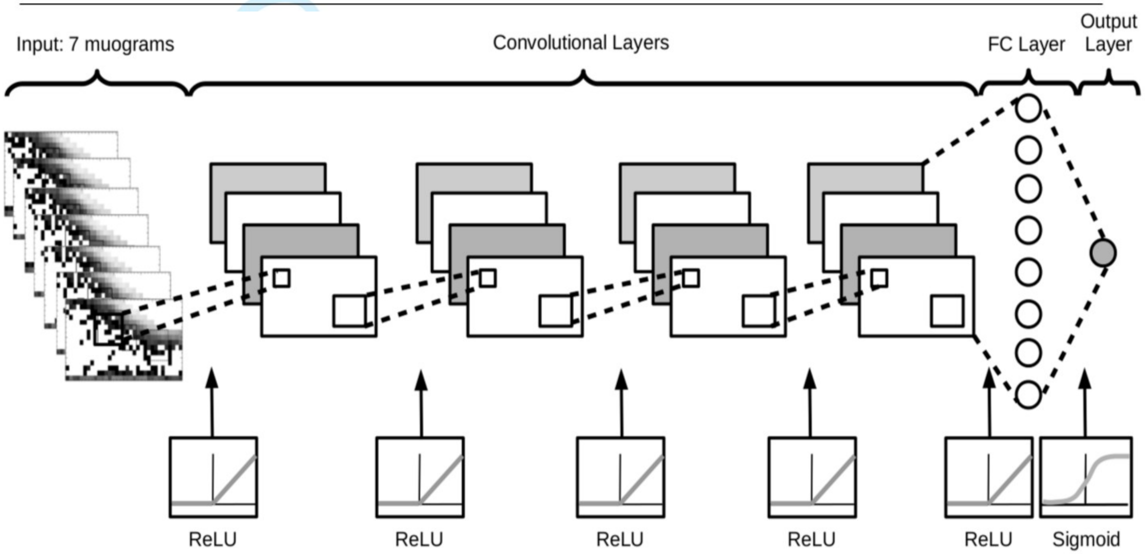
- Convolutional neural networks can learn the hidden patterns
  (originated from mass changes occurred beneath the crater) in the muon images

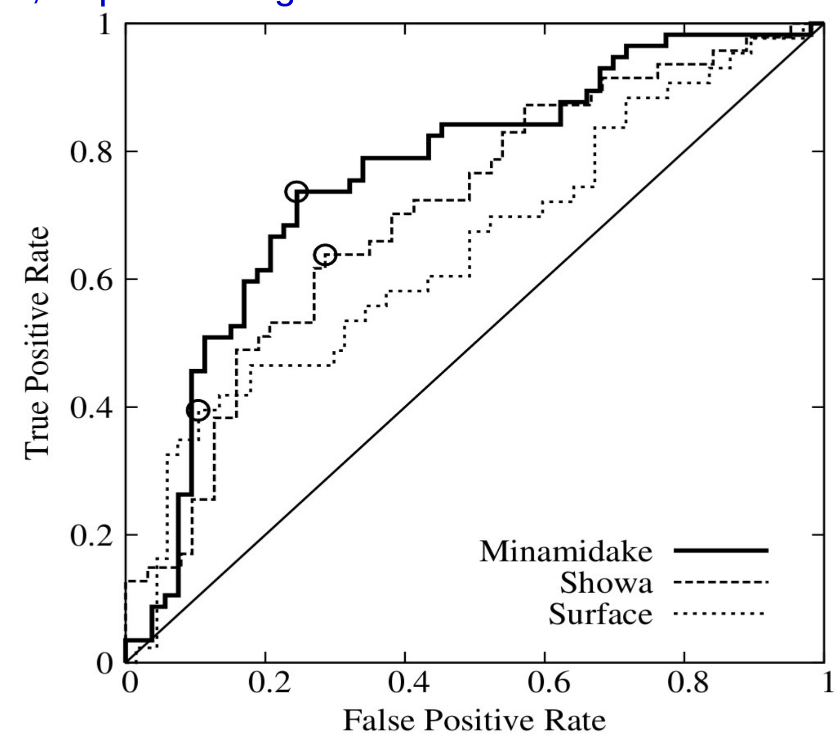
- Receiver Operating Characteristic (ROC) analysis to characterize forecasting performance

- Results of ROC analysis showed that CNN achieved a fair forecasting performance, e.g. Area Under the Curve (AUC) of 0.761, for the erupting Minamidake crater

L. Oláh & H.K.M. Tanaka: Geophys. Mon. Ser., 270, 43-54, 2022, https://doi.org/10.1002/9781119722748.ch4

	Minamidake	Showa	Surface
Area Under the Curve	0.761	0.704	0.644
Sensitivity	0.737	0.638	0.395
Specificity	0.755	0.714	0.896



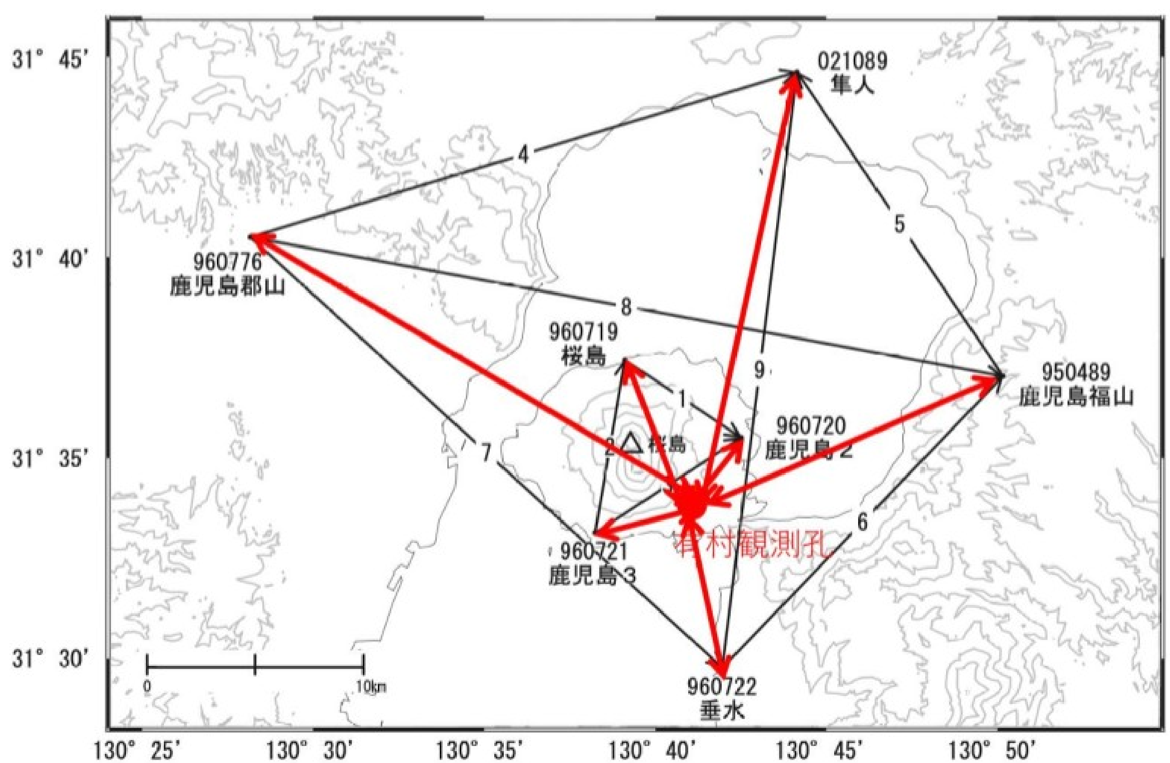


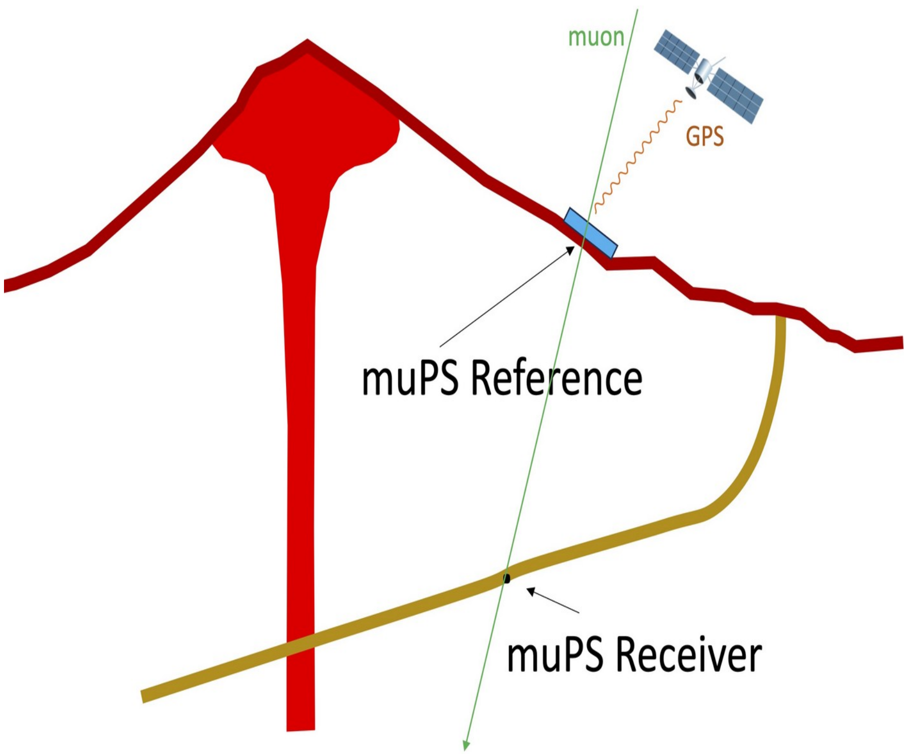
IV. Monitoring of underground position with Muometric Positioning (muPS)

Monitoring of Underground Position at Active Volcanoes with muPS

Goal: defining the underground coordinate within the national coordinate that means precise measurements of the baseline between far distant GPS station (more than 10 km away) and the muPS station at a sub cm level

桜島周辺GEONET(電子基準点等)による連続観測基線図(1)





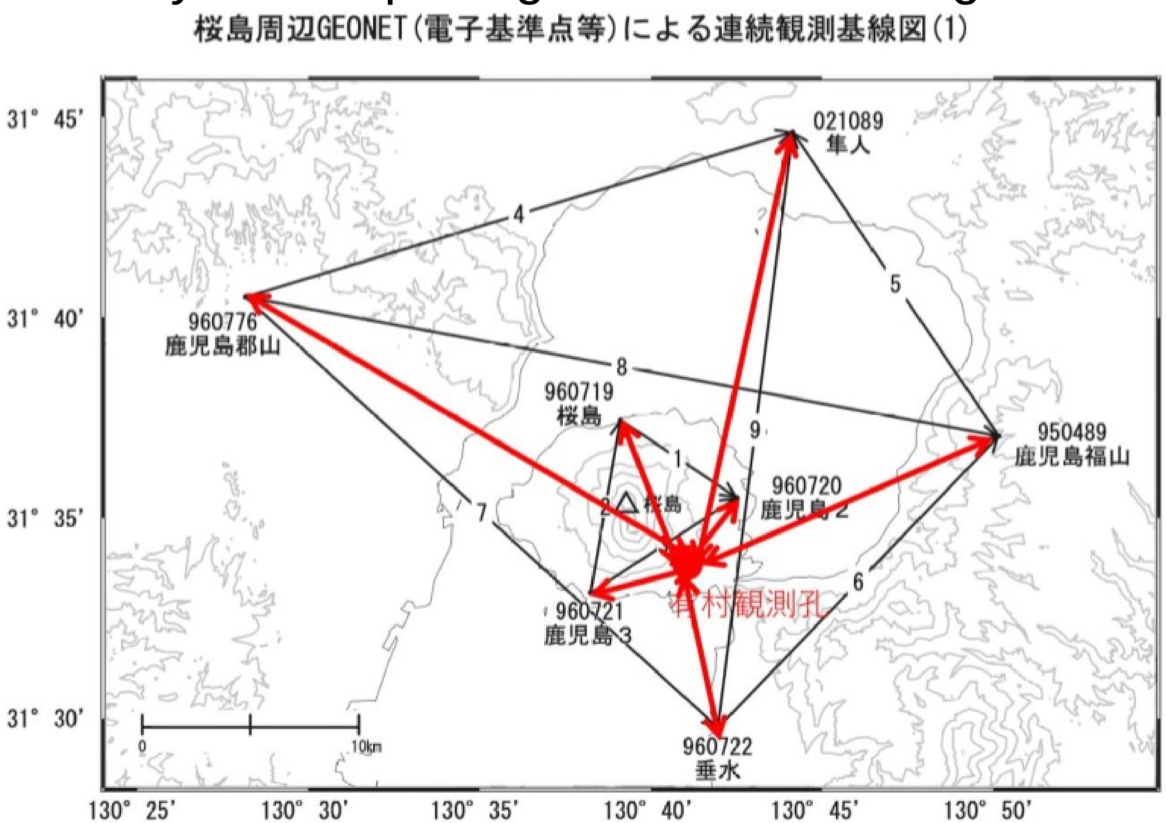
Source: https://www.jma.go.jp/jma/press/2307/12a/yochiren230712_3.pdf

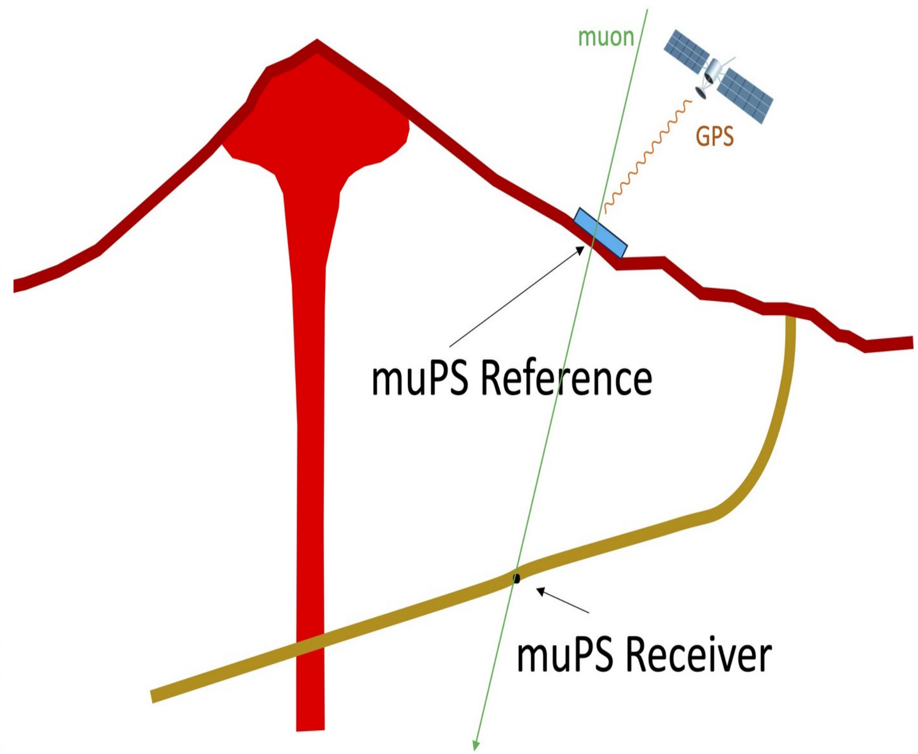
Source of figure: H.K.M. Tanaka

Monitoring of Underground Position at Active Volcanoes with muPS

Benefits of using cosmic-ray muons for positioning:

(1) Capability of monitoring,
(2) Applicability in deep bent boreholes, where triangulation is not possible,
(3) Capability of defining coordinate in global (national) coordinate system.
→ **Long-term goal:** measuring the deformation near the conduit in boreholes, similarly to Campi Flegrei and Krafla Magma Testbed

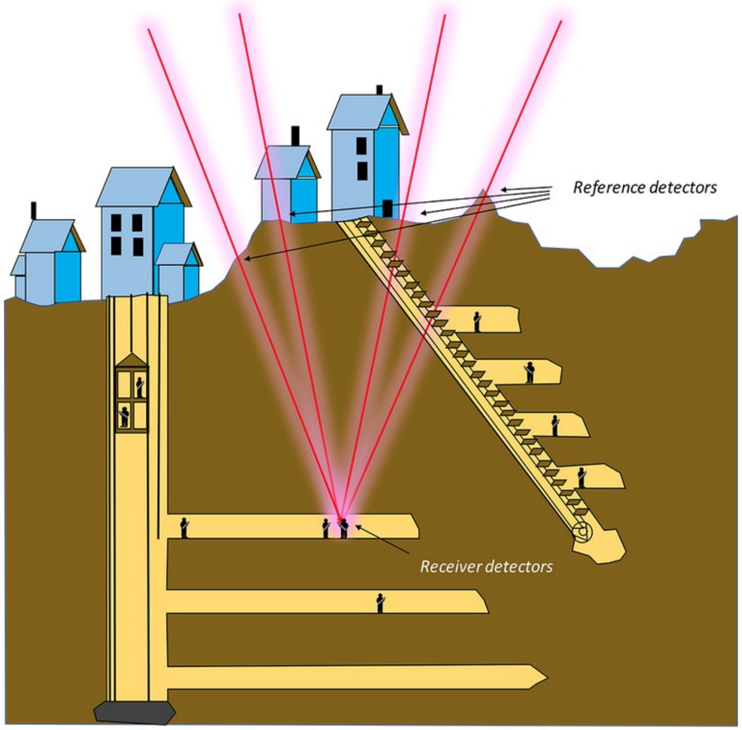




Source: https://www.jma.go.jp/jma/press/2307/12a/yochiren230712_3.pdf

Source of figure: H.K.M. Tanaka

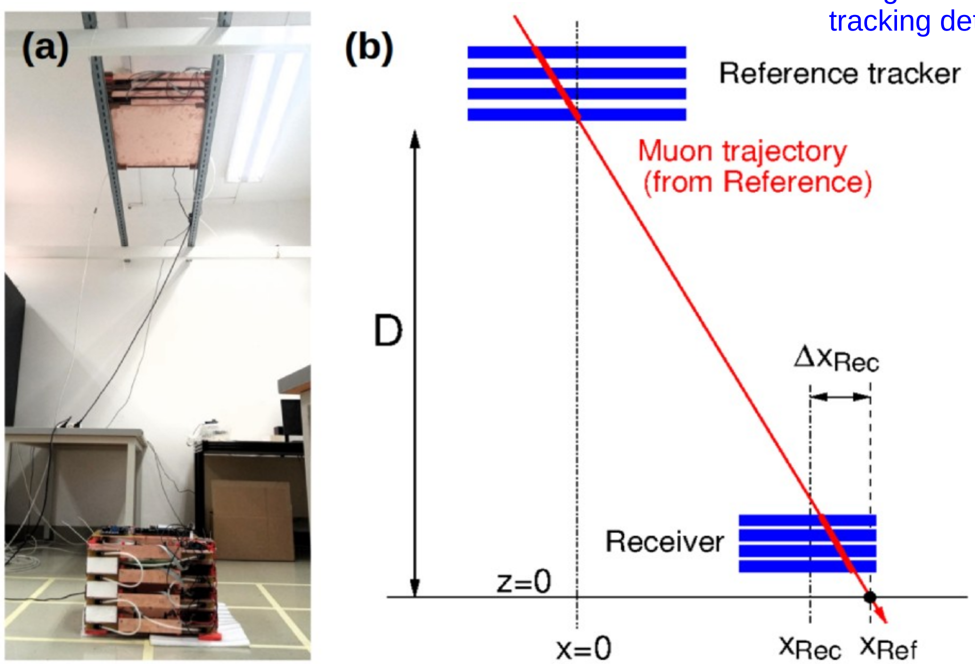
First Indoor Tests of muPS

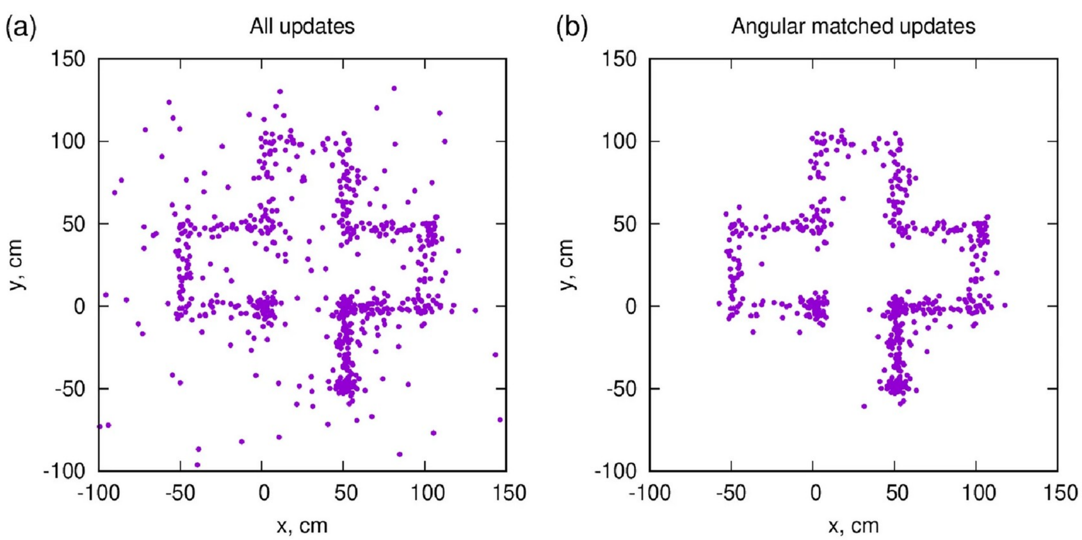


Unlike radio waves, acoustic signals, or laser beams, **muometric positioning accuracy is not influenced by obstacles in its surrounding environment**

Positioning is not required on event-by-event → statistics greatly improve accuracy

- Tanaka et al. First navigation with wireless muometric navigation system (MuWNS) in indoor and underground environments. Iscience, 26, 107000 https://doi.org/10.1016/j.isci.2023.107000
- Tanaka, H.K.M. Muometric positioning system (muPS) utilizing direction vectors of cosmic-ray muons for wireless indoor navigation at a centimeter-level accuracy. Sci Rep 13, 15272 (2023). https://doi.org/10.1038/s41598-023-41910-y
- Varga, D., Tanaka, H.K.M. Developments of a centimeter-level precise muometric wireless navigation system (MuWNS-V) and its first demonstration using directional information from tracking detectors. Sci Rep 14, 7605 (2024). https://doi.org/10.1038/s41598-024-57857-7





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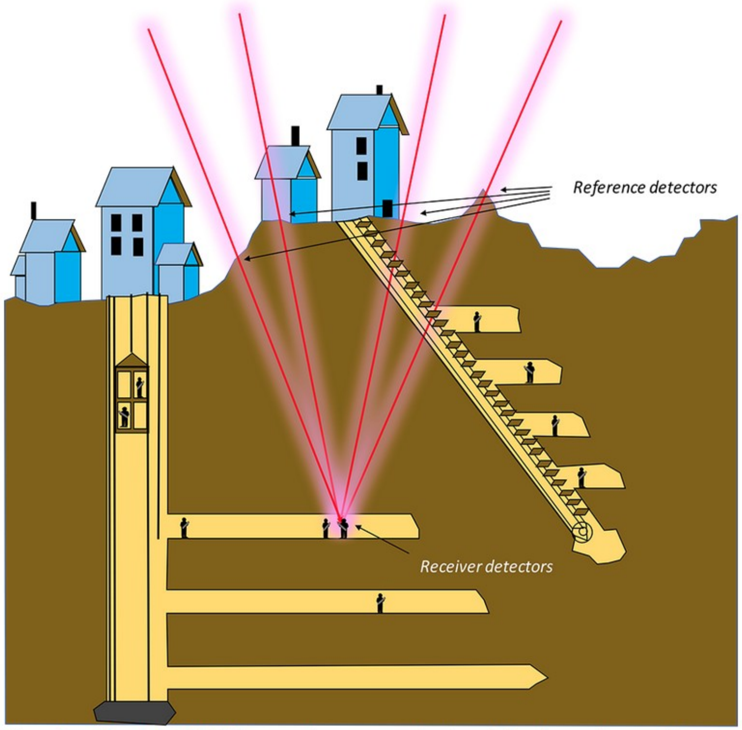

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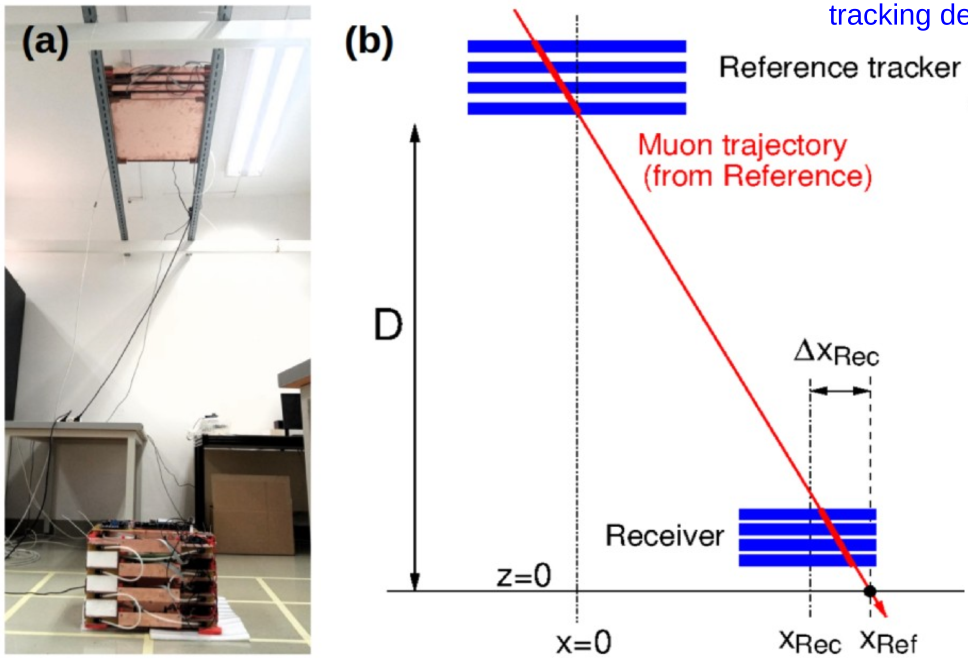
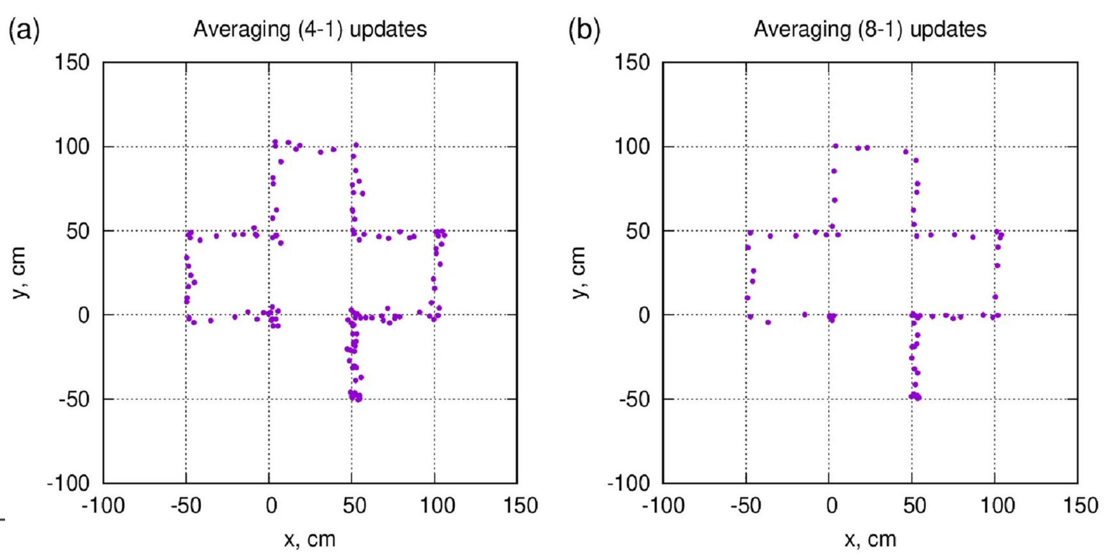
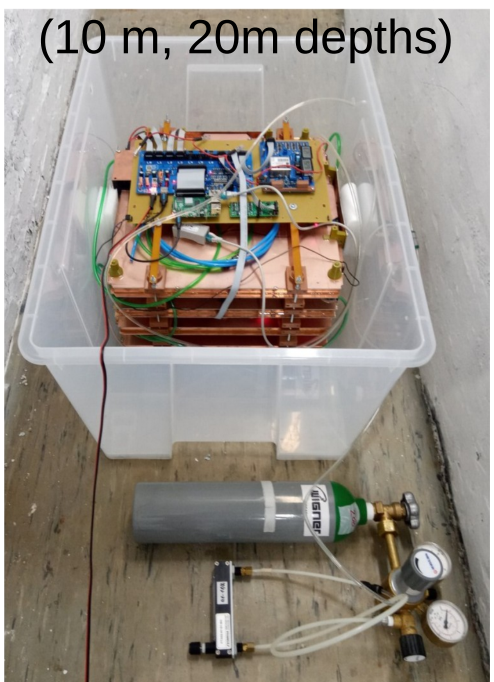




First Tests of muPS in Underground Tunnels in HUN-REN Wigner RCP, Hungary

Reference at ground level

Receiver in tunnels (10 m, 20m depths)

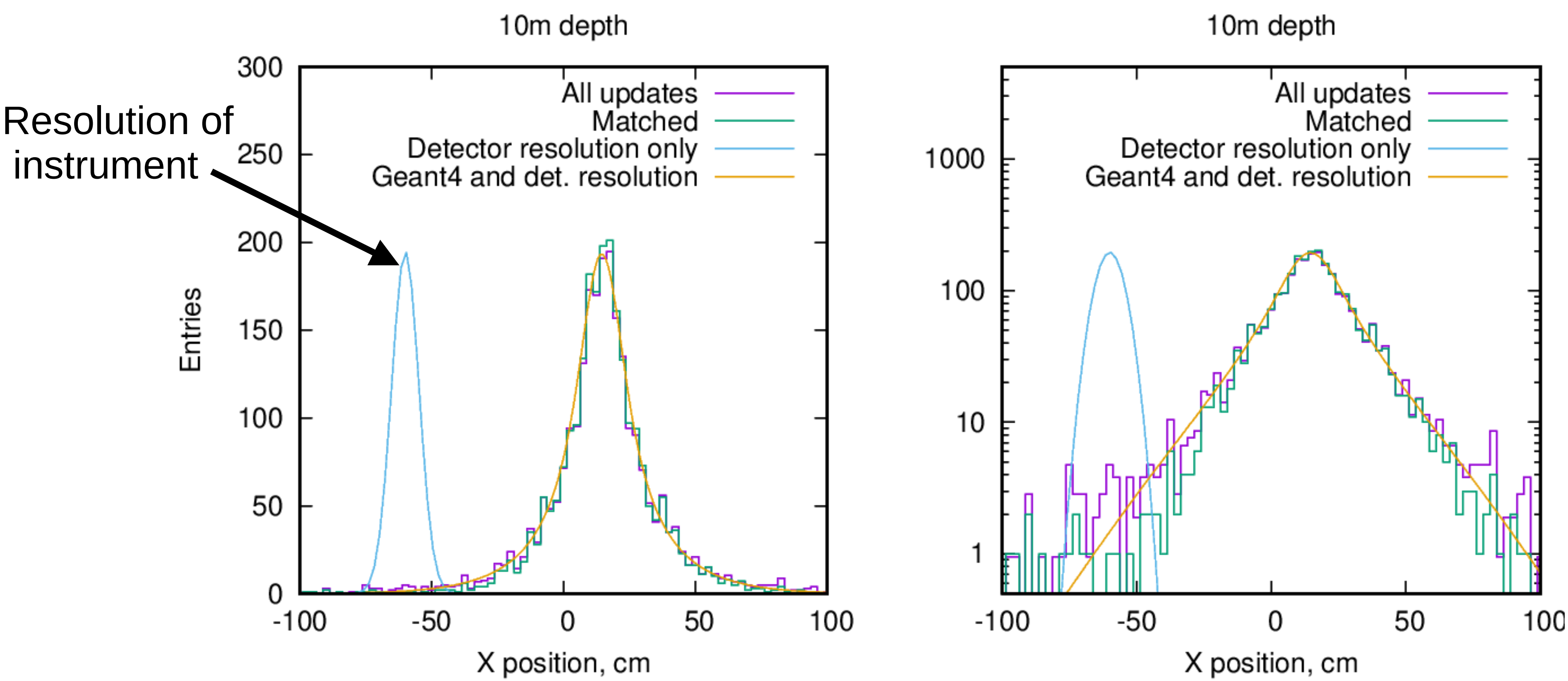


- Detectors are MWPC-s with 12mm pitch
- 2D projective geometry (field wires and perpendicular cathode wires)
- Surface Reference detector with 5mrad resolution
- Reference sensitive 760mm x 760mm (1150mm)
- Receiver sensitive 380mm x 380mm
- Update rate of Receiver detector at 10m (20m) depth: 15mHz (2mHz)
- Internal clocks:
  temperature compensated 10MHz oscillator
  IQXT-200-49, nominal precision 0.05ppm

Source of photographs: D. Varga’s talk at Muographers 2024 WS (Santa Fe)

Position Resolution of muPS at 10 m depth

- Reference angular resolution chosen to be sufficiently good, 5 mrad to measure the effects of muon scattering.
- Experimental data are consistent with Geant4 simulations: tails due to low energy muons. Furthermore, little background is available.
- FWHM is approx. 30 cm.

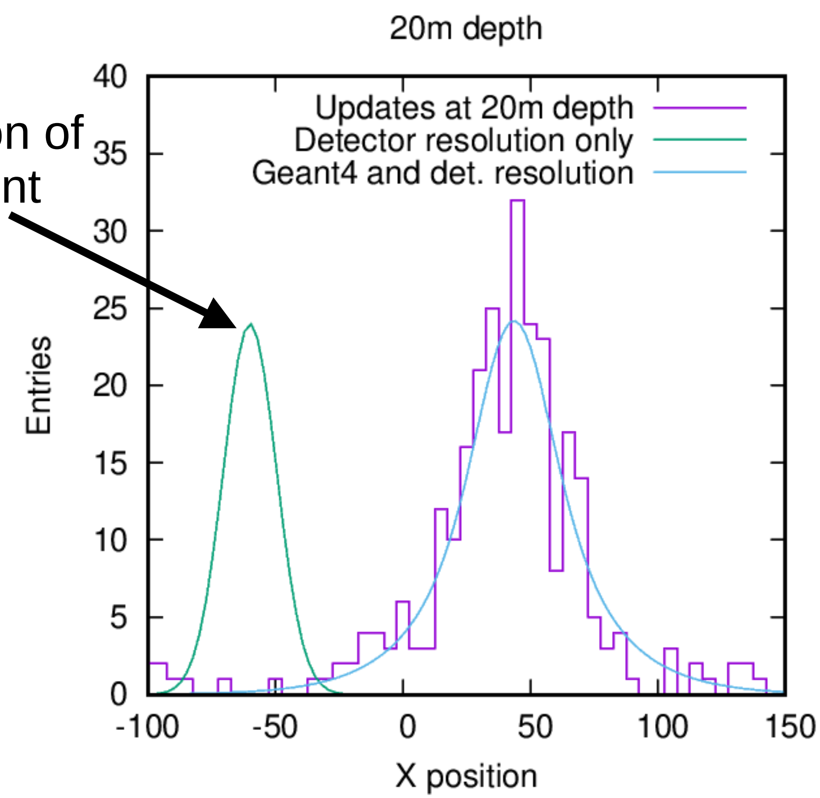


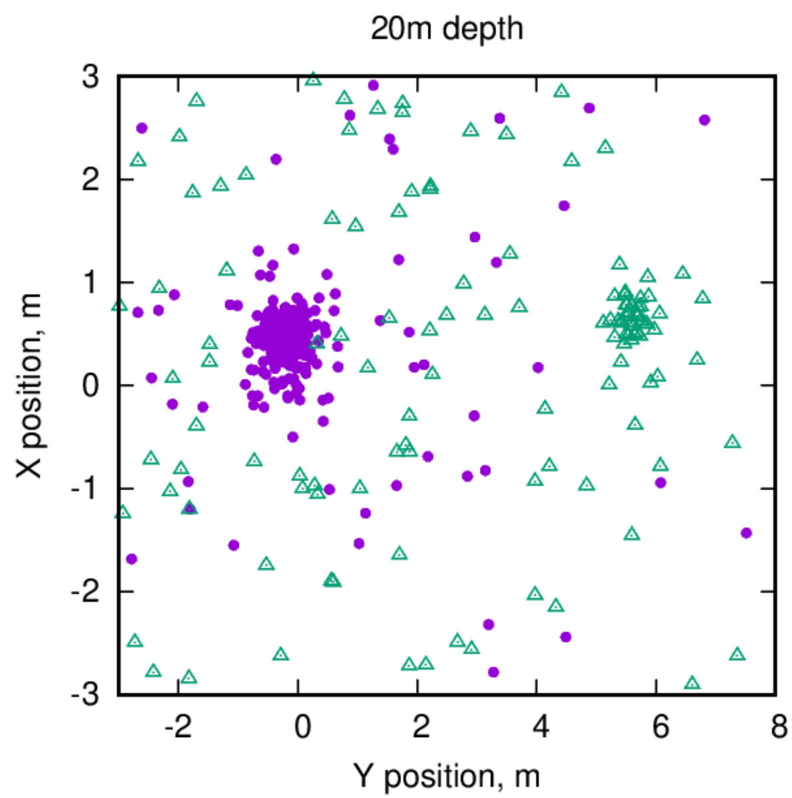
Source of figures: D. Varga’s talk at Muographers 2024 WS (Santa Fe)

Position Resolution of muPS at 20 m depth

- Update rate pretty low (1/D² dependence, 16m overburden)
- FWHM position resolution 47cm that is including muon multiple scattering
- Future measurements with multiple larger detectors → 3D positioning
- Improvement of positional resultion is planned:
  (1) larger distance between tracking layers,
  (2) smaller detector pitches (MWPCs and scintillators are under optimization),
  (3) application of energy cut.

Resolution of instrument





Source of figures: D. Varga's talk at Muographers 2024 WS (Santa Fe)

V. Summary

Contributions of cosmic-ray muon tracking to volcano monitoring at Sakurajima:

(1) Monitoring of hydrogeomorphic changes by ejecta deposition, erosion and lahars,
Scientific Reports 11, 17729, 2021, https://doi.org/10.1038/s41598-021-96947-8

(2) Monitoring of magma evolution (plug formation, drain-back process) and movements,
Geophys. Res. Lett. 46, 10417, 2019, https://doi.org/10.1029/2019GL084784

(3) Explaining the link between ground deformation and eruption frequency,
Geophys. Res. Lett. 50, e2022GL101170 https://doi.org/10.1029/2022GL101170

(4) Inferring to conduit structure from magma dynamics among two craters,
Journal of Geophysical Research: Solid Earth, 129, e2023JB028514. https://doi.org/10.1029/2023JB028514

(5) Monitoring of underground position with muometric positioning has been proposed: optimization is ongoing via underground measurements.

Thank you for your attention!

Supporters:

- **Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT) Integrated Program for the Next Generation Volcano Research**
  https://kazan-pj.bosai.go.jp/next-generation-volcano-pj-2019-jun
- **Joint Usage Research Project (JURP) from the ERI, University of Tokyo**
  https://www.eri.u-tokyo.ac.jp/en/joint-usage-top/
- **”INTENSE” H2020 MSCA RISE, GA No. 822185 in Horizon 2020 from European Comission** https://cordis.europa.eu/project/id/822185
- **TKP2021-NKTA-10 and othe grants for instrument development from National Research, Development and Innovation Office, Hungary**
  https://nkfih.gov.hu/english-nkfih
- **HUN-REN Welcome Home and Foreign Researcher Recruitment Programme KSZF-144/2023**

Contact information:
László Oláh olah.laszlo@wigner.hu https://wigner.hu/s/high-energy-geophysics/index_eng.html