The Integrated Program for Next Generation Volcanic Research and Human Resource Development (INeVRH) Workshop 2026, Tokyo, Japan

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

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東京大学 THE UNIVERSITY OF TOKYO

Muographix

EARTHQUAKE RESEARCH INSTITUTE THE UNIVERSITY OF TOKYO

HUN-REN Magyar Kutatási Hálózat

KAGOSHIMA | Kagoshima KOSEN

MEXT MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN

WIGNER

Outline

I. Introduction

II. Joint Muon and Ground Surface Deformation Monitoring

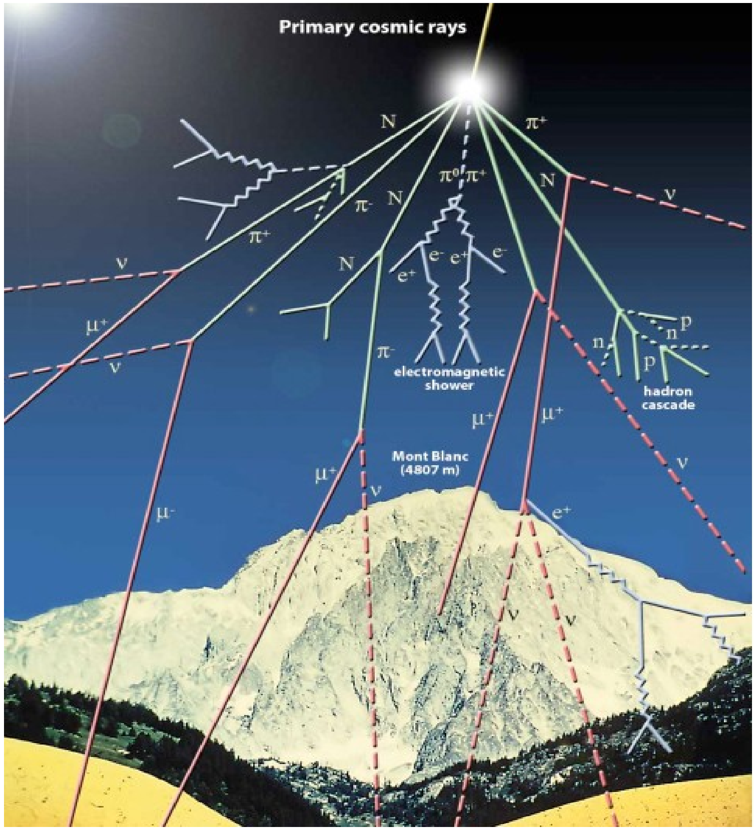
III. Toward Monitoring Underground Crustal Deformation

IV. Summary

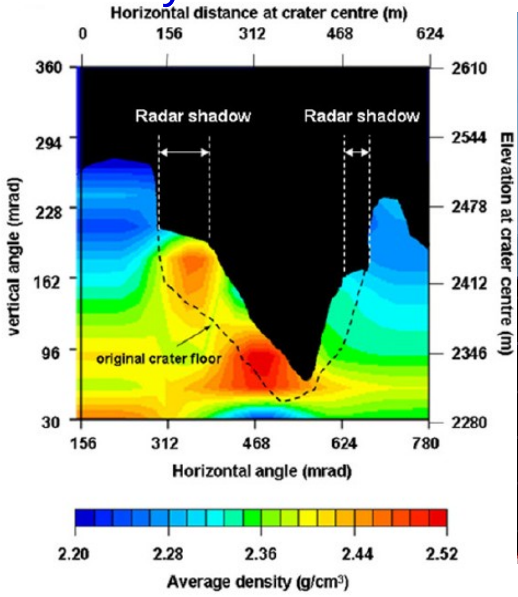
I. Introduction

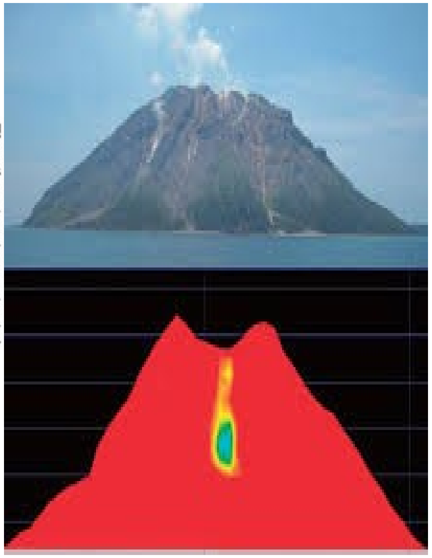
Cosmic-ray Muon Imaging

- **Cosmic-ray muons** continuously produced in the atmosphere and observed everywhere on Earth. Muons are **highly penetrative particles** penetrating across even a few km rock. The yield of penetrated muons depends on the density-length of penetrated materials.
- **Muography**: ”X-raying” of large structures via tracking of cosmic-ray muons
  → **passive, remote, high-resolutional imaging of shallow subsurface of volcanoes**
- Muographic density imaging allows (1) the monitoring of the evolution and movement of magma, (2) the monitoring of the mass of tephra deposition and erosion, (3) reconstructing of upper conduit structures, (4) localizing hydrothermally altered zones, etc.

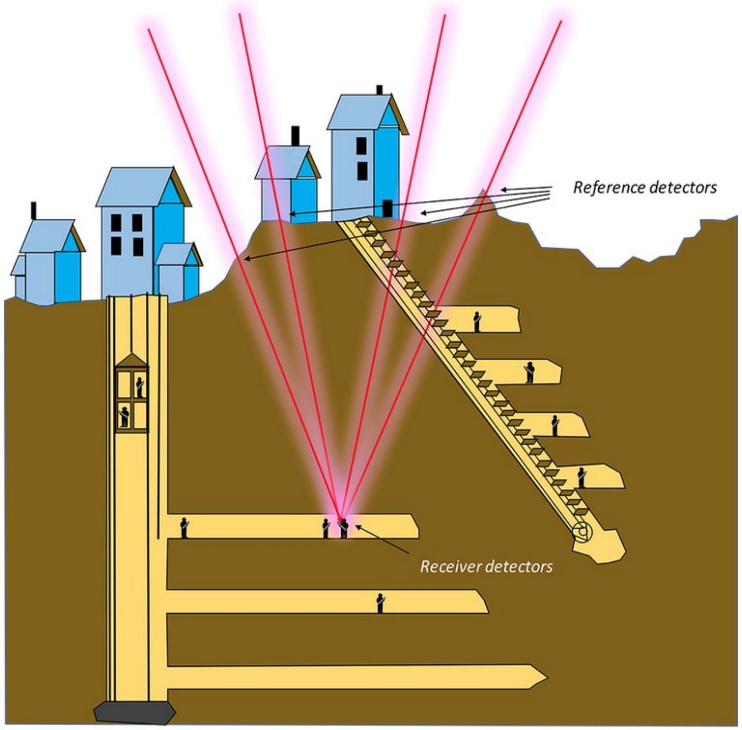


First muon images of volcanoes
by H.K.M. Tanaka et al. (mid 2000s)





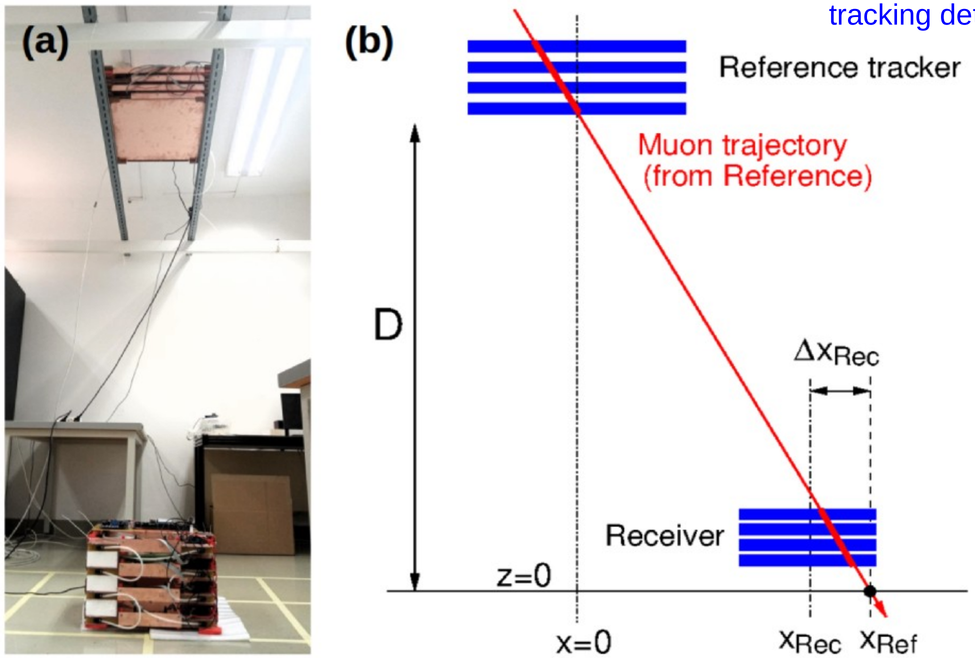
Muon Positioning (muPS)

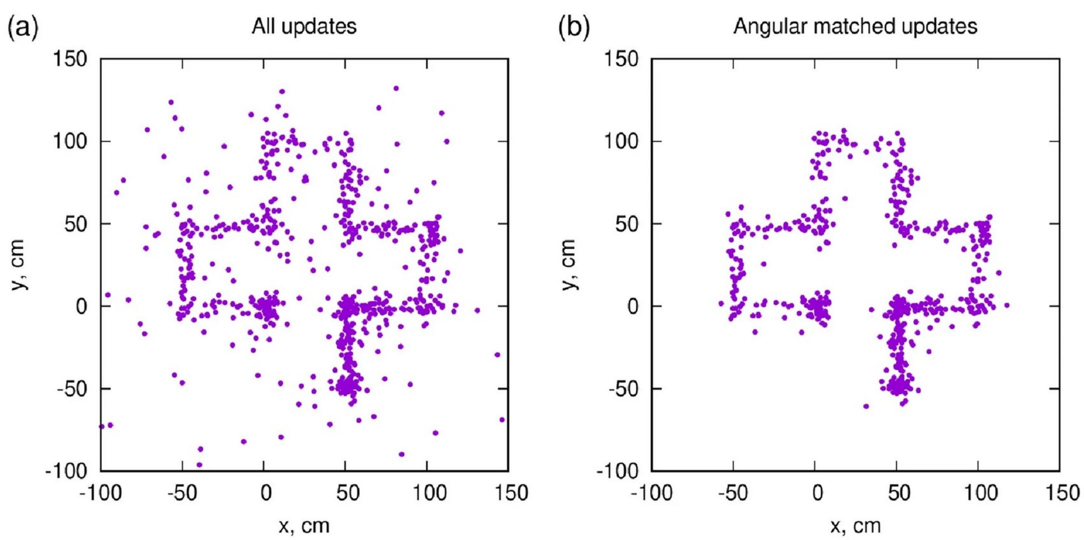


Unlike radio waves, acoustic signals, or laser beams, **muometric positioning accuracy is not influenced by obstacles in its surrounding environment**

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



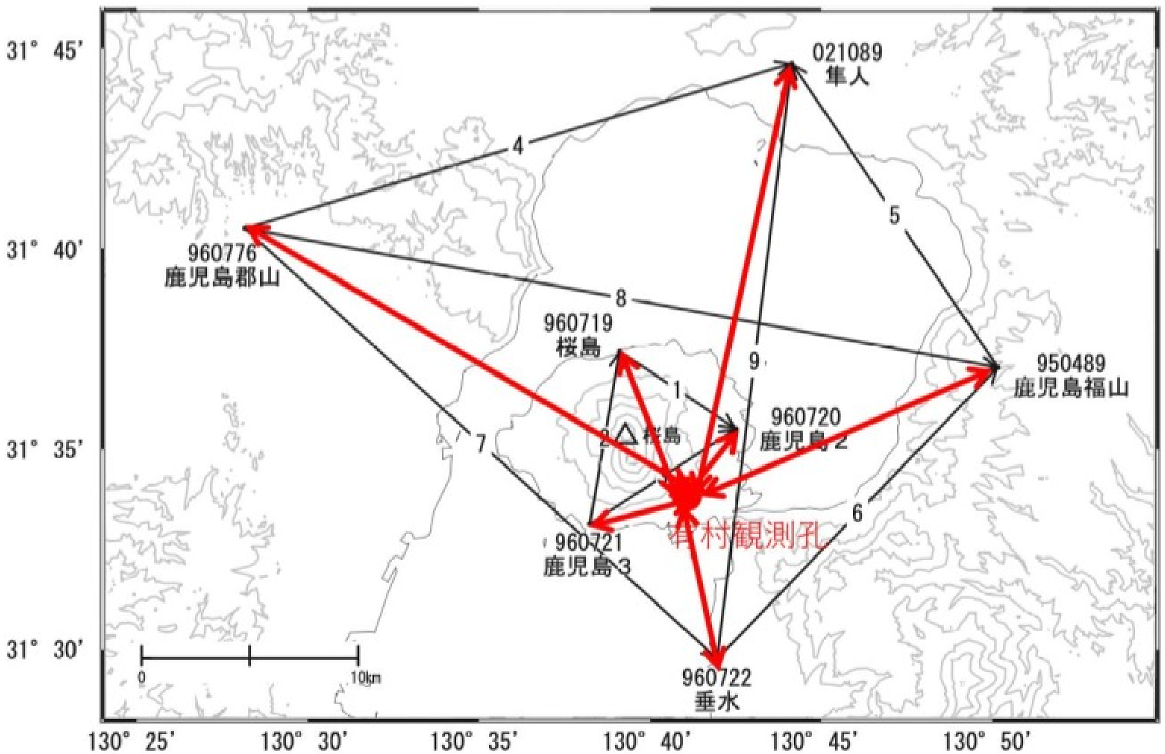


Monitoring of Underground Position at Active Volcanoes with muPS

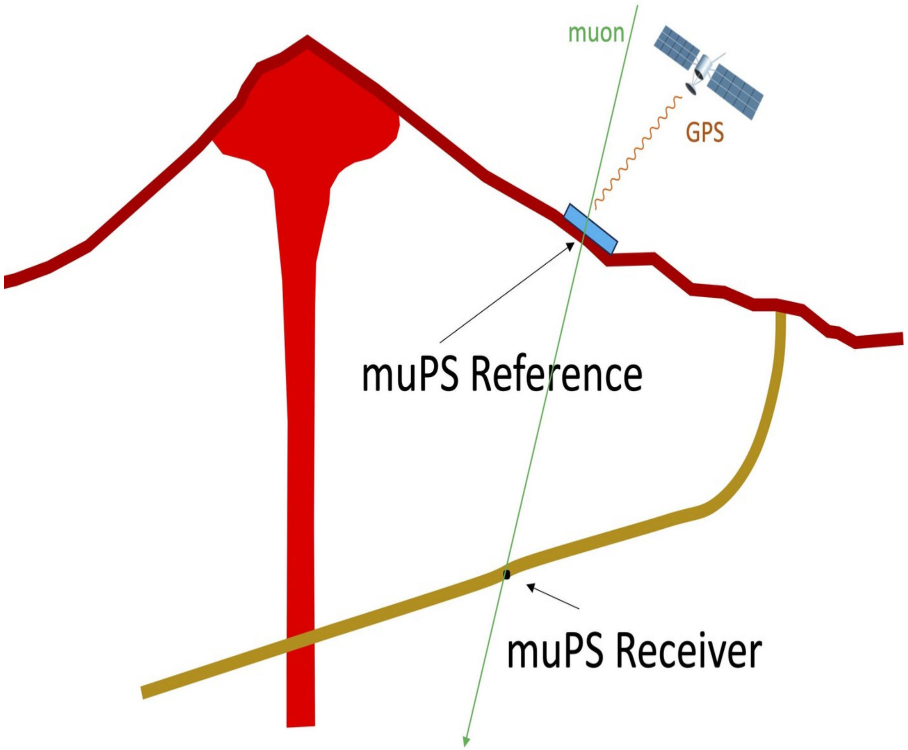
Goal:defining the underground coordinate within the national coordinate that means precise measurements of the baseline between far distant GPS station (>10 km away) and the muPS station at a sub cm level

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

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

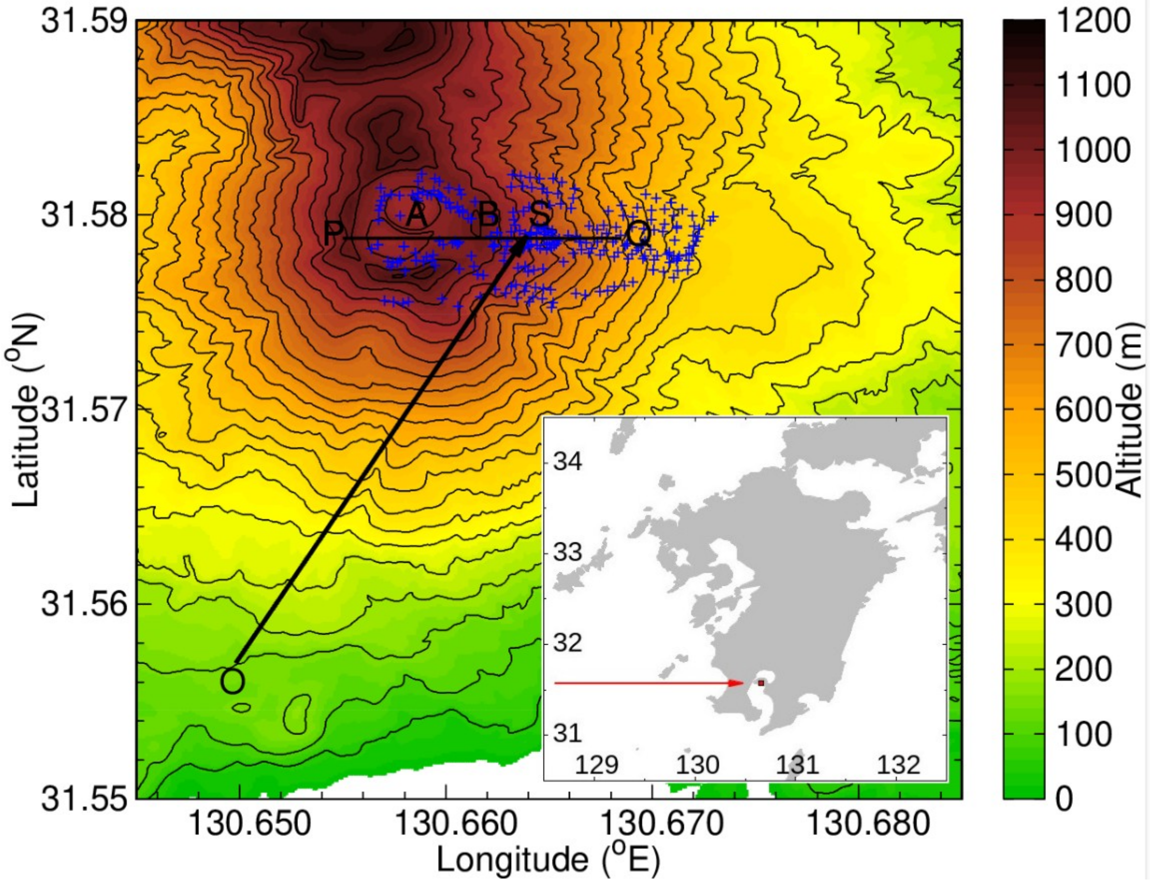


Source of figure: H.K.M. Tanaka

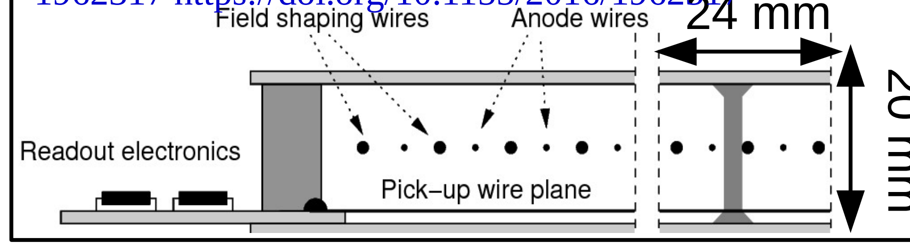
II. Joint muon and ground surface deformation monitoring

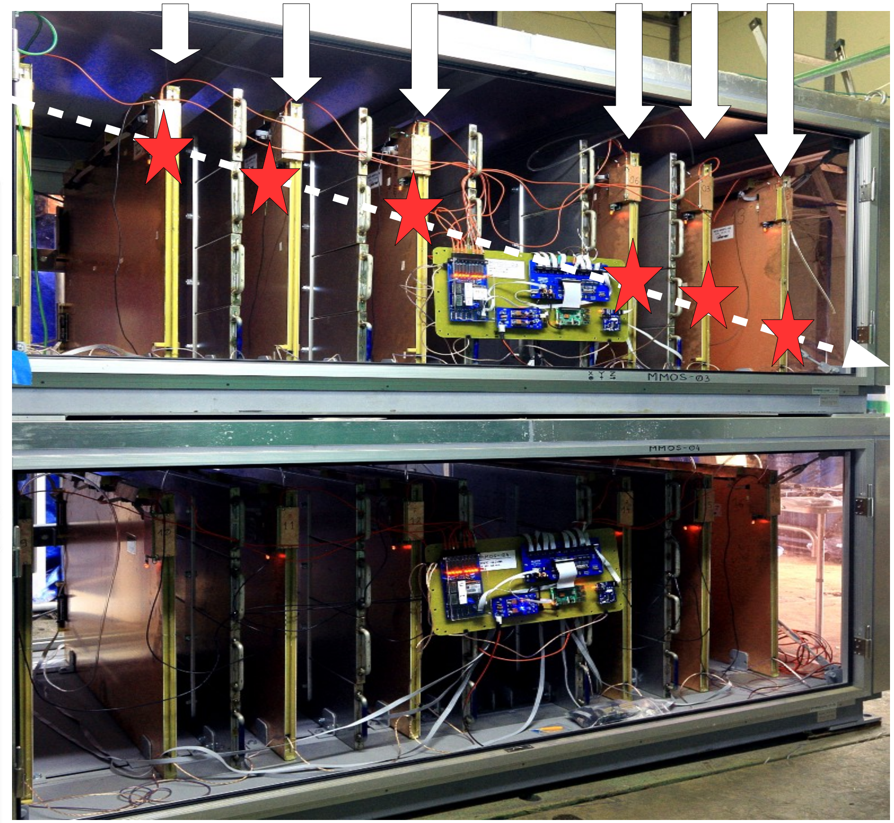
Sakurajima Muography Observatory

The University of Tokyo and HUN-REN Wigner RCP conduct muography of Sakurajima since January 2017 to study active volcanism



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

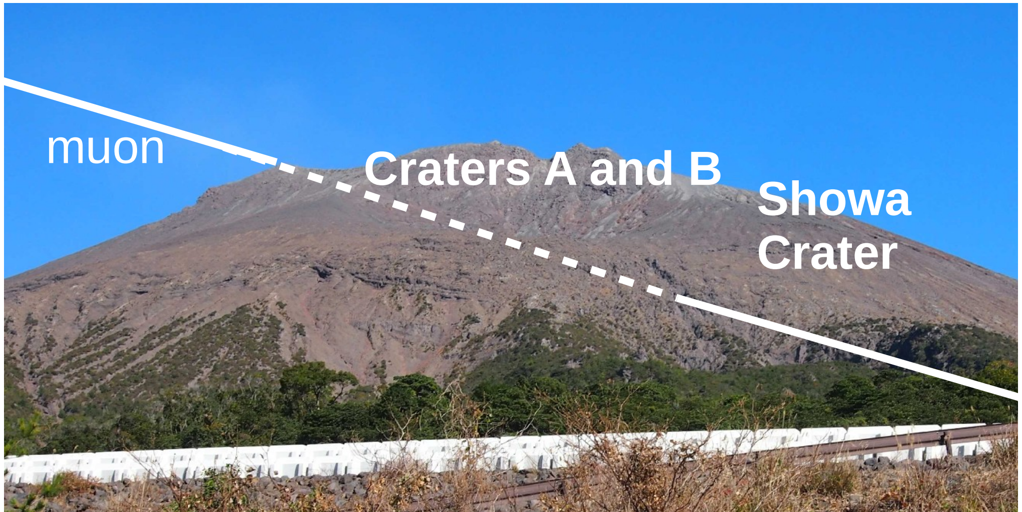


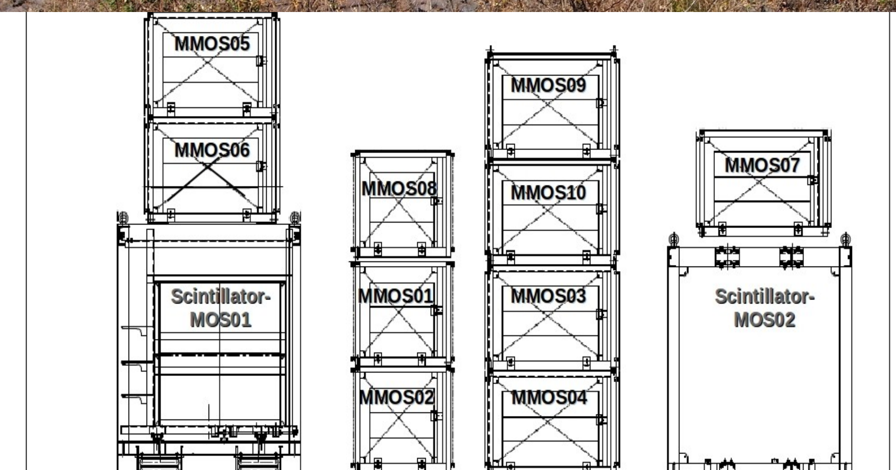


L. Oláh et al. Scientific Reports, 8, 3207, 2018, https://doi.org/10.1038/s41598-018-21423-9

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

Sakurajima Muography Observatory



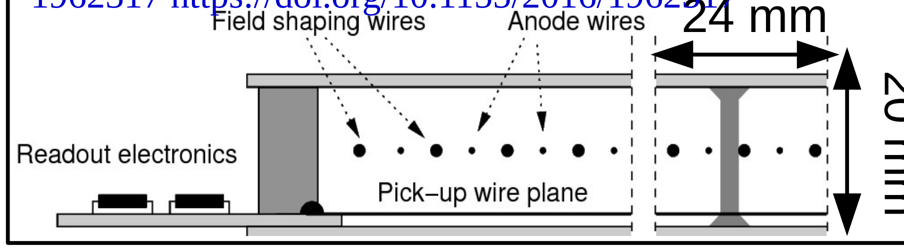


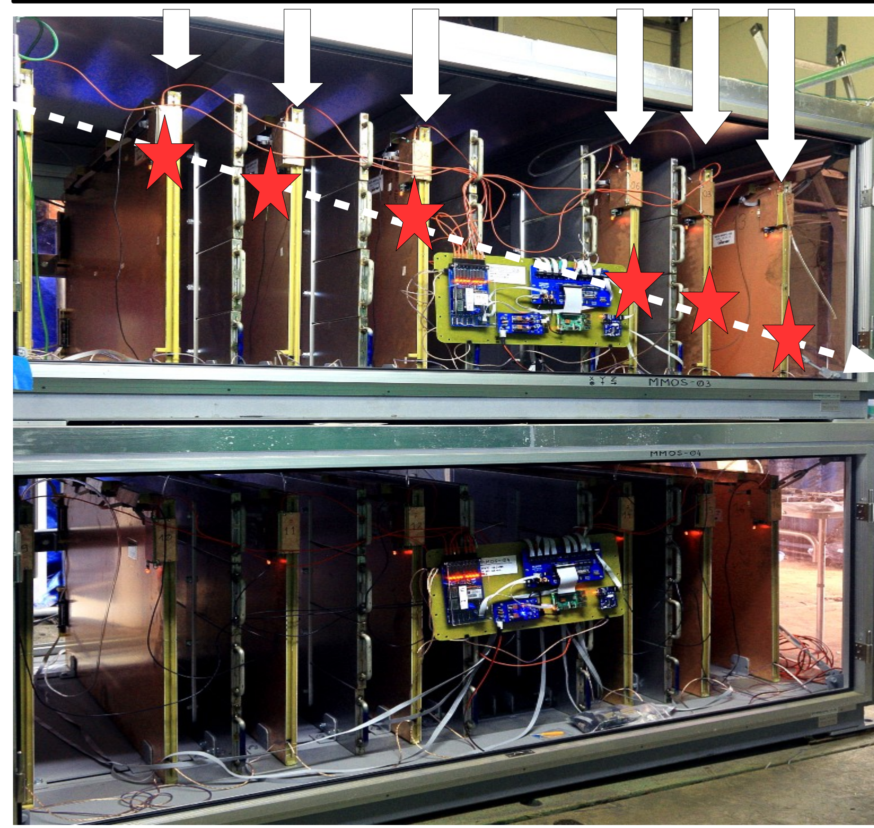
- Custom-designed electronics
- Micro-computer controlled
  → real-time DAQ & analysis
- Power consumption:
  ~ 6 W per MMOS

- **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

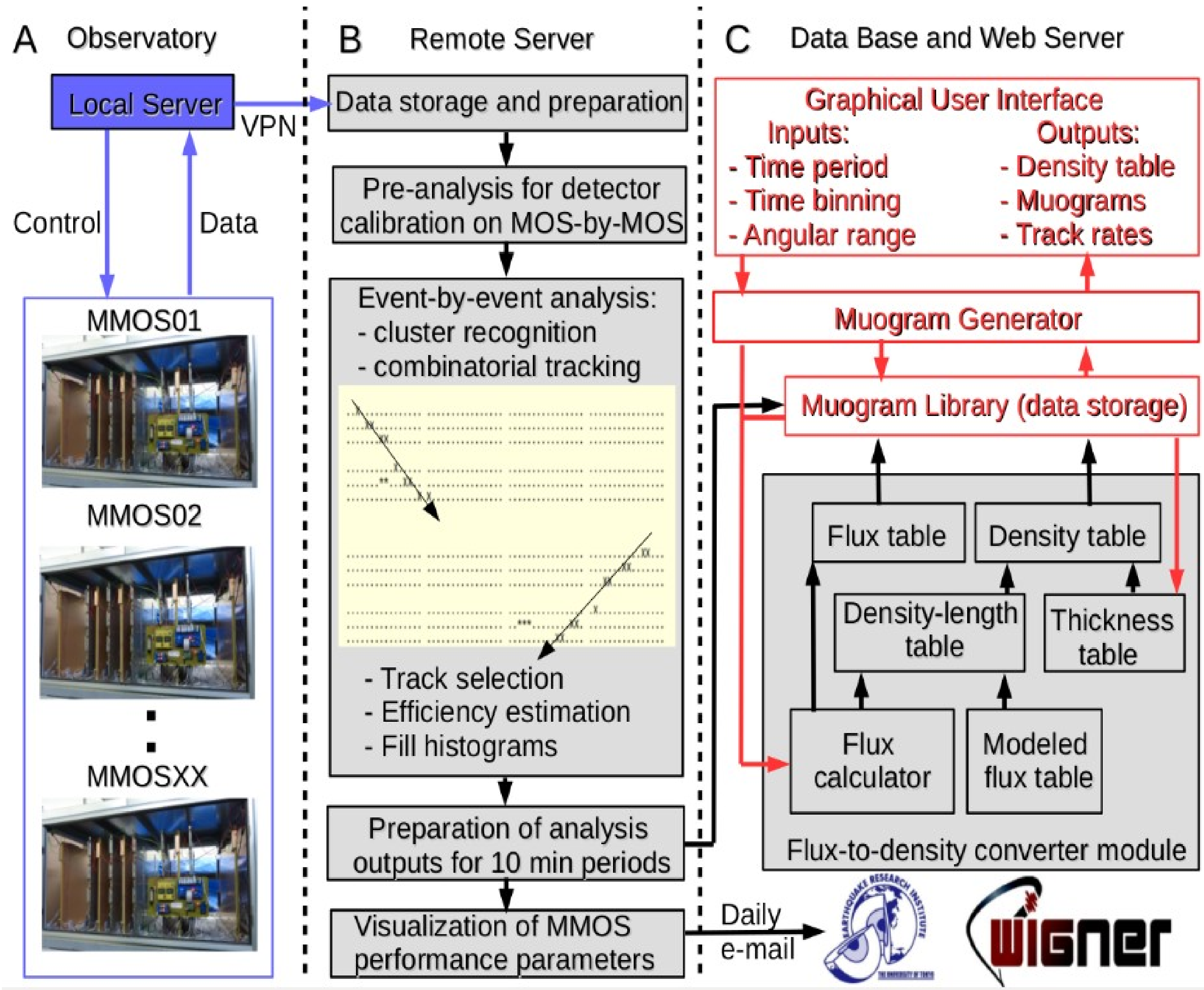


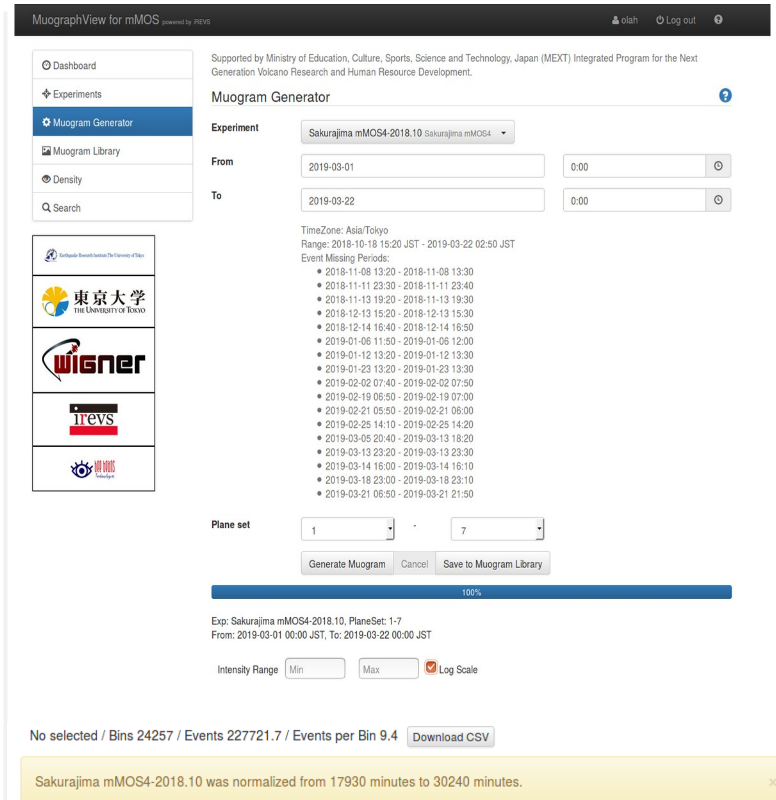


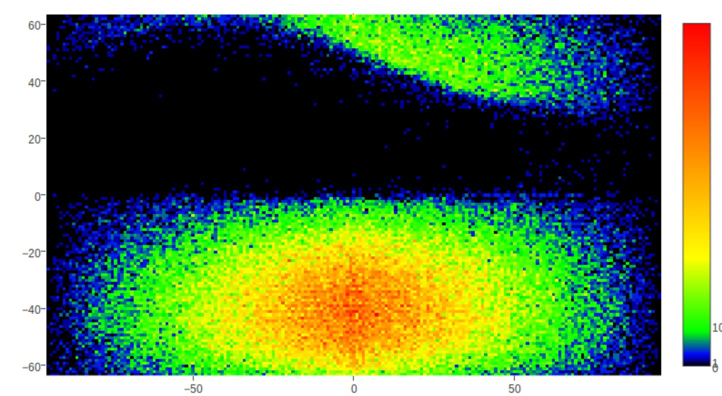
L. Oláh et al. Scientific Reports, 8, 3207, 2018,
https://doi.org/10.1038/s41598-018-21423-9

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

Data Processing





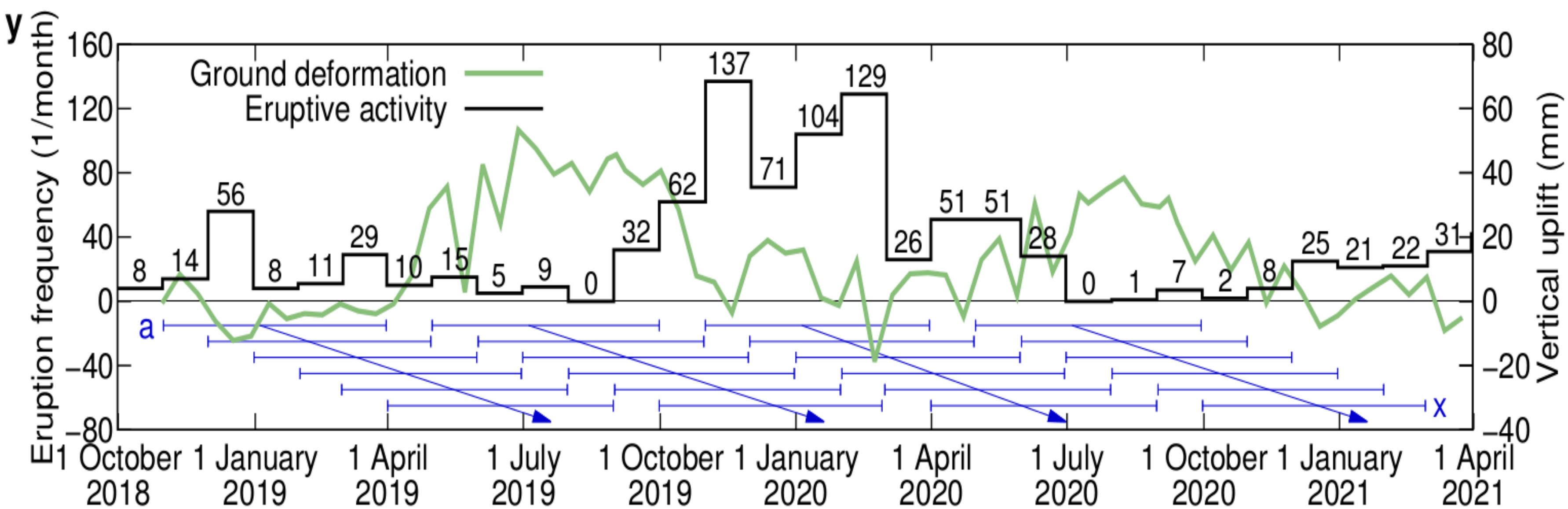


https://mmos.muographers.org

Oláh INeVRH WS 2026

InSAR Observations of Sakurajima

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.**



Highlights from Earlier Results

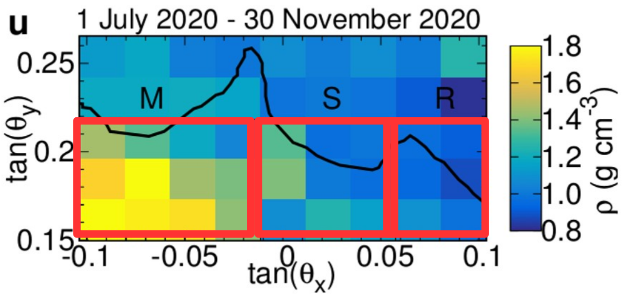
(1) Monitoring of hydrogeomorphic changes by volcanic ejecta deposition, erosion and lahars,
Scientific Reports 11, 17729, 2021, https://doi.org/10.1038/s41598-021-96947-8

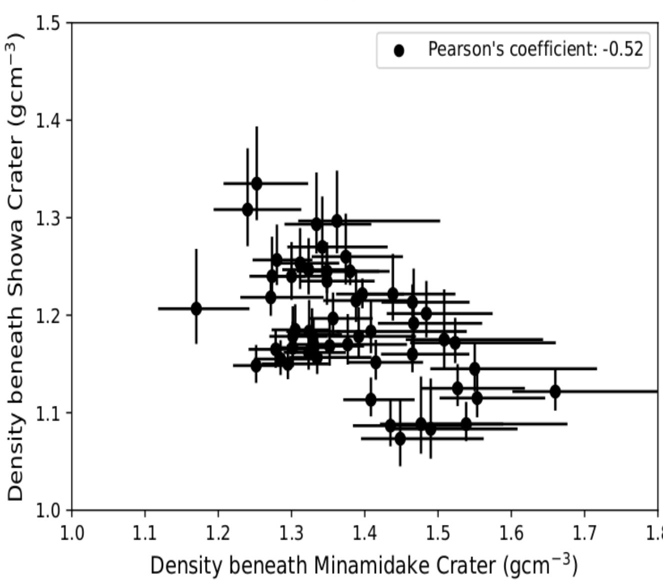
(2) Monitoring magma evolution (plug formation, drain-back process),
Geophys. Res. Lett. 46, 10417, 2019, https://doi.org/10.1029/2019GL084784

(3) Inferring to branched conduit structure from magma dynamics among two craters,
Journal of Geophysical Research: Solid Earth, 129, e2023JB028514, 2024 https://doi.org/10.1029/2023JB028514

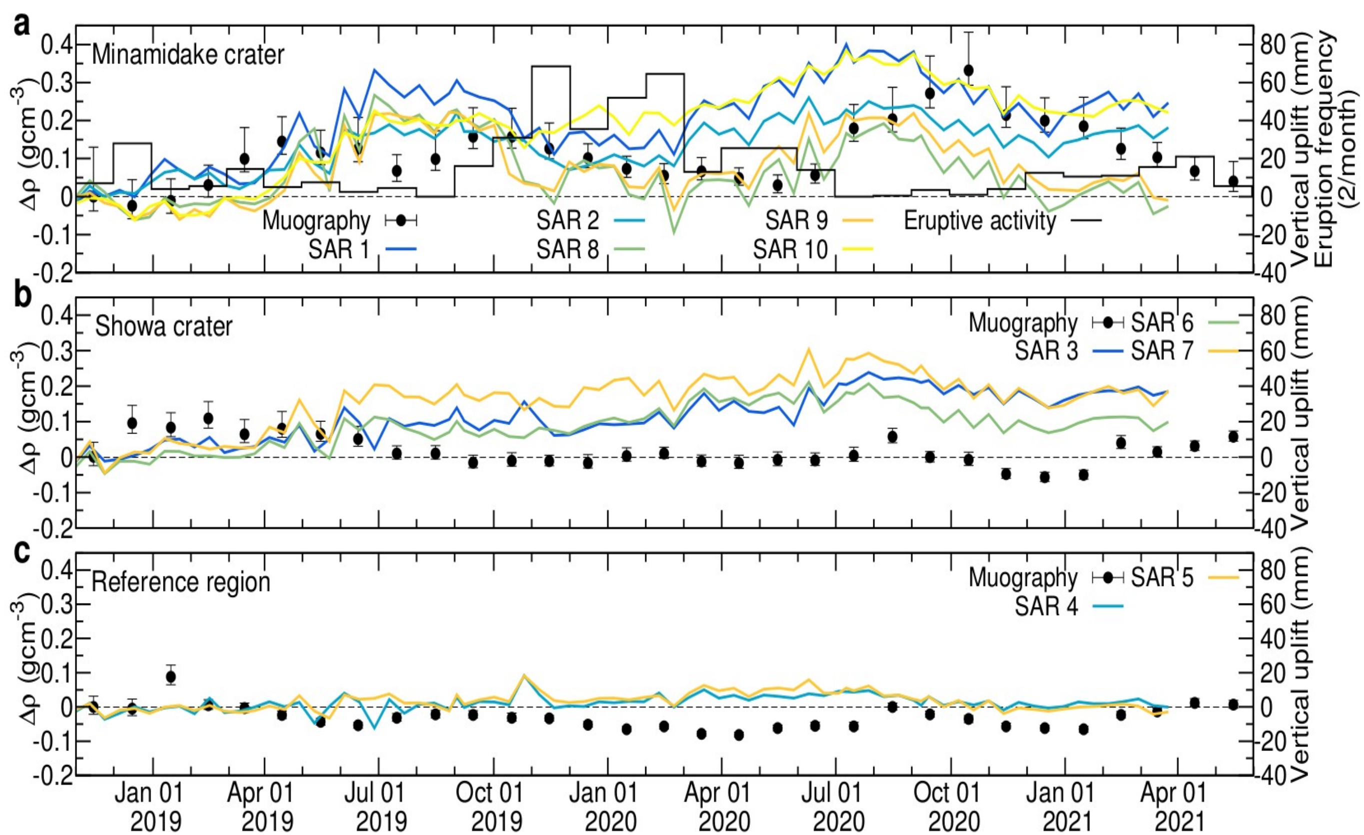
(4) Explaining the link between ground deformation and eruption frequency by revealing inconduit mechanism,
Geophys. Res. Lett. 50, e2022GL101170, 2023, https://doi.org/10.1029/2022GL101170

Minamidake Showa Reference

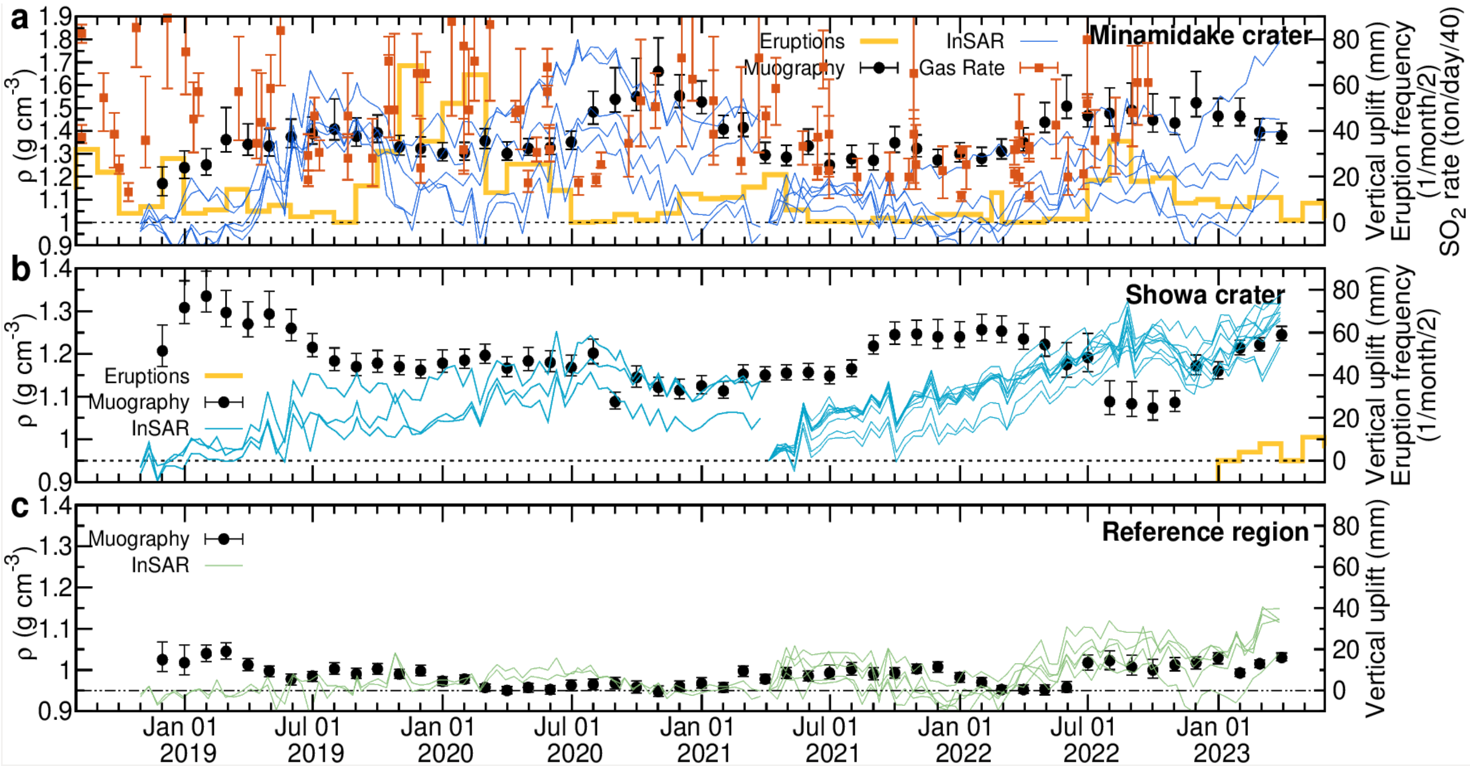




September 2018 – September 2021: 5 months moving average of relative densities



Volcanic Unrest Index (VUI) was determined using muographic, InSAR, and gas flux data



	0: no unrest	1: negligible unrest	2: minor unrest
Mass density rate	No change in the density	Low rate of density increase (<0.05 g/cm^3/month)	Moderate rate of density increase (0.05–0.15 g/cm^3/month)
Vertical ground displacement rate	No deformation	Low rate of deformation (<10 mm/month)	Moderate rate of deformation (>10 mm/month)
SO_2 gas flux rate	Low levels of gas flux rate (<1000 t/day)	Moderate levels of gas flux rate (1000–2500 t/day)	Moderate levels of gas flux rate (2500–5000 t/day)

The VUI semi-quantitatively evaluates the intensity of volcanic activity by comparing it with historical activity levels. Potter et al. (2015) Bull. Volcanol.77, 77. https://doi.org/10.1007/s00445-015-0957-4

We determined the VUI from the rates of change in density, the vertical component of ground deformation, and sulfur dioxide gas flux. In the table, low activity (VUI2) marks the point at which all three observational datasets reached their maximum values (September 2019 to December 2020). VUI2 is associated with the time period having the highest eruption probability. The less active (VUI1) and inactive (VUI0) states were linearly scaled relative to VUI2.

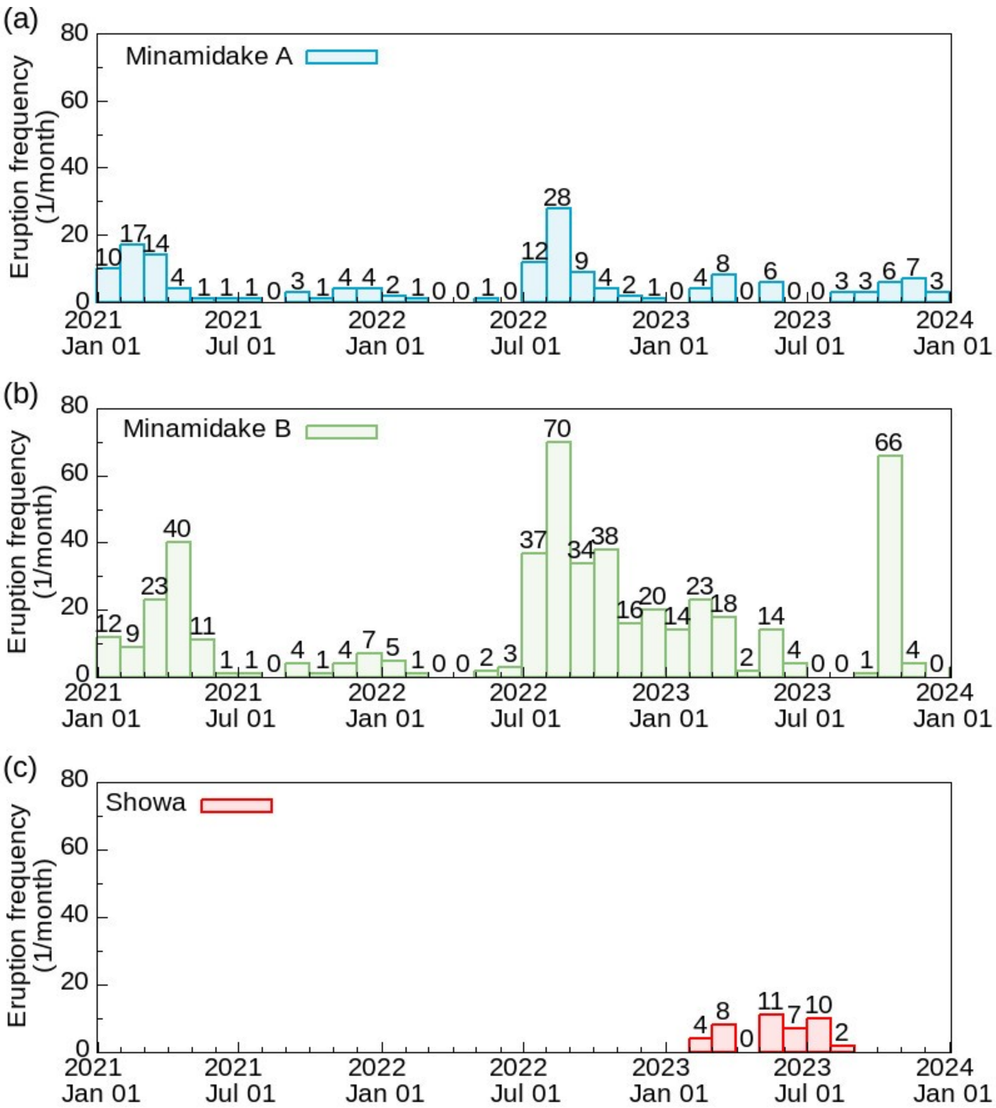
Uses of the VUI:

(1) Communicates complex observational data to society.

(2) Provides input information for event-tree models used to assess hazard levels.

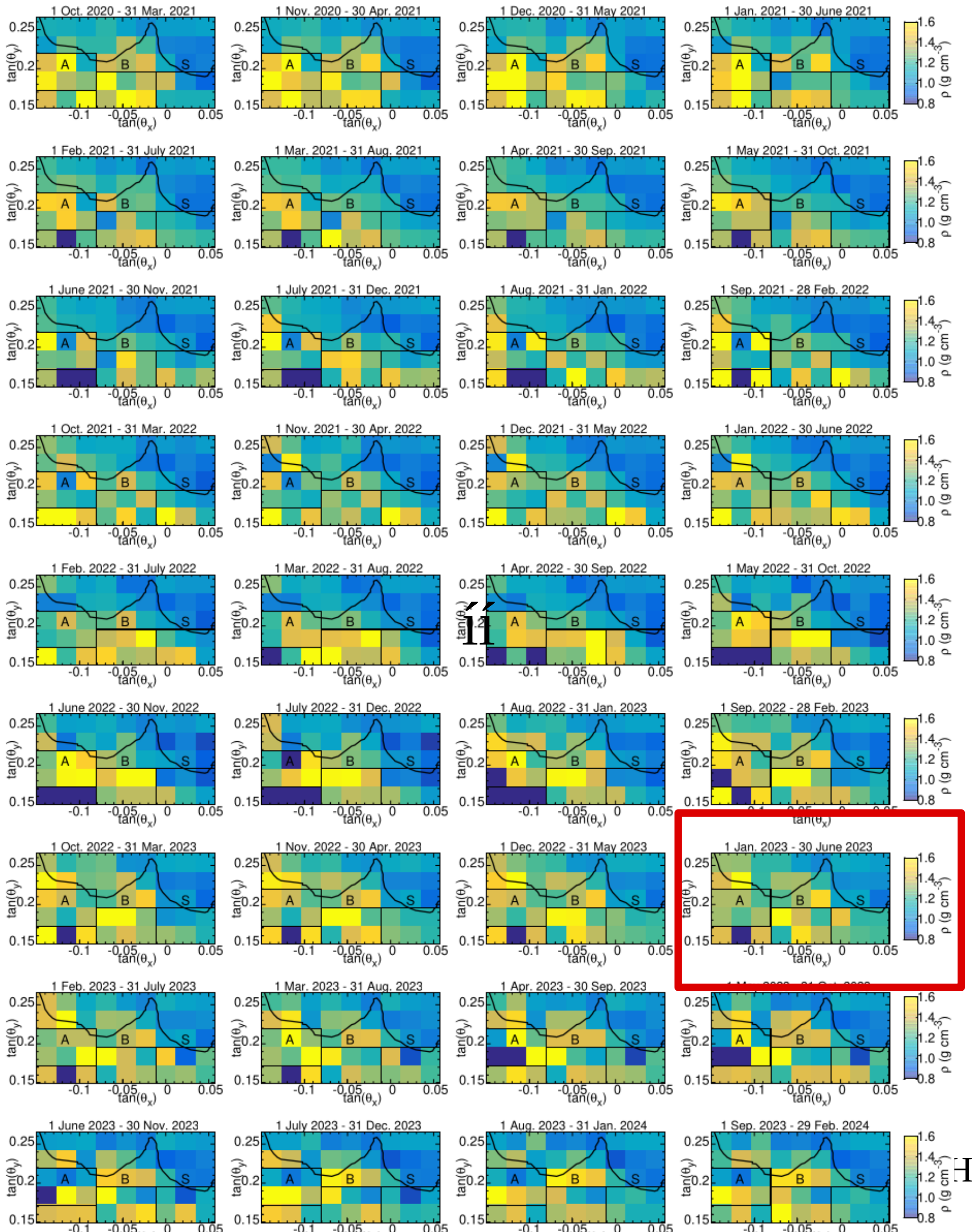
Oláh, L., Tanaka, H.K.M. (2025). Toward joint muography and ground deformation monitoring for volcanic unrest assessment. J. Appl. Phys.138, 060701 https://doi.org/10.1063/5.0275038

Monitoring of the movement of magma before the 2023 eruption of Showa crater

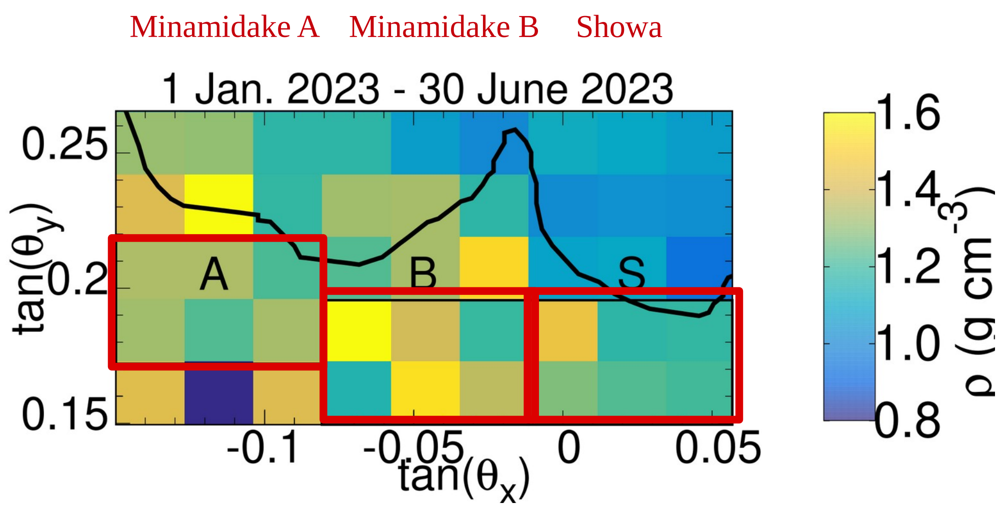


- The Showa crater activated in early 2023
- We investigated the underlying volcanic processes by joint muon and ground surface deformation monitoring.

Monitoring of the movement of magma before the 2023 eruption of Showa crater



- Density images were recorded from 1 Oct. 2018 to 29 Feb. 2024
- 6-month moving average values of densities were calculated beneath the Minamidake A, B and Showa craters

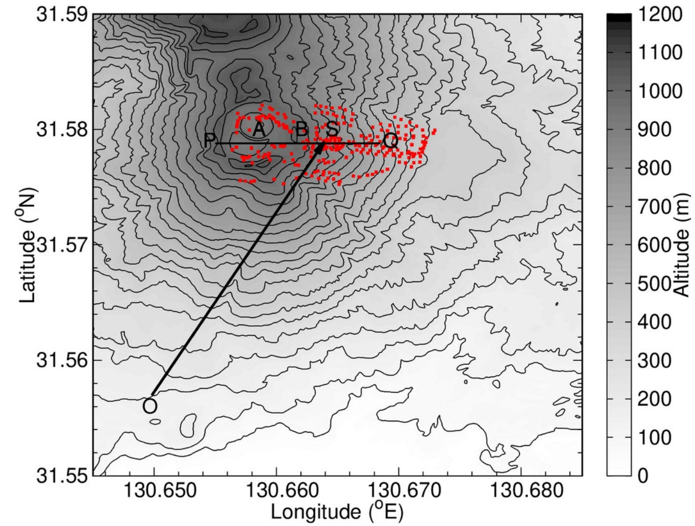


- **Masses were calculated for trapezoid volumes:**

$$m = N\,\rho_{mean} T_{mean}[D^2\Delta^2 + (D + T_{mean})^2\Delta^2 + D\,(D + T_{mean})\,\Delta^2]/\,3$$

Mogi and Yang Modeling of Ground Surface Deformations Measured by InSAR

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



- Comparison of modeled and measured (above altitude of 700 m) vertical uplifts enables us to determine volume change and spatial coordinates of pressure source

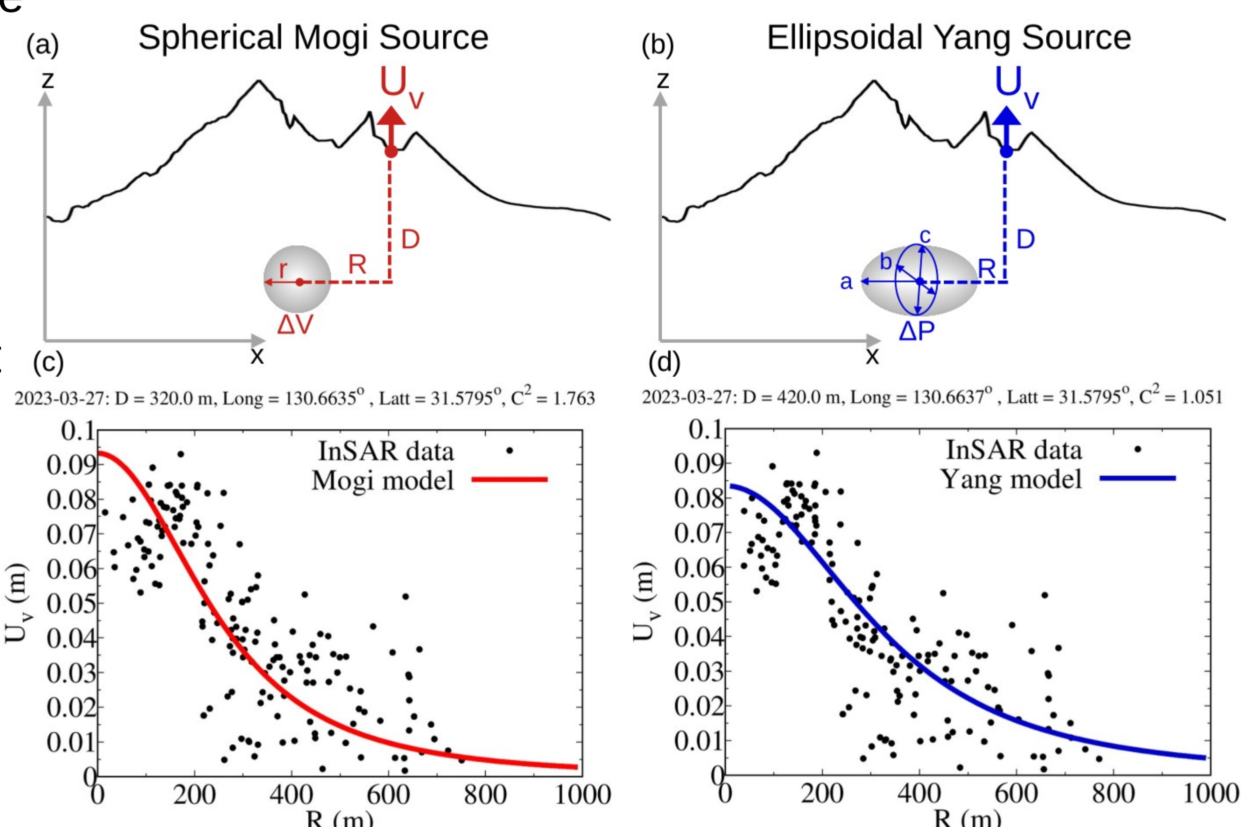
- **Parameter estimation procedure based on grid searching** via minimizing the square of relative difference between the measured and modeled vertical uplifts of ground surface as a function of the radial distance

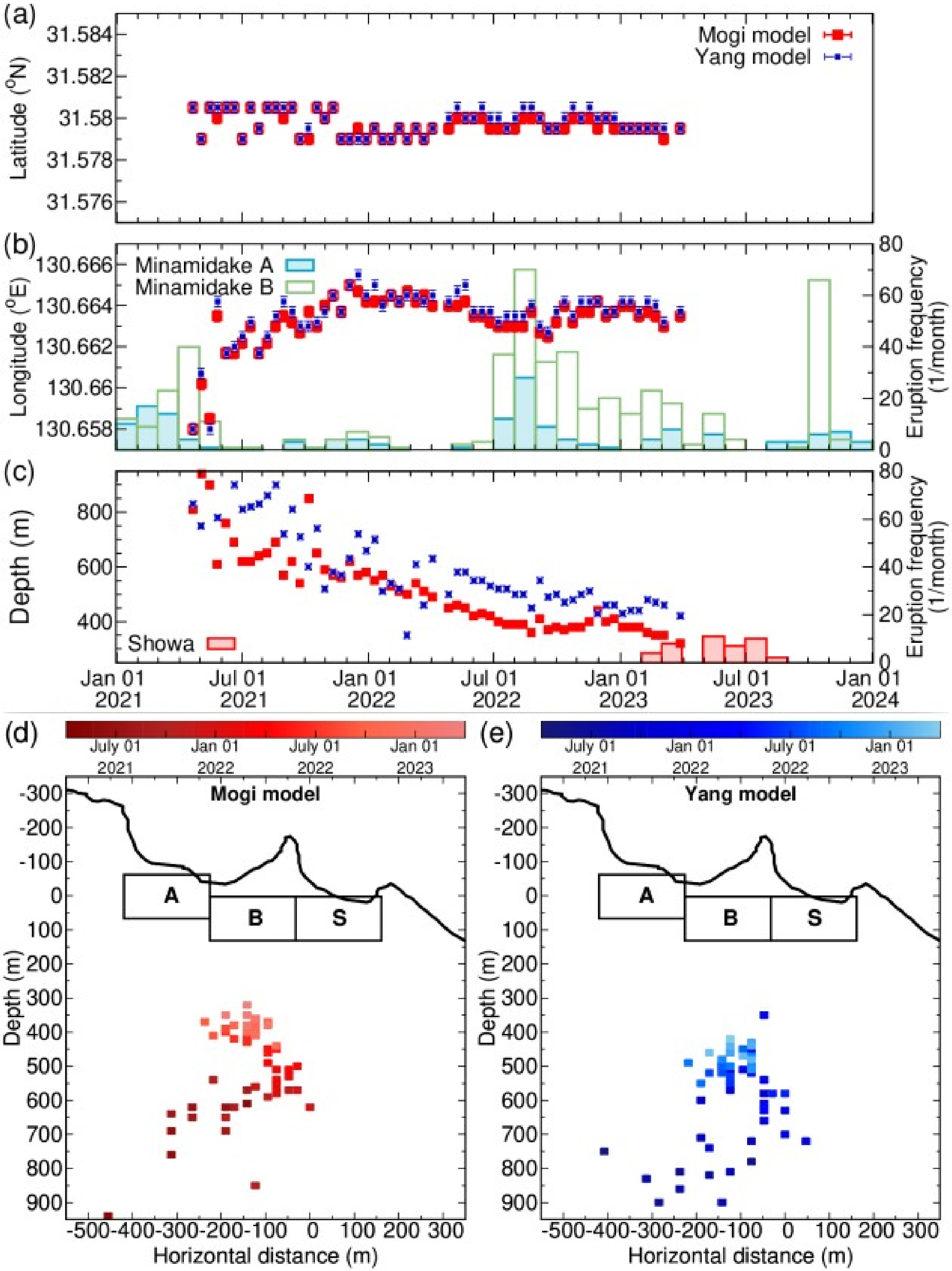
Mogi: $U_v = 3\,\Delta V\,D \;/\; [\,4\pi\,(R^2 + D^2)^{3/2}\,]$

Yang: $U_v = \Delta P abc \;/\; [\,\mu\,(R^2 + D^2)^{3/2}\,]$

where

μ is the shear modulus of medium.





Comparison of Mogi and Yang source modeling:

(1) Movement of source in south-north direction is negligible,

(2) Source movement of a few hundred meters in west-east direction,

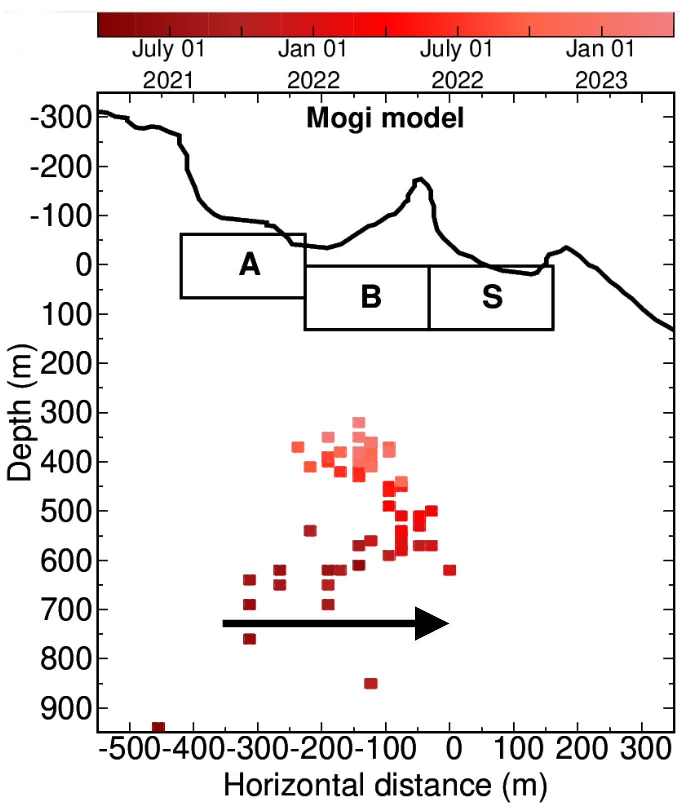
(3) source depth decreased over time. A slight shit is visible between the two depths.

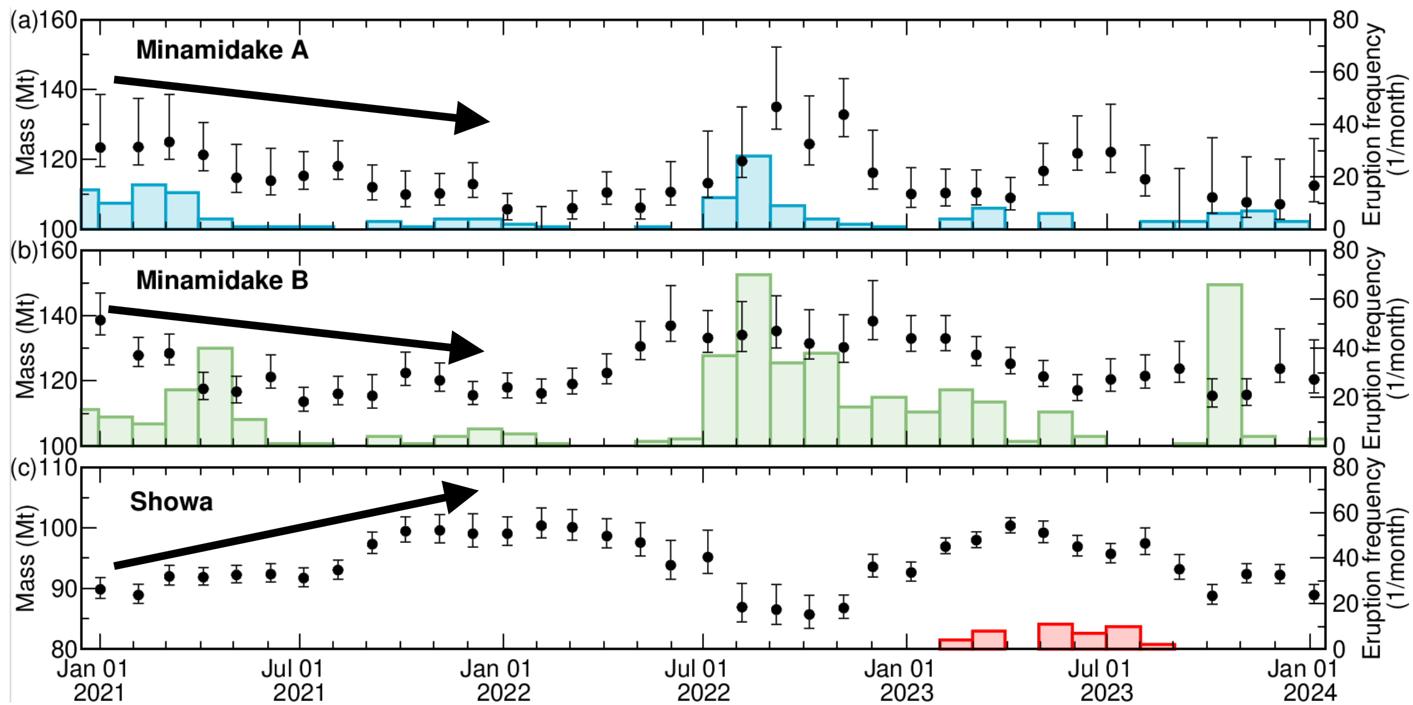
Magma migration towards east in 2021

Source modelling: The deformation source moved towards east beneath the active craters at a depth of 600-700 m.
Muography: the mass decreased beneath Mindamidake A and Minamidake B craters, and increased beneath the Showa crater.
Eruption frequency: Shifted from crater Minamidake A to crater Minamidake B.

→ **(1) Deep horizontal magma channel at 600-700 m beneath the active craters that feeds the Minamidake.**

Magnetotelluric measurements has already indicated similar horizontal structure at similar depht.
Aizawa, et al. (2011) J Volcanol Geotherm Res199:165-175. https://doi.org/10.1016/j.jvolgeores.2010.11.003





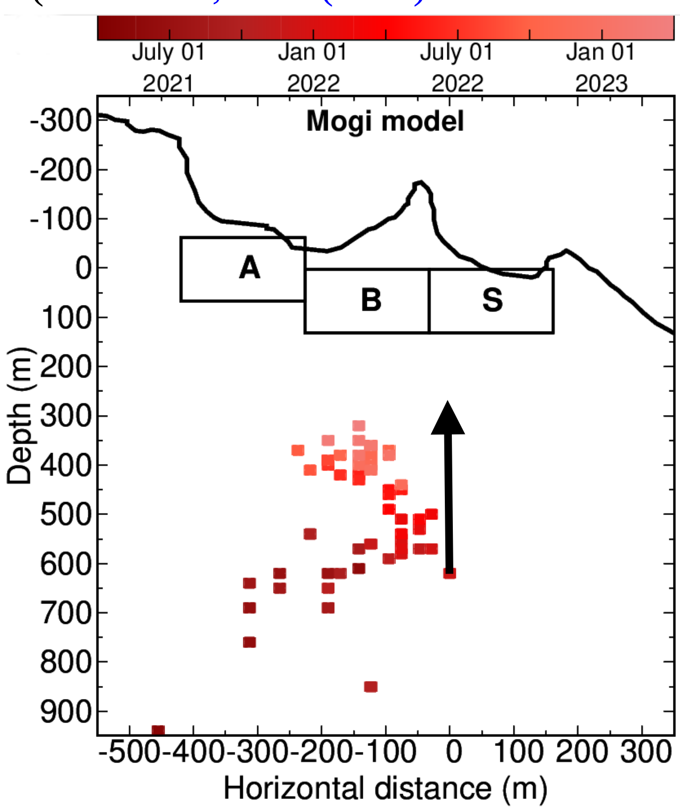
Oláh, L., et al. Magma migration beneath the active craters of Sakurajima volcano before the 2023 eruption of Showa crater inferred from ground deformation and muon monitoring. Earth Planets Space 77, 196 (2025). https://doi.org/10.1186/s40623-025-02325-3

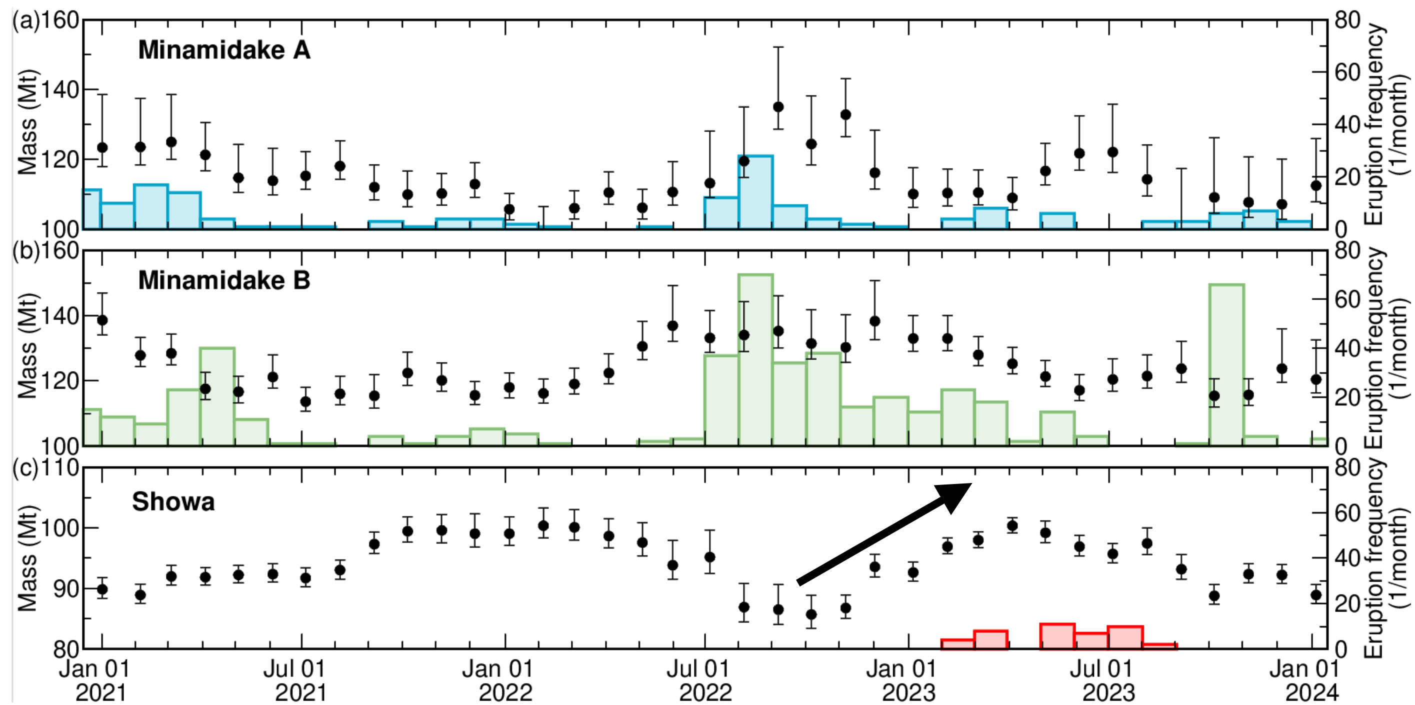
Magma rising before the eruption 2023 of Showa crater

Source modelling*:* the source of ground deformation rised about 350 m beneath the active craters
Muography*:* the mass increased beneath the Showa crater.
Eruption frequency*:* The Showa crater started to erupt in early 2023. The Minamidake craters remained actice.

→ **(2) Shallow magma reservoir that feeds all craters with magma**

Magma head rising was also observed earlier by absolute gravimetry
(Okubo, et al. (2013) Bull Volcanol Soc Japan 58:153-162. https://doi.org/10.18940/kazan.58.1_153).
Active seismic experiments and rock sample analysis also suggest the presence of a shallow magma reservoir
(Nishimura, et al. (2024). Bull Volcanol 86:27. https://doi.org/10.1007/s00445-024-01722-y).





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

Improvements on MuWNS-V (directional wireless muon positionig)

HUN REN

- Underground demonstration (10 and 20m depth)
- Improved timing precision: 10 microsec (from 100)
- Long term high positioning precision (mm level)

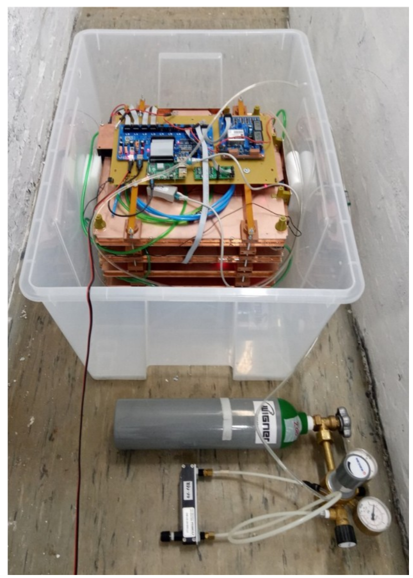
NATIONAL RESEARCH, DEVELOPMENT AND INNOVATION OFFICE HUNGARY

PROJECT FINANCED FROM THE NRDI FUND

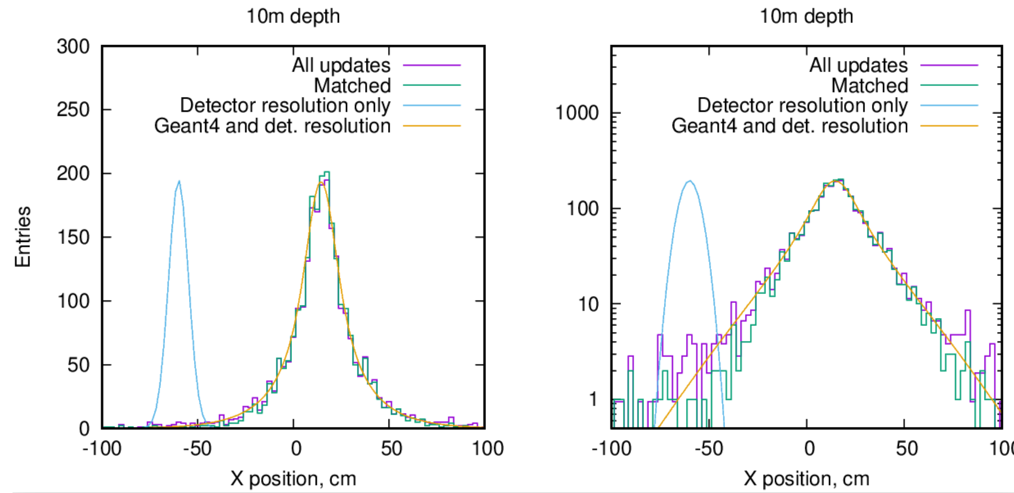
This slide was provided by D. Varga (varga.dezso@wigner.hu).

Underground demonstration

- 10m (and 20m) underground 8m (and 16m) overburden
- Surface Reference, underground 40cm size Receiver



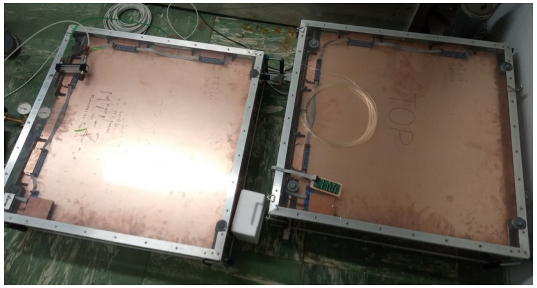
Position resolution predicted by GEANT4 simulation

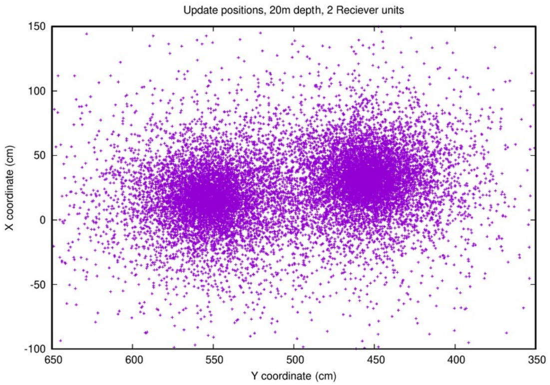


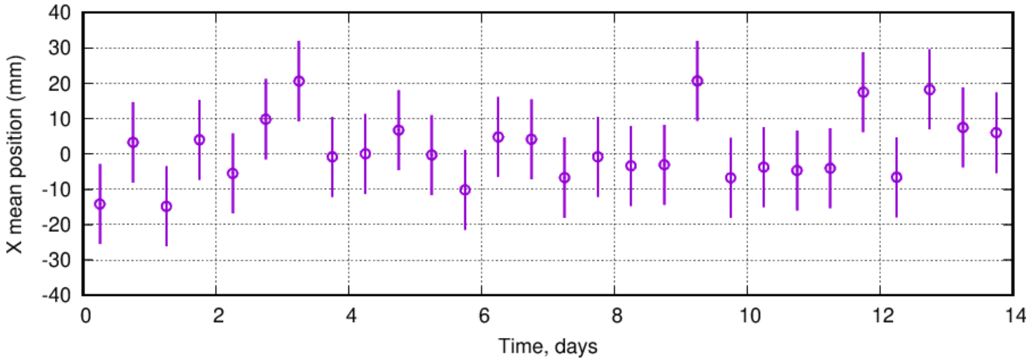
These figures were provided by D. Varga (varga.dezso@wigner.hu).

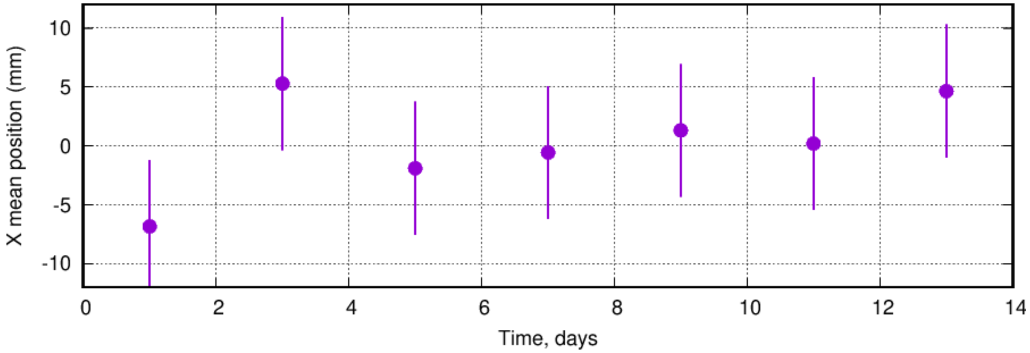
Long term mm-level underground measurements at Wigner RCP (20m)

- Total 1m2 (split) Receiver, 120cm Reference







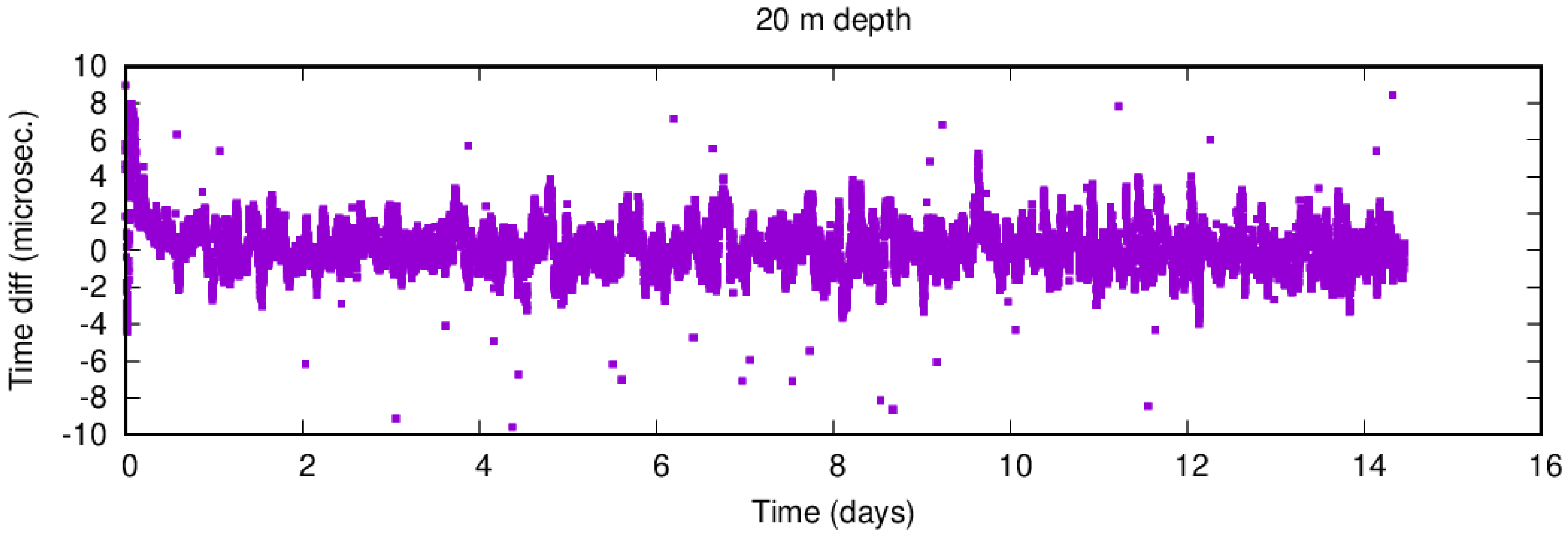


These figures were provided by D. Varga (varga.dezso@wigner.hu).

Improvement in timing

- At 20m depth, continuous CTC lock for 14 days
- Update time window* down to 10 microsecond!

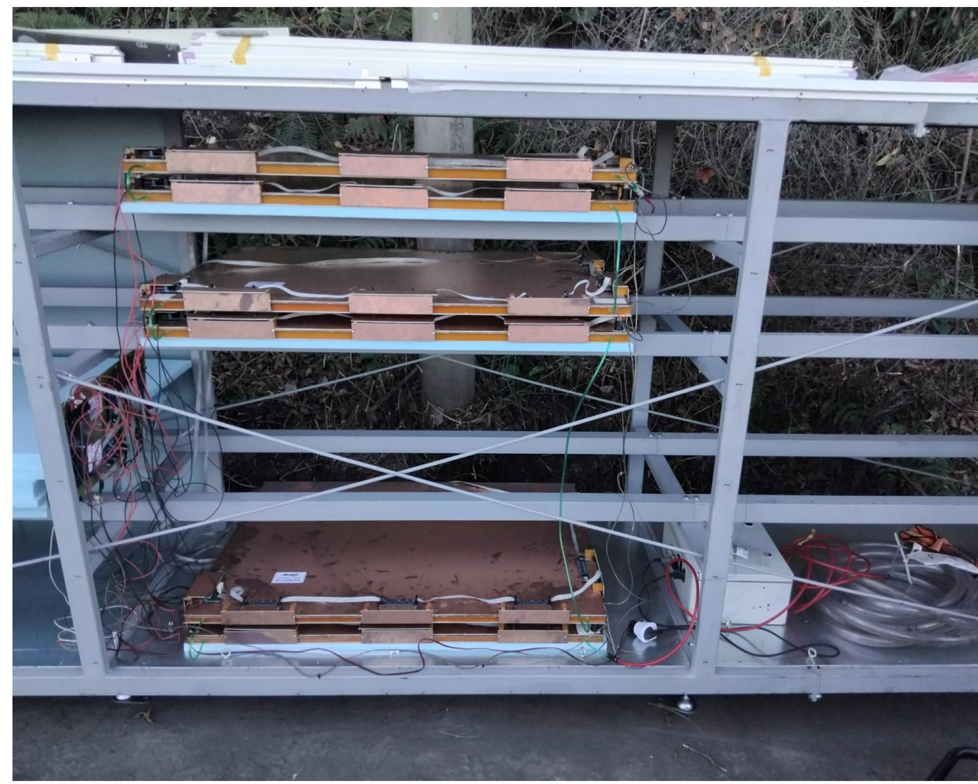
*(time difference between Reference and Receiver)



This figure was provided by D. Varga (varga.dezso@wigner.hu).

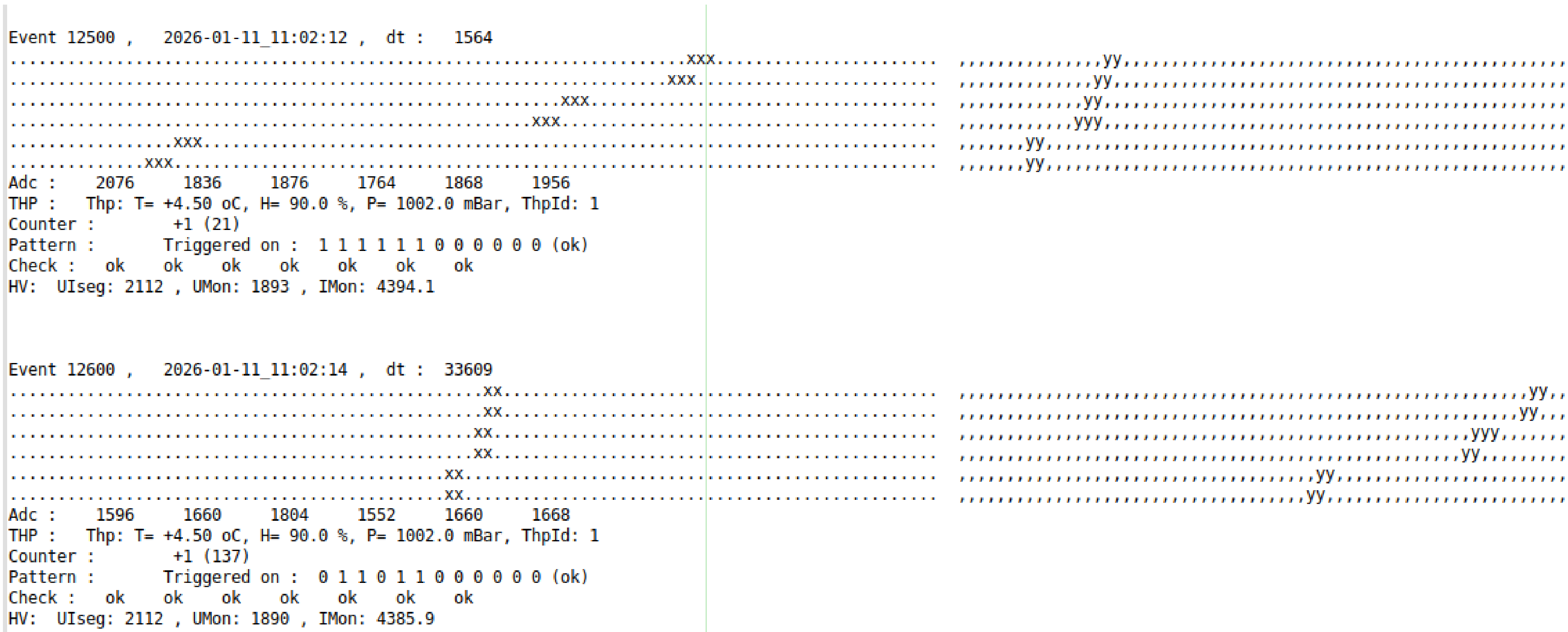
Installation of the first muPS module above Komen Observation Tunnel

- MuPS reference consists of six layers of gaseous tracking detectors has been installed



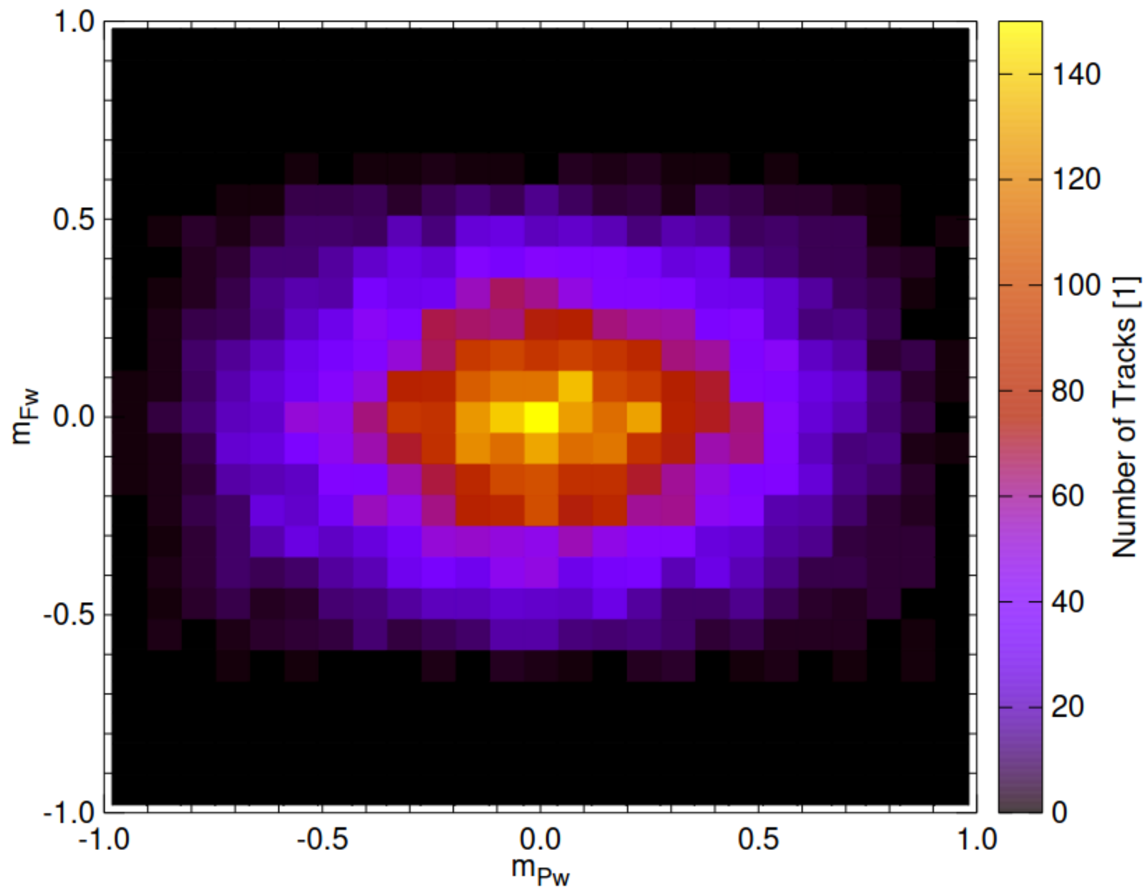
Installation of the first muPS module above Komen Observation Tunnel

- Tracking performance has been demonstated.
  Long-term operation is planned to be started in FY2026.



Installation of the first muPS module above Komen Observation Tunnel

- Tracking performance has been demonstrated.
  Long-term operation is planned to be started in FY2026.



IV. Summary

Highlights from FY2025:

I. Joint muon and ground surface deformation monitoring and modelling allowed to

(1) **determine** the time-evolution of Volcanic Unrest Index (**VUI**) for Sakurajima volcano using muograpic, ground surface deformation and gas flux data,

Oláh, L., Tanaka, H.K.M. (2025). Toward joint muography and ground deformation monitoring for volcanic unrest assessment. J. Appl. Phys.138, 060701 https://doi.org/10.1063/5.0275038

(2) **monitor magma migration** beneath the active craters **for probing the structure of the upper plumbing system** (horizontal magma channel and shallow magma reservoir at 600-700 m and shallow magma reservoir at 300-400 m beneath the craters, respectively)

Oláh, L., et al. Magma migration beneath the active craters of Sakurajima volcano before the 2023 eruption of Showa crater inferred from ground deformation and muon monitoring. Earth Planets Space 77, 196 (2025). https://doi.org/10.1186/s40623-025-02325-3

II. Monitoring of underground position with muometric positioning has been demonstrated and its optimization is ongoing via underground measurements. A reference detector has been installed above Komen Observation Tunnel at Sakurajima volcano.

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/
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

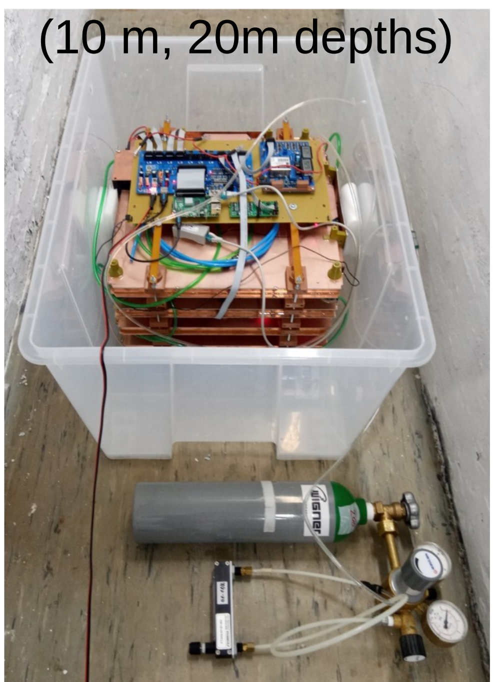
Contact information:
László Oláh olah.laszlo@wigner.hu https://wigner.hu/s/high-energy-geophysics/index_eng.html

Backup slides

Directional Wireless muPS System developed in HUN-REN Wigner RCP, Hungary

Reference at ground level

Receiver in tunnels
(10 m, 20m depths)

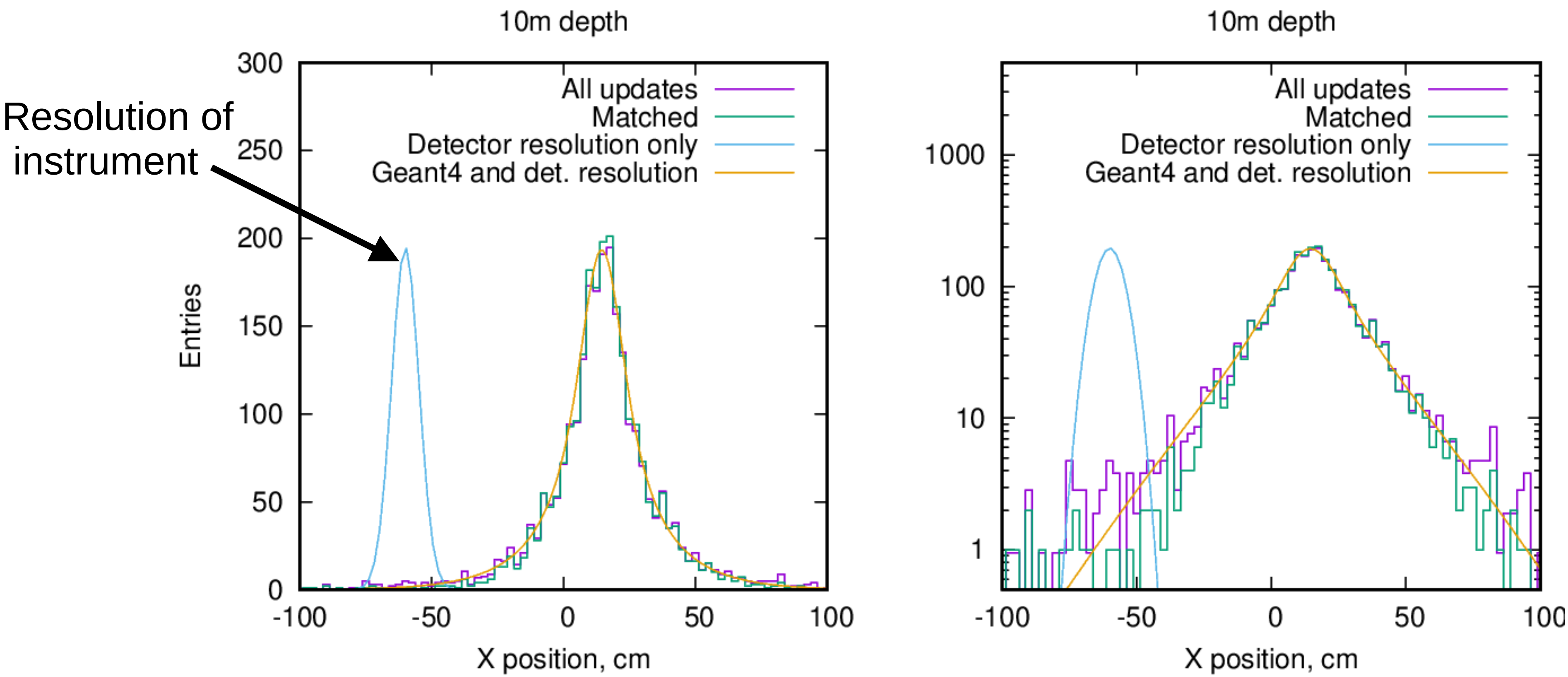


- Detectors are MWPC-s with 12mm pitch
- 2D projective geometry (field wires and perpendicular cathode wires)
- Surface Reference detector with 5mrad resolution
- Reference sensitive 760mm x 760mm (1150mm)
- Receiver sensitive 380mm x 380mm
- Update rate of Receiver detector at 10m (20m) depth: 15mHz (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

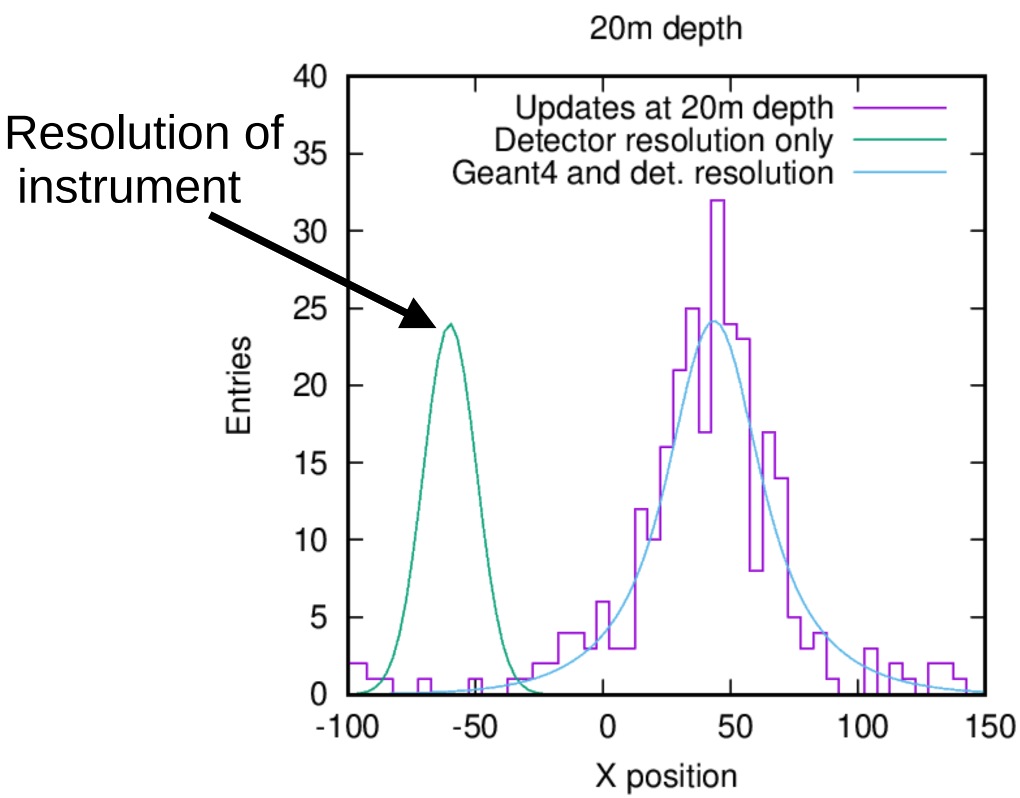
- Reference angular resolution chosen to be sufficiently good, 5 mrad to measure the effects of muon scattering.
- Experimental data are consistent with Geant4 simulations: tails due to low energy muons. Furthermore, little background is available.
- FWHM is approx. 30 cm.

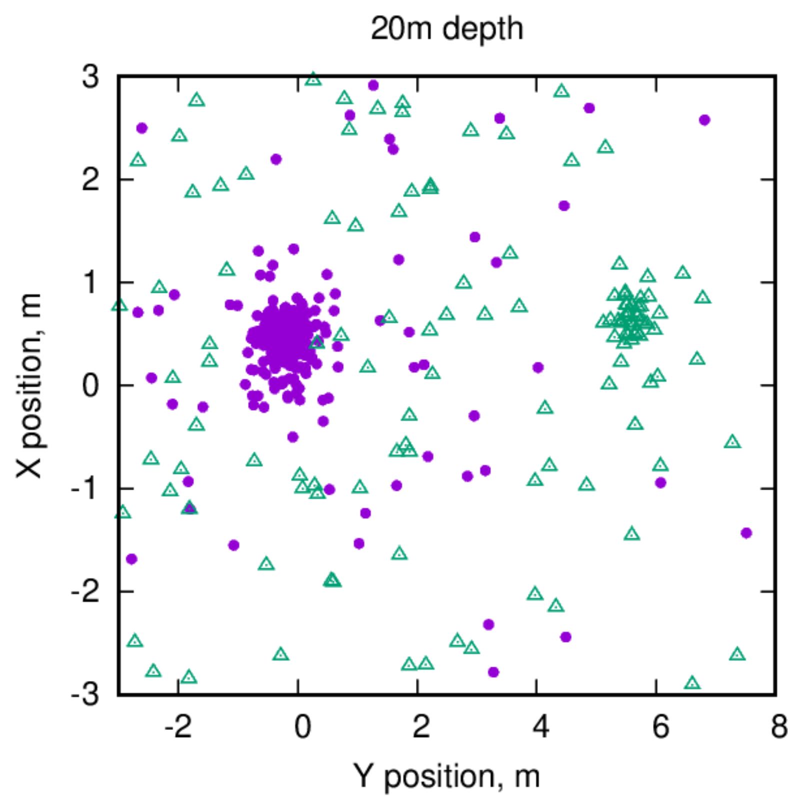


Source of figures: D. Varga’s talk at Muographers 2024 WS (Santa Fe)

Position Resolution of muPS at 20 m depth

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





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