

INTRODUCING MUOGRAPHY: PROBLEMS AND CHALLENGES

M. Holma^{1,2,3,9}, P. Kuusiniemi^{1,3,9}, J. Joutsenvaara^{1,2,3,9}, T. Enqvist¹, K. Loo^{1,9}, E. Kozlovskaya⁴, Z.-X. Zhang⁴, I. Hynynen⁴, R. Heikkilä⁵, P. Sarala^{4,6}, J. Torppa⁶, T. Öhman³, H. K. M. Tanaka^{7,8,9}, L. Oláh^{7,8,9}, S. Steigerwald^{8,9}, K. Sumiya^{10,9}, D. Varga^{11,9}, G. Hamar^{11,9}, G. Nyitrai^{11,12,9}, G. Leone^{13,9}, D. Lo Presti^{14,15}, G. Gallo^{14,16}, P. D’Incecco^{17,3}, and L. Thompson^{18,19,9}

¹*Muon Solutions Oy, Finland*

²*Kerttu Saalasti Institute, University of Oulu, Finland*

³*Arctic Planetary Science Institute, Finland*

⁴*Oulu Mining School, University of Oulu, Finland*

⁵*Faculty of Technology, University of Oulu, Finland*

⁶*Geological Survey of Finland*

⁷*Earthquake Research Institute, University of Tokyo, Japan*

⁸*International Muography Research Organization (MUOGRAPHIX), University of Tokyo, Japan*

⁹*Virtual Muography Institute (global)*

¹⁰*Kansai University, Japan*

¹¹*Wigner Research Centre for Physics, Hungary*

¹²*Budapest University of Technology and Economics, Hungary*

¹³*University of Atacama, Chile*

¹⁴*Department of Physics and Astronomy, University of Catania, Italy*

¹⁵*National Institute for Nuclear Physics, Italy*

¹⁶*Astronomical Observatory of Catania, National Institute for Astrophysics, Italy*

¹⁷*Università degli studi G. d’Annunzio, Italy*

¹⁸*University of Sheffield, UK*

¹⁹*Geoptic Ltd., UK*

email: marko.holma@muon-solutions.com

Cosmic-ray muography is a novel density imaging technique based on muon attenuation in material. It is currently emerging among the end-users of applied physics. Muography has already been applied to a wide range of disparate fields of science, including archaeology, volcanology, hydrology, geology, mining, and engineering. In these fields, muography is considered as a valuable new tool that has potential to fill gaps in the capabilities of the many conventional geophysical methods in applications in which it is critical or at least valuable to know density variations in solid materials (or solids mixed with liquids). The common first perception among non-physicists when hearing about muography for the first time is huge interest and, occasionally, awe. However, as most of the neophytes lack vocabulary and good

understanding about the basics of muon-related physics, it is clear that the global muography community, which is mainly composed of astroparticle physicists, detector designers, software developers, engineers, and geoscientists, must assist in building bridges between different branches of sciences. This is accomplished by active international cooperation and interdisciplinary publishing. Another example of the efforts the muography community has conducted itself in an attempt to consolidate muography as a new research field is the establishment of the international Virtual Muography Institute [1]. Other examples are the annual General Assembly of Muographers [1] and online meetings. Related to the latter, and promoting muography research in Finland, an online meeting “Muographers 2020: Muography and the Possibilities at Callio Lab” was organized in mid-January 2021, as a substitute to the physical meeting that was cancelled due to the COVID-19 pandemic. The meeting brought together muographers from Japan to Chile, the majority being from the EU [2].

In the present work, we explain the physical principles of muography and its common applications, and discuss the common challenges encountered by the muographers when trying to expand its usage. We also provide examples of how muography appears to fall into space between physics and other sciences, until it becomes uncertain where it belongs to and who is expected to fund research on muography. Therefore, we conclude that muography must carve its own niche in the field of sciences before it can reach maturity and global acceptance.

[1] H. K. M. Tanaka, and L. Oláh, *Philos. T. R. Soc. A* **377**, 2137 (2019).

[2] J. Joutsenvaara et al., Geophysics, particle physics, or something else: what is muography and what could be its applications for science and industry?, *this publication* (2021).