University College London

Literature Review

Key Advances in Cosmic Muon Imaging

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Supervised by Prof. Ryan J. Nichol

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Abstract

In the past 20 years, the field of muon imaging (muography) has seen a great increase in research interest, catalysed by the introduction of muon scattering tomography in 2003. This review explores how muography has developed from its conception in 1955 to the current state of the art, noting how the focus of the field has shifted over time. Two notable applications - volcanology and nuclear material detection - are examined, demonstrating how the techniques have been adapted to the unique contexts these areas present. Possible focuses for the future of the field are also briefly touched upon.

Contents

1 Introduction

For over two thirds of its lifetime, the field of muon imaging has seen relatively little development. This has changed recently, with the proposal of a new form of imaging (muon scattering tomography) generating a great amount of interest in the area and spurring on new developments in the field. This has led to the widespread application of muon imaging in fields ranging from archaeology to national security and causing muon imaging to become one of the fastest growing areas of applied physics research. This review focuses upon the key developments in the field that have brought it to this point, from the first application in 1955 to present day research. A limited number of key applications will also be discussed, focusing upon how muon imaging has developed within these contexts.

2 Background

2.1 History

Cosmic rays are a well-studied physical phenomenon, known to be produced by high energy nuclei (primarily protons and helium nuclei) incident upon the Earth's upper atmosphere producing showers of subatomic particles (Figure 1). These showers were first unknowingly detected at the beginning of the 20$^{\text{th}}$ century due to their tendency to ionise air and cause the spontaneous discharge of charged instruments. Initially, it was believed that these charges were due to nuclear decay of radioactive elements within the Earth, motivated by the relatively recent discovery of radioactivity by Henry Becquerel in 1896 [2]. Victor Hess later showed this hypothesis was not completely correct by demonstrating that while the electrical activity within air did fall with elevation close to sea level as expected, it in fact began to increase rapidly with ele-

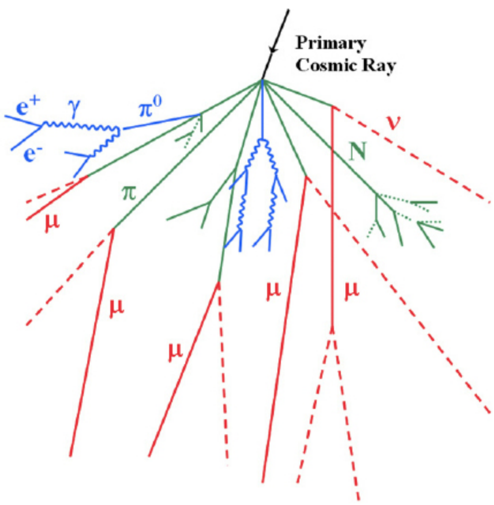

Figure 1: An illustration of the typical composition of a cosmic ray shower adapted from [1]. Separate particles are shown by separate colors and line styles as labelled. For ease of identification, all muons have been labelled.

vation at higher altitudes. Hess managed to rule out the Sun as the source of radiation through measurements during the 17th April 1912 eclipse over Europe, leading to the conclusion that the radiation source was 'a very high penetrating power [that] enters our atmosphere from above'. This discovery allowed the study of cosmic rays to begin in earnest throughout the start of the 20th century, and lead to the discovery of many particles such as the positron, the first experimentally confirmed anti-particle [3]. Among these particles was the muon, discovered in 1937 by Seth Neddermeyer and Carl Anderson when measuring the energy loss of cosmic ray particles incident upon a platinum plate [4]. These particles were found to be nearly identical to electrons, but with a mass that is approximately 200 times greater. This large mass causes the energy loss of muons when travelling through matter (via electron-muon scattering and Bremsstrahlung) to be low compared to other particles, particularly at the high energies at which cosmic ray muons are produced (roughly 6 GeV), hence allowing them to be extremely penetrating.

After this key discovery, all the underlying processes that allow muons to be used in imaging had been described: cosmic rays were known to be constantly producing high energy particle showers in the upper atmosphere, creating a constant flux of muons and anti-muons (in this context they are functionally identical) equal to approximately 1 muon cm^{-2}min^{-1} at sea level. Additionally, the mechanism through which these muons are scattered matter (Coulomb scattering) had been described in 1911 by Ernest Rutherford, while in 1932 Hans Bethe derived the relativistic Bethe-Bloch formula describing the energy loss of charged particles as they pass through matter.

2.2 Common Terms in Muon Imaging

Before discussing muon imaging, it is worth introducing some common terms in the field. The two main techniques used in muon imaging are muon transmission radiography (muon radiography) and muon scattering tomography (MST or muon tomography). Radiography is a term that describes techniques such as x-ray radiography which measure the attenuation (reduction in flux) of particles to produce a 2-dimensional projection of the internal structure of the target. Tomography is a term describing techniques that produce three-dimensional images by piecing together many lower dimensional measurements - a practice most commonly seen in CT (computerised tomography) scans and MRI scans. The details of how these two techniques are used in muon imaging are discussed further in section 3. In general, 'muography' is used as a general term to describe all techniques in the field of muon imaging.

3 Development

3.1 Muon Transmission Radiography

Despite the theory being known for some time, it took until 1955 for the properties of muons to be understood with enough confidence for them to be employed in the investigation of structures. The first application of the cosmic muon flux was performed by Eric P. George, who used a set of Geiger counters to measure the flux of muons both above and inside a mining tunnel in the Australian Snowy Mountains in order to estimate the density of matter overhead [5]. This investigation is often regarded as not being a true example of muon radiography, as the data gained from the cosmic muon flux was not able to produce an image of the target due to the low angular resolution of the detector used. However, the principles applied are very similar to those used in modern muography techniques, and this example demonstrates well that the main limitation at the time was technological, rather than one of understanding. In 1965, this technological hurdle was overcome through the production of a spark chamber which was able to digitally record each detected event in a manner that was far more efficient than the alternatives at the time, making muon detection more cost effective [6]. This led directly to one of the most well known uses of muography, when in 1970 a team lead by Luis W. Alvarez conducted an investigation within the Pyramid of Khafre (the second largest of the ancient pyramids of Giza) to search for hidden rooms [7]. In this investigation, two spark chambers were installed in a chamber at approximately the centre of the base of the pyramid, along with three scintillation counters (one above and two below the spark chambers) to act as detection triggers. These detectors allowed a region described by a cone with a half-angle of 35° to be imaged above the chamber in which they were situated, corresponding to 19% of the pyramid's volume. Directional data was collected for each muon detection event, allowing muon paths to be projected backwards to produce an 'x-ray photograph' of the pyramid's volume. The raw data of these detections initially suggested an unknown structure may be present to the north of the detectors due to an anomalously high absorption of muons in this region, however this region disappeared when corrections were made for the geometry of the detectors used and the known structure of the pyramid (such as corners and the limestone cap) as shown in Figure 2.

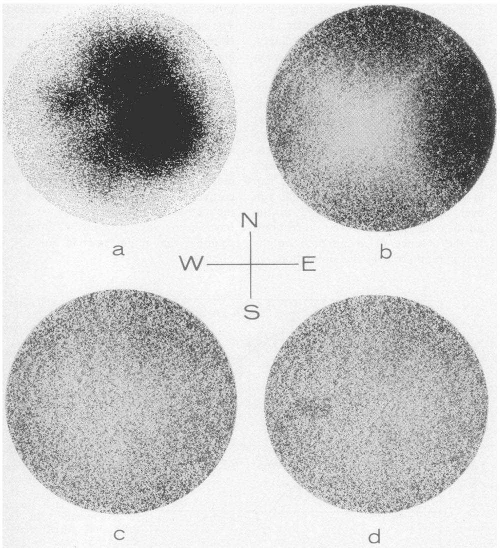

Figure 2: Scatter plots of muon detection produced in [7] showing stages of data correction: (a) Uncorrected data. (b) Data corrected for detector geometry. (c) Data corrected for the pyramid structure. (d) Corrected data containing a simulated chamber to the West

Further analysis confirmed that there was no hidden chamber present in the explored volume. This conclusion was made with a high degree of certainty, as the method was shown to be able to discern distinct details of the pyramid such as its corners and the limestone cap present at its summit. This acted as proof that muography could be used to image large structures with important historical value such as the pyramids of Giza, demonstrating the great potential of cosmic muons as an imaging tool. This investigation served as an excellent proof of concept for the method, motivating further developments to be pursued. Despite this, the development of muography was relatively slow during this time, taking a further 9 years from 1970 for a new paper to be published in the field. This paper was an investigation by L. Malmqvist et al into using muons to identify high density rock formations at various depths [8], building upon the work of E.P. George and helping to show the relevancy of muography to the geological sciences. This paper demonstrated that muon radiography was possible up to depths of roughly 700m, despite the greatly decreased muon flux at this level. This was only possible with greatly increased time of measurement - for example a measurement at 740m would take roughly 11 days to gather enough data for analysis.

The next major development for muon radiography was the use of cosmic muons travelling horizontally to image structures, as proposed by K. Nagamine et al. in 1995 [9]. Muons travelling at this angle allow the application of muon imaging in areas where it is not feasible to place a detector underneath the target, opening up the possibility of muography being used in various new contexts such as volcanology, nuclear reactor imaging and industrial applications. The feasibility of this method was demonstrated via measurement of the horizontal muon flux through Mount Tsukuba in Japan, displaying the possibility for this form of muography to be used in predictions of volcanic eruptions. A key limitation of this method comes from the angular distribution of the muon flux.

As shown in Figure 3, muon flux decreases approximately as a function of $\cos^2\theta_z$, where θ_z is the zenith angle measured from the vertical [10]. This causes horizontal muons (those travelling with a zenith angle of approximately 90) to have a very low flux. For this reason, muography using the horizontal cosmic flux requires the use of either greater exposure time, larger detectors or a combination of the two. In the case of [9], measurements using a set of 4 detectors each with an area of 1.6m^2 took 33 days. In order to improve on this, the authors propose using a detector with 12$\times$ greater detection area which could theoretically produce images in roughly 3 days, though the feasibility of this system is not clear.

This technique was developed further by the authors throughout the following years. In 2001 a measurement was made of Mount Asama (an active volcano in Japan), showing promising results as the inner density of the crater was shown clearly in the resulting images [11]. In 2003, the system was updated to allow for longer term measurements and more reliable elimination of background events (such as electrons or high energy photons which may be picked up by the detectors) [12]. Further development of this these techniques has continued since 2003, and this is further discussed in section 4.

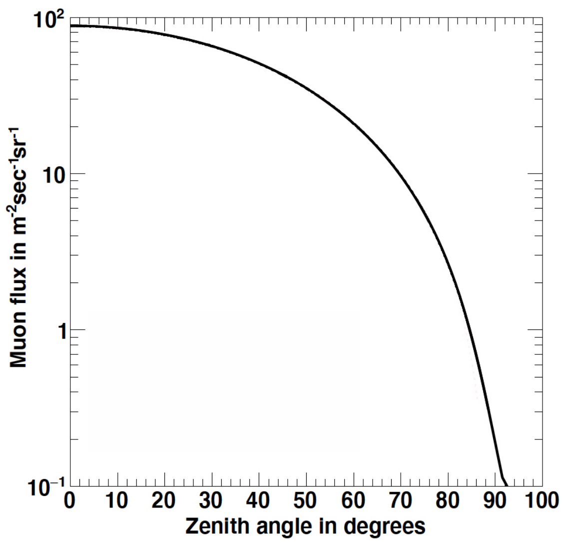

Figure 3: Approximate distribution of the cosmic muon flux with zenith angle, adapted from [10]

3.2 Muon Scattering Tomography

2003 marks one of the most significant developments in muon imaging techniques with the proposal of the method of muon scattering tomography by Borozdin et al. [13] [14]. This technique is markedly different from all previous muon imaging techniques, as the source of information is the multiple Coulomb scattering that muons undergo within a substance, rather than their attenuation. In applications before this proposal such as [7], this effect had been a notable cause of uncertainty. The effect of many coulomb scattering events upon muons in a given material has an approximately Gaussian distribution with respect to scattering angle θ, with a mean of zero and a standard deviation σ_θ given by Equation 1. An illustration of this scattering is shown in Figure 4 - note these angles are exaggerated, and θ is often far lower than shown on this diagram.

$$\sigma_\theta = \frac{13.6}{\beta cp}\sqrt{\frac{L}{L_0}}\left[1 + 0.038\ln\left(\frac{L}{L_0}\right)\right] \tag{1}$$

Here, p is the momentum, βc is the velocity relative to the speed of light (≈ 1 for cosmic muons), L is the length of material traversed by the muon and L_0 is the radiation length of the material which decreases with the materials atomic number (Z). This distribution allows image reconstruction algorithms to infer the probable paths of muons through the material and then correlate the points which show high scattering with areas of high density in the material, hence allowing areas of high nuclear density to be contrast with areas of low nuclear density. A notable limitation of this method comes from the effect of muon attenuation: as high energy muons are attenuated better by materials with high-Z, this reduces the muon flux in these areas hence making imaging more challenging in settings with large amounts of higher Z materials.

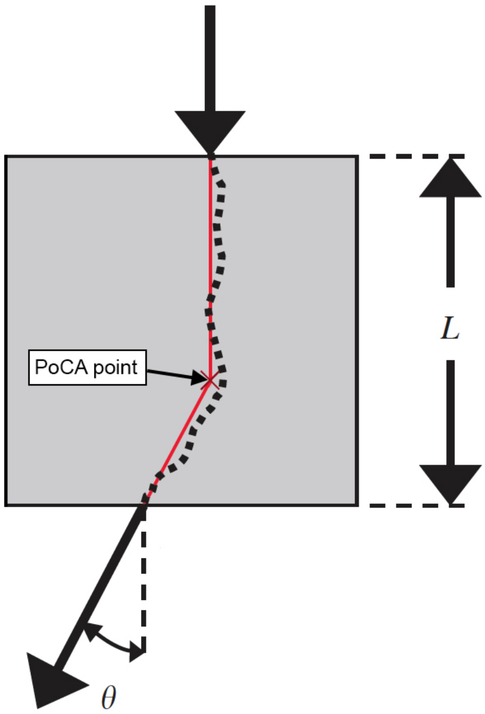

Figure 4: Illustration of muon scattering with exaggerated angles adapted from [14]. The true muon path is shown as a dashed line, while the PoCA path and scattering point used in reconstruction algorithms based upon the PoCA algorithm are shown in red.

As muon scattering occurs in three dimensions, muon tomography is capable of producing three-dimensional images of its target. This feature greatly increased the number of potential applications for the field, with the most prominent being the detection of nuclear contraband. Due to this, activity in the field of muography saw a great rise after the proposal of this new method as its applications began to be realised and its methods improved upon. After its initial proposal, a main focus for the development of MST was the reconstruction algorithm. Under optimal conditions, reconstruction is one of the main bottlenecks in the process of MST, and as the applications of MST are often time-sensitive this was a clear area to focus upon. Borozdin et al. [13] proposed three algorithms, the most successful being the point of closest approach (PoCA), and maximum likelihood scattering and displacement (MLSD) algorithms. PoCA is quick to execute and capable of producing satisfactory results but lacks precision, while MLSD acquires more accurate images but is more computationally expensive to execute [15]. These algorithms have been the basis for most new reconstruction algorithms since.

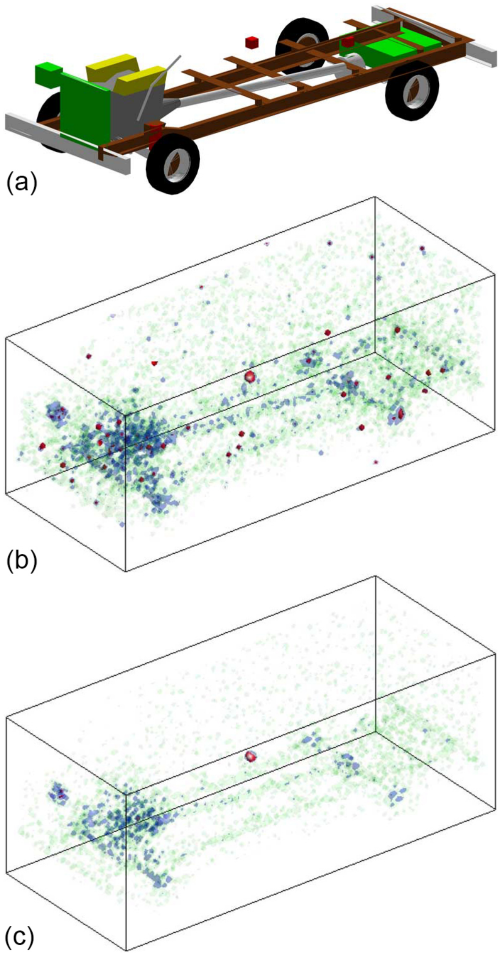

Figure 5: A demonstration of the ML/EM algorithm via Monte Carlo simulation produced in [16]. (a) shows the target structure with a high-Z object shown in red. (b) Shows the reconstruction using the mean method. (c) Shows the reconstruction using the median method.

In 2007, Schultz et al. produced the maximum likelihood/expectation maximisation (ML/EM or MLEM), a highly successful algorithm based upon MLSD which uses an expectation maximisation algorithm to calculate the maximum likelihood in a more efficient way to MLSD [16]. This algorithm is capable of reproducing images far faster than its predecessors, taking just 1 minute to produce a satisfactory image of a passenger van containing anomalous high density objects in a Monte Carlo simulation (though this included the assumption that detectors were perfect, which is unlikely to be completely true). In the testing of this algorithm, a further limitation of the assumptions made of the muon flux was shown. As previously stated, the distribution of scattering angles may be approximated well by a Gaussian distribution, however this approximation is only valid for the central 98% of the distribution. The tails of the distribution are in fact much larger than the Gaussian model predicts, and hence can produce anomalous data points which may then be shown as false positives for high Z material. This can be accounted for via use of median values where means would otherwise be used which are less affected by the distribution tails. This effect is demonstrated in Figure 5.

Additional algorithms have been developed using the principles of the PoCA algorithm. One of the most successful of these uses the path of muons generated by PoCA (shown in red on Figure 4), but only analyses those muons which scatter in similar regions to others. This greatly reduces the processing time required for the algorithm, while sacrificing only a small amount of accuracy [17]. Further research continues into developing additional algorithms to this day, with new bespoke algorithms being made as new applications are explored. More recently, research has begun into applying machine learning to this problem, which has great potential to quickly analyse detections to produce images with reduced noise [18]. The main problem with this approach is the scarcity of data which may be used to train the neural networks, as the vertical muon flux is particularly low, though this problem may be solved simply through the use of sophisticated Monte Carlo simulations which allow large amounts of data to be generated with ease. The use of Monte Carlo simulations in this field has been commonplace since its introduction as a way of testing the feasibility of proposed methods [14], with the GEANT4 framework developed by CERN being the industry standard for this [19]. While the use of simulated data does come with implications about introducing biases to the training of models used due to the assumptions made when creating the Monte Carlo model, this effect is likely to be negligible due to the depth with which the underlying physics is understood. While the application of machine learning to the problem of tomographic reconstruction is a promising one, it has yet to become commonplace.

The other main focus for the development of MST since its proposal has been the production of novel detectors. The development of this area of muography has been less linear than the development of reconstruction algorithms, as detectors have in general been purpose built for their specific applications rather than for general use. Each of these applications have different constraints upon detector size, reconstruction time and image quality and therefore require more specialised approaches. For this reason, the relevant developments in detectors will be discussed while reviewing the various applications of muography in the following section.

4 Applications

As previously mentioned, muographic techniques have applications in a very many disciplines. Figure 6 summarises many of these applications.

ranging from inspection of archaeological structures [20] [21] to the monitoring of sequestered

CO_2 [22] - a visualisation of some of the main applications of the field is shown in Figure 6.

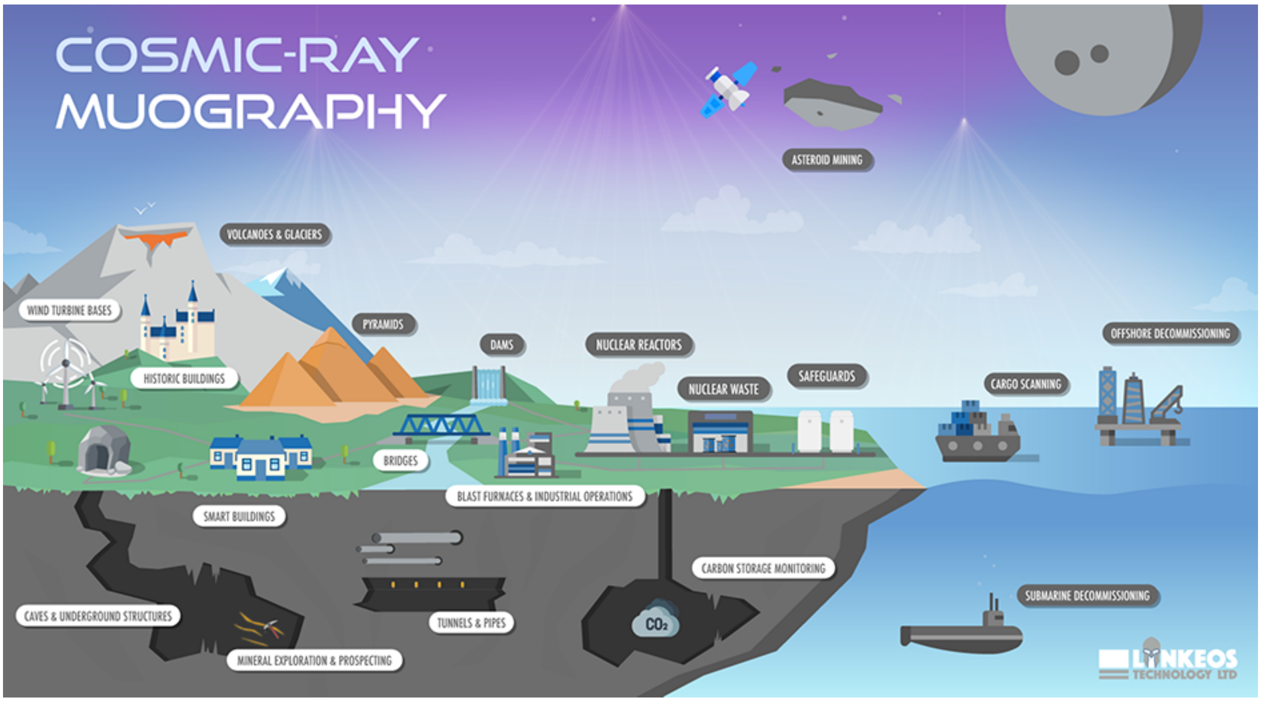

Figure 6: An infographic produced by Lynkeos Technology Ltd. [23] showcasing key applications of muon imaging techniques.

It would be beyond the scope of this review to discuss all of these applications in detail, so instead two key applications will be focused upon: the imaging and detection of nuclear material and the imaging of volcanoes. These areas make up a large proportion of the research in the field of muography and have both been strong drivers of development for each of the techniques discussed in sections 3.1 and 3.2.

4.1 Nuclear Material Detection

The detection of high-Z nuclear material has been a prominent focus for the field of muography since the proposal of MST in 2003. This technique was initially designed by researchers at Los Alamos National Laboratory (LANL) specifically with the purpose of detecting hidden nuclear material in ports and at borders, aiming to replace current techniques which utilise x-ray radiography [13]. This is motivated mainly by two inherent advantages of using cosmic muons for imaging when compared to x-rays: firstly, muons are far more penetrating than x-rays, meaning muon scans cannot be shielded by thicknesses of lead or similar materials as x-rays can. Secondly, cosmic muons are a natural source of background radiation and hence pose no extra risk to people in and around the scanning area.

Since 2003, this project has continued to develop, along with similar projects from other groups such as the Italian National Institute for Astrophysics (INAF). Research at LANL has been focused upon developing reconstruction algorithms (discussed in subsection 3.2, and on harnessing new characteristics of the muon flux. In 2014, an investigation into utilising the horizontal muon flux to perform muon tomography was undertaken [24] with similar conclusions to previous investigations of the horizontal flux [9]. Imaging of a hollow lead ball of inner radius 2.5cm and outer radius 10cm took 8 times longer when using the horizontal muon flux than when the vertical muon flux was utilised in [25]. This is a severe limitation in the application of nuclear material imaging, as the time scales required for the technique to be commercially viable are around 1 minute. Additional investigations have been undertaken into using nuclear reactions involving muons which occur in high-Z nuclei [26] as an information source. Muons can interact with nuclear material to produce neutrons which will then go on to produce a chain of fission reactions in fissile materials such as uranium-235, thus creating a detectable shower of neutrons. The detection of neutrons can hence be correlated with the presence of nuclear material such as uranium-235, as long as the background flux of neutrons (mostly produced via cosmic rays and background nuclear decays) is accounted for. This technique was shown to be viable, producing a reliable detection of nuclear material within one hour and producing a reliable image of the objects shape within tens of hours. Additionally, data was taken using both of the other methods of muography and the results were presented together. This provides a good demonstration both of the effectiveness of this new technique and also of the other techniques and is presented in Figure 7. While these time scales are not feasible for imaging at borders, the authors propose that this method may have applications in treaty verification. The ability to provide information on whether an object contains material without giving away its exact geometry could potentially be used to ensure warheads are free of nuclear material without exposing their designs. This application is however quite highly specialised, and further development has not yet occurred since the publication of this paper.

Research into nuclear material identification has also occurred at the INAF, where the Muon Portal project was based. This project was focused upon creating a full scale (6m $\times$ 3m $\times$ 3m)

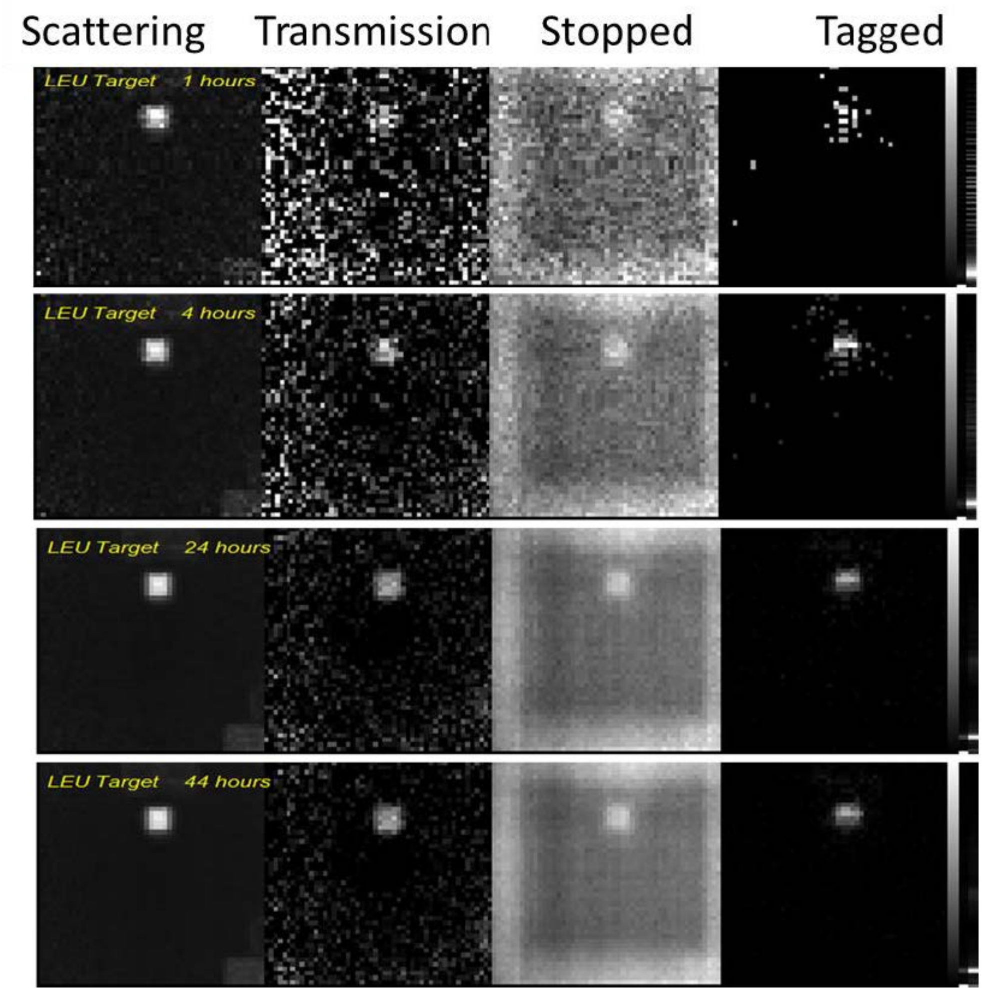

Figure 7: The results of the investigation into use of muon capture data from [26]. Scattering refers to MST, transmission to muon radiography, stopped to muon capture events, and tagged to a combination of stopped and transmission data. The target was a 19kg cube of low enriched uranium.

tomographic detector for the investigation of cargo containers in ports, motivated by regulations on US imports and other international security concerns [27]. The design of the detector began in 2013, in which the detector design and corresponding GEANT4 simulation were presented [28]. Further investigation was then undertaken into reconstruction algorithms, determining that the PoCA algorithm was the only viable choice for this application despite its various shortcomings, agreeing with previous literature [29]. Specific research was also undertaken into the detector design, concluding that plastic scintillator strips connected to silicon photomultipliers were the best option when attempting to balance cost, efficiency, simplicity and reliability of detection [30]. In 2018 the project was brought together to present a full detector and results [31], demonstrating imaging was possible though with some limitations. The main point identified for improvement here was the efficiency of detection, as the large number of lost data points causes the time required for a scan to be far higher than is theoretically possible. Research is ongoing to improve the detector and methods of data analysis, with the most recent development being a successful attempt to incorporate forms of multiparametric analysis to improve upon the PoCA algorithm's efficiency [32].

Muography may additionally be used to image high-Z material within nuclear reactors, most notably being applied within the Fukushima Daiichi reactor after the disaster in 2011. Two prominent investigations have occurred: one led by researchers at LANL which utilised muon tomography to image Unit 2 of the reactor [33], and another by a Japanese collaboration primarily composed of researchers from the High Energy Accelerator Research Organisation (KEK) which applied muon radiography to Unit 1 of the reactor [34]. The different approaches were justified via GEANT4 simulations in the case of LANL and via testing upon active nuclear power plants in the case of KEK [35]. Additionally, the relative expertise of each team may have played a role here, as LANL and KEK researchers have each played significant roles in the development of muon tomography and radiography respectively. Each investigation found that this environment posed its own set of challenges for the application of muography. Muography was chosen to image these sites partly due to its long range, which allows detectors to be placed far from the reactor cores thus minimising the harmful radiation does. Despite this, there is still a large excess of background radiation present around these sites which is picked up by the detectors adding both noise and possible bias to the results. To account for this, each investigation included radiation shields: 6cm of steel for LANL's investigation and 5cm of iron for KEK's - the difference being due to the relative distance of the detectors from the cores and the varying radiation levels in each of the reactor units. From these investigations, reliable images have been produced of the fuel distribution within each of the reactors hence helping with the radiation management process. This process can further be applied to the monitoring of nuclear waste, albeit in a much more controlled environment. Nuclear waste is stored within sealed containers along with radiation shielding materials such as concrete to reduce the emission of harmful radiation. However, this makes it extremely challenging to analyse its composition via conventional methods. Muon tomography has been shown to provide an excellent insight to this problem [36] and has recently been applied in power plants in the UK after development of a commercial detector [37].

4.2 Volcanology

As seen in subsection 3.1, a key application of muography is volcanology. Here, muon radiography is used here to measure the internal density distribution of a volcano, allowing their inner structure to be visualised. These techniques have been used by many groups across the world for the visualisation of several volcanoes. Researchers in Japan have been at the forefront of developing these methods, producing the first muon images of a volcanic crater [11] and the first muon images of internal volcanic structure in 2007 [39]. This group went on to produce and the first three dimensional images using muon radiography in 2010 through combination of data from two detectors [38]. The results of this investigation are shown in Figure 8.

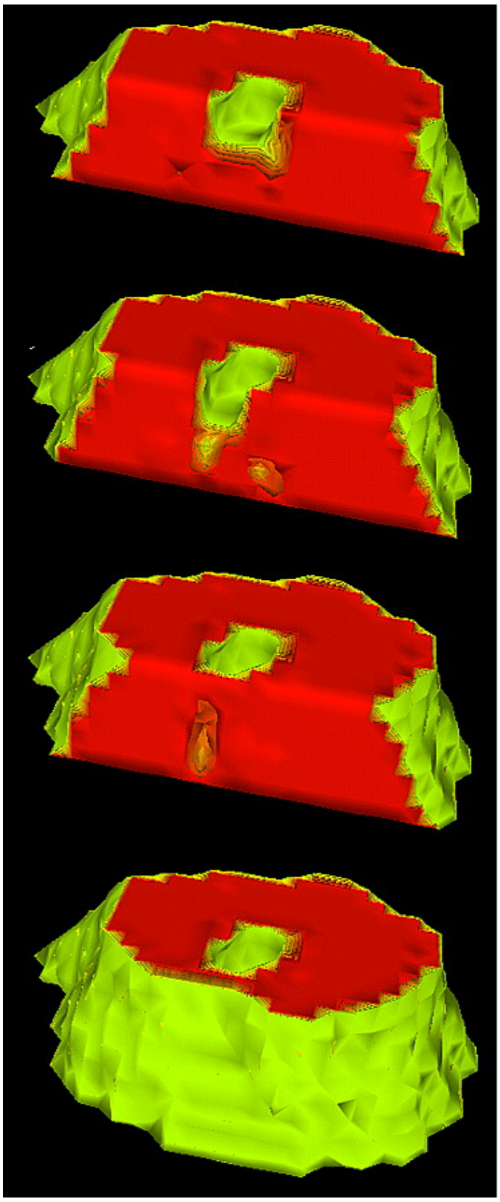

Figure 8: The results of the investigation by Tanaka et al. in 2010 to produce a 3-dimensional image of [38]. The figure has been modified slightly for clarity though results are unchanged

Additionally, this group produced the first measurements of the dynamics of an eruption in 2014 through continuous radiographic measurement [40] - an investigation which has been particularly influential in establishing muography in the field of volcanology. Imaging the internal dynamics of an eruption provides valuable data for eruption prediction and is almost impossible to obtain via other methods due to the hazardous conditions of an eruption, making these measurements particularly valuable. More recent investigations have attempted to use this data to train neural networks to predict eruptions, with promising results [41].

Other research groups across the world have focused upon imaging specific volcanoes, with the most prominent groups being the MURAVES, TOMUVOL and DIAPHANE collaborations. The MURAVES project is an Italian collaboration and successor to the MURAY project [42], aiming to produce images of Mount Vesuvius using a 3m^2 detector [43]. The French TOMUVOL collaboration targets the inactive Puy de Dôme volcano in central France as a case study to compare muography to other established methods [44]. DIAPHANE is a similar French collaboration mainly focusing upon studying the active La Grande Soufrière volcano in Guadeloupe, though the project has also aided in further muographic investigations of other volcanoes and non-geological targets [45]. Key results from these groups are focused largely upon comparing muon radiography with other established methods, particularly gravimetry, as well as additional developments in detector design. Comparisons with common techniques note that muography allows for long term passive measurements, but is easily biased by background radiation [46]. This particular study concludes that muon tomography could be used as a complimentary method to gravimetry to provide more accurate data - an approach that has very recently been attempted by the TOMUVOL collaboration [47] with positive results.

The focus of detector design in volcanology is quite different from the focus seen in the imaging of nuclear material and highlights well the differences in these applications. Volcanological muography often requires placing a detector in inaccessible regions with harsh conditions, hence a large amount of work goes into ensuring the detectors can be robust and self sustaining. These detectors aim to consume very little power, require little to no maintenance and be as portable as possible - considerations that are less critical for detectors that aim to be used in ports as is the case with nuclear imaging. For this reason, plastic scintillator detectors are preferred as they have low dependency upon temperature, low cost and low power consumption [48]. In contrast, nuclear imaging applications tend to favour the use of drift chambers due to their high efficiency and resolution, though MST scanners have also been built using other types of detector. Resistive plate detectors are also used by the TOMUVOL group despite their strict temperature requirements, though this is likely reflective of the milder conditions of the inactive Puy de Dôme volcano compared to other volanic targets.

Additional muographic groups continue to be founded in the field of volcanology as muon radiography continues to show its benefits. The Italian MEV project began testing a detector for investigation of Mount Etna in 2017 [49], and even more recently the Colombian MuTe project has developed a detector containing Cherenkov radiation sensors to allow for easier background discrimination [50]. The variety of groups and investigations demonstrates the excitement in the field of volcanology for this new technique, and the promising results already presented show that muography is likely to become commonplace in this field.

4.3 Future Developments

Current trends in research suggest two main focuses for development will be detector technology and reconstruction algorithms. Portable detectors would greatly increase the potential of muon radiography for applications such as volcanology and archaeology, where the sites being imaged are often reasonably inaccessible. This would also increase the ease with which commercial radiography could be deployed by companies such as Lynkeos Industries Ltd. [23] and Decision Sciences [51]. In this case, this financial incentive may further motivate this area of development. Reconstruction algorithms mainly see their application in the area of the detection of nuclear material - an application sees a large amount of government interest and therefore funding due to its relevancy to nuclear non-proliferation. An interesting possibility is the application of muography in the exploration of Mars, as proposed in 2013 by researchers at NASA. As muography requires little to no power, it is a promising candidate for a geological probe on a Mars rover [52]. Despite this, muon tomography on other planets has yet to be realised, mainly due to the size and delicacy of current detector technology.

5 Conclusion

Muography is now a well established research technique in many fields, becoming commonplace in some of its key applications such as volcanology. Despite the underlying theory being known since 1955, it took a long time for the interest in the field to develop to a level comparable to today, with most of the notable developments occurring in the past 20-25 years. Much of the recent interest was generated by the introduction of muon scattering tomography in 2003, which has been one of the most significant developments for the field. Since then, interest in muography has become widespread - so much so that muography now sees commercial applications, with companies across the globe offering muographical services to the wider public. The success of these companies demonstrates that demand is present for these techniques providing another source of motivation for further research.

This success is further indicative of the

Overall, muography is currently approaching maturity, however there is still room for improvement in several areas, including portability of detectors and reconstruction algorithms. Research will certainly continue into these techniques, however the most interesting developments in future years are likely to come from the application of muography to new areas, such as astronomy.

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