The COSMICS (Container Scanning by Muon-based Imaging using Cosmic rayS) Project; an introduction and preliminary results.

1st Sarah Barnes
Institute for the Protection of Maritime Infrastructures
Deutsches Zentrum für Luft- und Raumfahrt
Bremerhaven, Germany
sarah.barnes@dlr.de

2nd Maurice Stephan
Institute for the Protection of Maritime Infrastructures
Deutsches Zentrum für Luft- und Raumfahrt
Bremerhaven, Germany
maurice.stephan@dlr.de

3rd Frank Sill Torres
Institute for the Protection of Maritime Infrastructures
Deutsches Zentrum für Luft- und Raumfahrt
Bremerhaven, Germany
frank.silltorres@dlr.de

4th Arto Niemi
Institute for the Protection of Maritime Infrastructures
Deutsches Zentrum für Luft- und Raumfahrt
Bremerhaven, Germany
arto.niemi@dlr.de

5th Alexander Gabriel
Institute for the Protection of Maritime Infrastructures
Deutsches Zentrum für Luft- und Raumfahrt
Bremerhaven, Germany
alexander.gabriel@dlr.de

6th Carl Wrede
Institute for the Protection of Maritime Infrastructures
Deutsches Zentrum für Luft- und Raumfahrt
Bremerhaven, Germany
carl.wrede@dlr.de

7th Nicola Wendt
Institute for the Protection of Maritime Infrastructures
Deutsches Zentrum für Luft- und Raumfahrt
Bremerhaven, Germany
nicola.wendt@dlr.de

8th Verena Nickel
Institute for the Protection of Maritime Infrastructures
Deutsches Zentrum für Luft- und Raumfahrt
Bremerhaven, Germany
verena.nickel@dlr.de

***Abstract*—Muon tomography represents a new and promising imaging technique, making use of ambient high-energy cosmic ray muons to generate images of three-dimensional volumes. The technique predominantly combines measurements of the Coulomb scattering of muons with sophisticated analysis methods to estimate the composition of objects and their distribution within an unknown volume. The COSMICS project will use this technique to design a passive tomographic system capable of detecting the presence of high atomic mass materials within a shipping container. The initial physics simulation studies are presented in this work. Consideration is also given to the ethical and legal concerns associated with the development of such a system and the impact on low- and middle-income countries (LMIC). Initial studies into potential risk scenarios relating to the trade of illicit and counterfeit goods have been undertaken, and a data-driven pre-screening concept is outlined.**

***Index Terms*—muon tomography, maritime safety and security**

I. INTRODUCTION

The international shipping industry constitutes a critical element in the global supply chain. With its more than 50,000 merchant ships [1] transporting about 90% of internationally traded goods [2], the industry forms a network that sustains economic growth but also infrastructure, food and livelihood security on an global level. Yet, especially in the wake of post-9/11 securitization, seaborne cargo containers have increasingly been considered a potential threat to national security. As possible carriers of illicit and hazardous commodities, ranging from drugs and weapons to radioactively contaminated consumer goods or so called “dirty bombs”, an increasing number of port and container security measures have been introduced over the past decades [3]. The standard technology used for container monitoring is based on X-ray radiography, which despite its enormous success comes with limitations, such as the inability for X-rays to penetrate dense objects, difficulties in reconstructing 3D structures and the risk to health due to radiation exposure.

Muon tomography is a novel imaging technique, which makes use of ambient high-energy cosmic ray muons to generate images of macroscopic three dimensional volumes [4]. The technique is particularly sensitive to the discrimination between high and low atomic mass materials, making it well suited to aid in the detection of threatening high atomic mass materials along with any shielding materials present. An inspection system based on muon tomography has been suggested [4] as an inexpensive, harmless and effective alternative, capable of reliably detecting the presence of threatening materials within a large volume.

This paper will present preliminary results and aims of the Container Scanning by Muon-based Imaging using Cosmic rayS (COSMICS) project. COSMICS will use the principles of muon tomography to simulate and produce a conceptual design report for a low-cost tomographic system capable of detecting the presence of high atomic mass materials within a shipping container. The sensitivity of the system to other lower atomic mass contraband items will also be assessed. The key motivation for this work is to increase safety and security in ports by providing a safer alternative to X-ray scanning systems, which can rapidly assess the contents of a shipping container, particularly with respect to any shielded nuclear materials which may be present.

System requirements necessary for use in a realistic port scenario will be derived through discussion with stakeholders and taken into consideration for the conceptual design. Potential risk scenarios will be comprehensively researched, to allow a thorough understanding of potential target materials. Container screening concepts will also be investigated in order to assess how results from a muon tomography scanner may be deployed to improve the safety and security of a port. Finally, the potential impact on low- and middle-income countries (LMIC) following a future market introduction of such a system, particularly regarding the ability of such countries to access the world market, will be studied.

Section II will discuss the theoretical groundwork. Section III will introduce a preliminary muon tracking simulation developed using the GEANT4 [5] framework. A description of muon trajectory reconstruction and analysis algorithms as well as material classification algorithms will then be described in Section IV. Preliminary technical results will be presented in Section V followed by a discussion of risk scenarios and cargo screening concepts in Section VI. An introduction to future studies to assess the potential impact of the technology for LMIC will be given in Section VII. Finally, the conclusions and outlook for this work will be given in Section VIII.

II. THEORY

Cosmic rays are charged subatomic particles accelerated to high energies by astrophysical sources. Primary cosmic rays, predominantly protons, interact with the Earth's atmosphere to produce extensive air showers of secondary particles. Muons produced within these air showers have a spectrum covering a wide range of energies and angles. Generally, the spectrum can be described by a parameterisation proposed by Gaisser [6] modified to correctly treat muons incident at large zenith angles, muon decay in the atmosphere and the fraction of prompt muons [7]. At sea level the average muon energy and flux are 4 GeV and 0.0167 $\text{cm}^{-2}\text{s}^{-1}$ respectively, with a flux proportional to $\cos^2\theta$ where θ is the zenith angle.

Muon tomography is based on the interaction of atmospheric cosmic ray muons with a material via multiple Coulomb scattering, which causes a deviation in the path of the muon according to a Gaussian distribution with rms width

$$\theta_0 = \frac{13.6\text{MeV}}{\beta c\rho} z\sqrt{x/X_0}[1 + 0.038\ln x/X_0], \tag{1}$$

where βc is the relatavistic muon velocity, c is the speed of light, ρ is the muon momentum in MeV/c, z is the charge of the incoming muon and x/X_0 is the thickness of the scattering medium measured in radiation lengths [1] (X_0) [8]. From Equation (1) it is evident that the rms of the muon path deviaion increases with increasing density of the scattering medium, allowing material density to be deduced through the measurement and analysis of θ_0. One limitation is the inability to distinguish between a large volume of low density material and a small volume of high density material. In order to solve these kinds of ambiguities it is possible to consider both the 3-dimensional shape of the reconstructed object and also rarer processes occuring within the volume. Rare processes include stopped muons which occur as a result of total energy loss and muon capture [9]. Both processes increase in likelihood with increased material density allowing for an additional method by which material density can be estimated.

III. SIMULATION

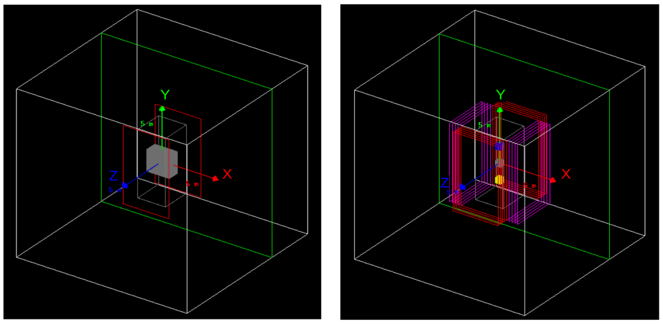
A preliminary simulation environment was set up using GEANT4 v10.5 p-01 with the "Shielding" physics list. GEANT4 is used to simulate the passage of particles through matter using the Monte-Carlo method [5]. All relevant processes are included in the framework; the geometry and materials within the system, the generation of initial particles and the physics processes which occur during particle interactions.

Two main geometries were considered for this work; a simple geometry and complex geometry. The simple geometry, visualised in Figure 1(a), consists of a 15m^2 'world' volume filled with air containing single upper and lower ideal detector planes (7m x 4m) modeled as a 1mm thick vacuum, shipping container walls (2.44m x 6.1m x 2.59m) modeled as 4mm thick steel and a target block of lead of size 2m x 2m x 1m, centered at the origin. The complex geometry presented in Figure 1(b) is similar to the simple geometry, however contains 5 layers of upper, lower and lateral ideal detector planes, separated by 25cm, allowing the possibility for multiple positional measurements to be made to simulate particle tracking and study the impact of detector resolution. This configuration was selected based on prior optimisation studies described in [10]. Target materials are defined as 0.5m^3 blocks of water, concrete and lead centered at (0, -1.5m, 0), the origin and (0, 1.5m, 0) respectively, with the coordinate system defined in Figure 1. Lead was chosen to represent a high density material since it is commonly used as shielding for radioactive materials. Concrete and water were chosen to

---

[1] $X_0 = 716.4\text{gcm}^{-2}\frac{\text{A}}{\text{Z(Z+1)ln}\frac{287}{\sqrt{2}}}$, where Z is the atomic number and A is the mass number of the nucleus.

test the discrimination ability through the inclusion of common medium and low density materials.



(a)

(b)

Fig. 1. GEANT4 simulation geometries. (a) represents a simple geometry and (b) complex geometry. In both cases the white box represents the world volume corresponding to the limit of the simulation, the red/pink volumes represent the detector plates, the green plane represents a measurement plane for verification of muon spectra, the central blue/yellow/grey solid volumes represent target materials of water/concrete/lead, finally the shipping container walls are represented by the hollow grey rectangle.

The initial muon distribution is simulated using a modified Gaisser parameterisation [7], interfaced to GEANT4. The energy range was defined as between 100 MeV and 100 GeV, with incident angles between $-\pi$ and π rad where the zenith is located at $\theta = 0$ rad. Simulated muons originate from a 10m^2 plane positioned above the highest detector plane. Muons are propagated along the z-axis as defined in Figure 1, with measurements of muon momentum, energy, direction and position made in the measurement plane and at each detector plane. For the simple geometry all muons entering through the top detector and exiting the bottom detector are considered for analysis as a fast and simple first step. For the complex geometry all muons entering through at least three top detector layers and exiting through at least three layers of either the lateral or lower detector planes are considered, this represents a more realistic scenario.

IV. MUON RECONSTRUCTION, ANALYSIS AND MATERIAL CLASSIFICATION

A. Reconstruction algorithms

In order to reconstruct target materials which represent container contents, both the magnitude and location of muon interaction within the volume must be deduced. Two algorithms are considered for this; the Point of Closest Approach (PoCA) algorithm [11] and the Maximum Likelihood algorithm [12].

The PoCA algorithm is a simple heuristic algorithm, assuming a single point of scatter for each muon. Assuming the incoming and outgoing muon tracks can be measured, it is possible to extrapolate each track to their point of closest approach. The scatter point is then defined to be the midpoint between the extrapolated tracks. The steps for the algorithm are given below, the full mathematical description can be found in [11].

1 Split the container volume into N voxels, along the x, y and z axes
2 Establish initial position and direction for each incoming and outgoing muon track (i=1 to i=M, where M is the number of muons)
3 Calculate PoCA
4 Calculate the scattering
5 Add the scatter angle to the corresponding voxel within which the PoCA lies
6 Calculate the average angle of scatter for that voxel
7 For each value of M repeat steps 3-6

The maximum likelihood algorithm is a statistical method which attempts to predict the most likely distribution of scatter per voxel, based on the iterative minimisation of a log likelihood function given by

$$\log\left(P(H|\lambda)\right) = \sum_{j \leq N} \sum_{i : L_{ij} \neq 0} \left(-\log \lambda_j - \frac{H_{ij}^T A_{ij}^{-1} H_{ij}}{2 \lambda_j p_{r,i}^2} \right), \tag{2}$$

where, λ_j is the scattering density (λ) of the j^{th} voxel, H_{ij} is the ”hidden” data (H) which should be reconstructed for the i^{th} muon and j^{th} voxel, A_{ij} is the covariance weighting for the i^{th} muon and j^{th} voxel, L_{ij} is the path length of the i^{th} muon through the j^{th} voxel and $p_{r,i}^2$ is the square of $(4 \text{ GeV})/p$ where p is the momentum of muon i and 4 GeV is the average muon energy at sea level.

Compared with the PoCA algorithm, the maximum liekihood is significantly more complex and computationally intense, though promises to provide a more accurate reconstruction of container contents and therefore better overall resolution for the scanner. The key steps are summarised below, with a full description given in [12]

1 Measure the angle of scatter and momentum for each muon
2 Estimate the amount of interaction between each muon and each voxel
3 Calculate a weight matrix for each muon-voxel pair based on step 2
4 Initialise scattering density for each voxel
5 Update scattering density estimation corresponding to the iterative minimisation of the log likelihood function
6 Repeat step 5 until convergence of the algorithm

B. Classification Algorithm

In order to identify the nature of the reconstructed container contents a classical topological clustering algorithm [13] is utilized. This algorithm clusters together neighboring voxels based on the principle that the signal in that cell is significant compared with the background noise threshold T_0. Seed voxels are first selected, defined by the ratio of average scatter in that voxel $\langle S \rangle_{vox}$ to the average scatter of the volume $\langle S \rangle_{vol}$, such that $\langle S \rangle_{vox} / \langle S \rangle_{vol} \geq T_1$, where T_1 is a user defined threshold, in this case based on target material properties. Neighbors with

$\langle S \rangle_{vox} \geq T_1/2$ are then added to the cluster. If the number of neighbors added is less than T_2, the seed voxel is removed, where T_2 is defined to be a statistically insignificant number. Next-neighbors are then added with criteria $\langle S \rangle_{vox} \geq T_1/4$, followed by next-next-neighbors with threshold $\langle S \rangle_{vox} \geq T_0$. Once individual clusters are defined, those which overlap are merged. The size of the remaining clusters are then calculated in the geometrical x, y and z directions based on the number voxels. Also, the average scattering density $\langle S \rangle_{cluster}$ for the cluster is calculated. The size of the cluster gives an approximation of the size of the reconstructed object, and the average scatter density indicates the material density. Through use of a look-up-table the approximate composition of the reconstructed material can be inferred, allowing an operator to determine if the cluster is of interest.

V. PRELIMINARY RESULTS

The validity of the PoCA algorithm was tested by propagating five million muons at sea level, corresponding to a scanning time of five minutes, through the complex simulation geometry as described in Section III. Five minutes was chosen as a realistic upper limit on the available scanning time based on preliminary discussions with industry experts. Voxels are considered for analysis only when the number of PoCA entries ≥ 4 and $\langle S \rangle \geq$ 17mrad (approx 1°) within that voxel. This threshold was chosen to allow clear identification of the target objects, as shown in Figure 2. Further optimization is required to tailor the applied selection criteria to a specific material density or contraband item.

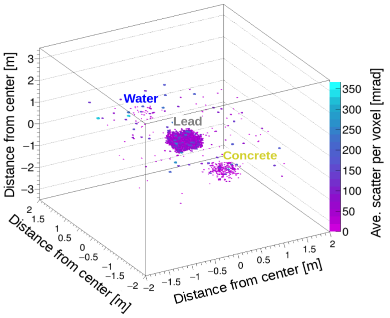


Fig. 2. Results of PoCA reconstruction for complex simulation geometry. The 3D figure represents the container volume. Three test objects (labeled as water, concrete and lead) are clearly distinguishable over the background.

The results displayed in Figure 2, are provided as input to the classification algorithm, which is configured to search for high density materials, in this case parameters are set such that $T_1 = 200$ and $T_0 = 0$. The results following clustering are visualised in Figure 3(a). The clustering algorithm identifies a single central lead block of size 55 x 55 x 50cm, which is accurate to within 5cm of the simulated target size. The measured average angle of scatter of 80.6 mrad is also consistent with previous measurements for a 50 cm^3 block of lead when considering the full muon spectra at sea level [10].

Figure 3(b) shows results when attempting to classify a 1m^3 block of lead, analysed with identical reconstruction and classification setups as for the 50cm^3 block. In this case, though the calculated average scatter density per voxel is similar, the algorithm does not perform as well since three individual clusters are identified within the block. A possible reason for this is the use of too few additional next-neighbors when constructing initial clusters. Further work and optimization is therefore required in order to ensure the robustness of the clustering algorithm for all object sizes and densities.

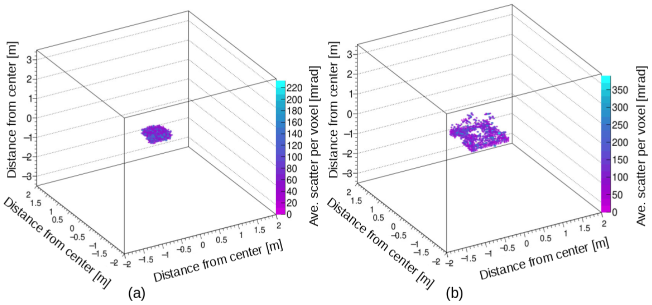


Fig. 3. Results from the clustering algorithm for (a) a 50cm^3 block of lead, and (b) a 1m^3 block of lead. The 3D figure represents the container volume.

Due to the complexity of the maximum likelihood algorithm, the simple simulation geometry was utilized for validation. Also, due to limited availability of computing resources a sample of only 2000 muons was used and a maximum of seven minimization iterations performed. Figure 4(a) shows a reconstruction of the scatter density after one iteration, the initial muon trajectories through the volume can be seen. Figure 4(b) shows the evolution of the scatter density after seven minimization iterations. It is shown that the algorithm begins to converge on the location of the target block, however more statistics and iterations are required in order to achieve an accurate reconstruction of the container contents. A dedicated computing server is now available which will make additional testing, validation and optimization of the maximum likelihood algorithm possible.

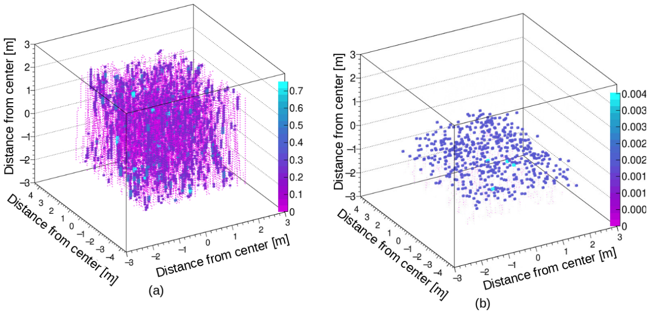


Fig. 4. Results of maximum likelihood reconstruction for simple simulation geometry after (a) one minimization iteration and (b) seven minimization iterations. The color bar shows the relative value of the average scatter per voxel.

VI. RISK SCENARIOS AND SCREENING CONCEPT

A. Risk scenarios

Illicit trade deals with goods such as narcotics, arms, persons (human trafficking), counterfeit tobacco, consumer goods or medicine, and endangered wildlife species [14]. Of these, the narcotics market is the largest. It contains also the so-called ”precursor chemicals” that are used in the manufacturing of narcotics. Licit goods can also be traded illicitly [15]. In these cases, the criminal modus operandi can be wrongful valuation or wrongful declaration of the tariff code to avoid taxes. Also, the country of destination, origin, or the consignee can be falsified to avoid an embargo or other trade restrictions.

A considerable threat is caused by wrongly declared hazardous goods [16]. Without a proper declaration, the potential risk of fire or explosion is not taken into consideration when the container is handled. A container can also be used as a means of attack by hiding a bomb inside it. Report [17] estimates that this is the easiest way to attack a ship. Since muon tomography is proven to be effective at detecting high atomic mass materials, it is interesting to estimate the minimum amount of material to cause a threat. For a nuclear weapon, this depends on the sophistication of manufacturing and ranges from 2 to 50 kg [18]. In the case of a ”dirty bomb”, even a hundred grams of gamma-emitting radioactive material used for radiotherapy can severely contaminate a few square kilometers [19].

B. Data-driven pre-screening

Today, only a small portion of containers are scanned, since scanning all containers would require a significant investment in facilities. Increasing the odds of detecting illicit trade or threats requires intelligent selection procedures to decide which containers to scan. This selection is done based on data available relating to a container. Potential sources of the data are the custom declarations and the required cargo declaration for the inbound ship.

The methods used for selecting containers to be scanned are classified as this knowledge could help criminals avoid detection. Therefore, only a few published articles exist. Hintsa et al. [15] describe the concept employed by a method used by Transport Security Administration (TSA) in 2008. The calculated risk index is based on over 20 inputs such as the shipper, receiver and country of origin. Currently, the number of inputs used for risk estimations is significantly higher [20]. The Automated Targeting System (ATS) has access to dozens of databases, some of which include sensitive information such as criminal records and biometrics.

The solution for the Belgian customs, however, uses only custom declarations and a machine learning method trained with a supervised learning approach [21]. The paper claims that if only 1% of the containers can be checked, the method can determine the correct containers to check with 65% accuracy. The paper also compares different types of methods to detect these containers. The issue with supervised learning is that it uses data on known cases to detect fraud. Unsupervised learning can be used for detecting anomalies. Based on literature these techniques seem to be less efficient, but incorporating them would allow the detection method to evolve with criminal behavior and identify potential new types of noncompliance. Another option is to use the so-called knowledge-based rules approach, where rules on which container is scanned are based on statistics and expert knowledge. In this application, knowledge-based rules approaches are challenged by the high number of distinct values like the commodity codes, which are used in international shipments for declaring the traded goods. Criminals further try to adapt their behavior to avoid detection, which requires recurring updates to the rules. This makes the system burdensome to maintain.

It is unlikely that a single method could perform well in all situations. Fig. 5 shows a concept where the decision to scan a container can be based on detection by different methods. The system performs random inspections to evaluate the performance of different methods and to collect new training data. A decision to scan a container can also be based on external intelligence. The implementation of this concept will be considered within the COSMICS project following the procurement of suitable input data.

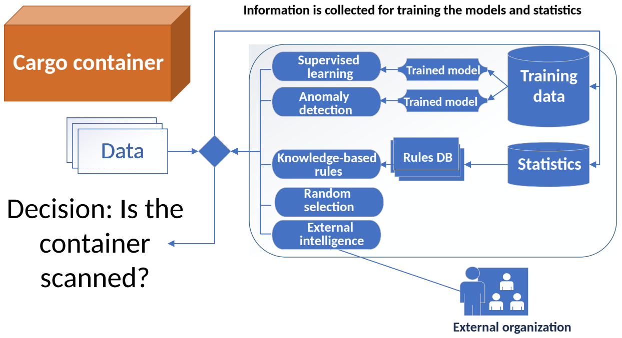


Fig. 5. Conceptual illustration of a system to choose the scanned containers.

VII. RESPONSIBLE TECHNOLOGY TRANSFER – TRANSFORMATION AND DISRUPTION OF CONTAINER PORT SECURITY PRACTICES

In 2007, the U.S. Congress passed a law requiring all seaborne containers to be scanned for radioactive material and other contraband prior to being loaded aboard any ship bound for the United States [22]. The Department of Homeland Security (DHS) was mandated with the implementation of this approach by 2018 under which U.S. Customs and Border Protection collaborate with the Customs Services of the respective country to screen containerised cargo on-site [22]. It has been widely discussed whether externally imposed security measures such as this U.S. Container Security Initiative affect the competitiveness of foreign ports. For instance, in the European [23] or South Asian [24] context, such measures have been claimed to raise local compliance costs while reducing operational efficiency. As novel scanning technologies emerge, such as passive muon tomography scanners, further questions regarding the implications of increasing standardized specification of security requirements paralleled by ever-evolving technological progress come to the fore.

Within the framework of the COSMICS project and against this backdrop of evolving international container security regulations, the potential impact of passive cosmic-ray tomography-based imaging systems' market introduction shall be examined. Focusing particularly on possible implications for LMICs, effects on the countries' access to the world market shall be explored; as shall be the opportunities and methods to circumvent unintended consequences. In this context, it shall for instance be discussed how novel technologies can be better adapted to local conditions in order to facilitate success and purposeful technology transfer in line with international guidelines, e.g. the United Nations Sustainable Development Goals. These aspects of responsible technology transfer shall further be addressed through overarching theoretical considerations regarding the research community's responsibility to evaluate, anticipate and address potential unintended consequences for LMIC following the market introduction of innovative technologies.

VIII. CONCLUSIONS AND OUTLOOK

The concept of the COSMICS project has been outlined and preliminary studies undertaken in all key areas.

From a technical perspective, a simulation and analysis framework has been set-up and tested in initial scenarios. This provides the framework for studying the capabilities of muon tomography based scanning systems. First results confirm the ability of the PoCA algorithm to successfully reconstruct container contents. Classification algorithms have been implemented and are able to successfully identify clusters of high density materials, however work is still needed to improve the robustness of the algorithm for all target sizes and compositions. The maximum likelihood reconstruction method also shows promise, though additional computing resources are required to fully test and validate the implementation. The next steps are the further refinement of the algorithms introduced in this paper, followed by testing with, and the study of complex container scenarios.

Potential risk scenarios relating to the trade of illicit and counterfeit goods have been studied, and a data-driven prescreening concept has been outlined. Challenges relate to the availability of required data due to security classification and lack of electronic data formats. The next-steps lie in obtaining relevant data and using this to enhance the pre-screening concept.

Finally a study into the impact of the market introduction of a muon tomograhy scanner for LMICs has been introduced. Future studies will highlight any potentially negative consequences for such countries, and address the responsibility of the research community to fully assess and negate them.

The final aim of the COSMICS project is the production of a conceptual design report for a low-cost scanning system which improves upon standard X-ray technology in certain key areas. Muon scanners have the potential to revolutionize port scanning technology due to an inherent lack of risk to human and animal health and the potential to provide a faster, relatively inexpensive scanning platform.

REFERENCES

[1] United Nations Conference on Trade and Development Handbook of Statistics, "Maritime Transport – Merchent Fleet." https://stats.unctad.org/handbook/index.html, accessed 30/06/2021 (2020)

[2] International Chamber of Shipping, "Shipping Fact – Shipping and World Trade: World Seaborne Trade." https://www.ics-shipping.org/shipping-fact/shipping-and-world-trade-world-seaborne-trade/, accessed 30/06/2021 (2021)

[3] Ireland, R., "The customs supply chain security paradigm and 9/11: ten years on and beyond", WCO Research Paper, (18), 9 (2011)

[4] K. Borozdin et.al., "Radiographic imaging with cosmic-ray muons," Nature volume 422, page277 (2003)

[5] S. Agostinelli et.al., "GEANT4–a simulation toolkit," Nucl. Instrum. Methods A, Volume 506, Issue 3, pp. 250-303 (2003)

[6] T. K. Gaisser, "Cosmic Rays and Partcle Physics". Cambridge University Press (1991)

[7] V. A. Kudryavtsev, "Muon simulations for LBNE using MUSIC and MUSUN," Computer Physics Communications, Volume 180, Issue 3, March, Pages 339-346 (2009)

[8] G. R. Lynch and O. I. Dahl, "Approximations to multiple Coulomb scattering", Nucl. Instrum. Methods B, vol. 58, no. 1, pp. 6 – 10 (1991)

[9] D. Measday, "The nuclear physics of muon capture," Physics Reports, vol. 354, no. 4–5, pp. 243 – 409 (2001)

[10] T. Blackwell, "The use of Cosmic-Rays in Detecting Illicit Nuclear Materials", PhD Thesis, The University of Sheffield (2015)

[11] L. J. Schultz, "Cosmic ray muon radiography". PhD thesis, Portland State University, (2003)

[12] L. J. Schultz et al., "Statistical Reconstruction for Cosmic Ray Muon Tomography". IEEE Transactions on Image Processing, Vol. 16, No. 8 (2007)

[13] The ATLAS Collaboration, "Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1," Eur. Phys. J. C77 (2017) 490

[14] OECD, "Governance Frameworks to Counter Illicit Trade", Paris, OECD Publishing (2018).

[15] J. Hintsa, T. Männistö, L. Urciuoli, and J. Ahokas, "Customs perspectives on detection of deliberate regulatory violations in global supply chains - the role of information and data in risk identification", Proceedings of Inland Transport Security Discussion Forum OSCE & UNECE, pp. 55 – 72 (2013)

[16] Hapag-Lloyd,"The watchdog that detects explosives", Hapag-Lloyd Lookout, number 4/2015. Hapag-Lloyd (2015)

[17] M. D. Greenberg, P. Chalk, H. H. Willis, I. Khilko, and D. S. Ortiz. "Maritime Terrorism: Risk and Liability", chapter 7, RAND Corporation, pp. 111–132 (2006)

[18] Union of Concerned Scientists, "Preventing nuclear terrorism - Fact sheet" (2004).

[19] J. Medalia."Dirty Bombs: Technical Background, Attack Prevention and Response, Issues for Congress", Congressional Research Service (2011).

[20] J. R. Cantor. "Privacy Impact Assessment Update for the Automated Targeting System", DHS/CBP/PIA-006(e). U.S. Department of Homeland Security (2017)

[21] J. Vanhoeyveld, D. Martens, and B. Peeters. "Customs fraud detection", Pattern Analysis and Applications, 23:1457 – 1477 (2020)

[22] Congressional Budget Office (2016/18), "Scanning and Imaging Shipping Containers Overseas: Costs and Alternatives", https://www.cbo.gov/publication/51478, accessed 30/06/2021 (2021)

[23] Zhang, X, "The United States container security initiative and European Union container seaport competition", Doctoral dissertation, University of Plymouth (2018)

[24] Sakhuja, V., "Container Security Initiatives: A South Asian Perspective. In *The Security of Sea Lanes of Communication in the Indian Ocean Region*", pp. 196-209, Routledge (2016)