Technical Report

Latest Developments in Tomographic Research of Underground and Large Structures with Muographic Expertise, TRUST-ME

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Abstract

The TRUST-ME project aims at validating a new application of MUon Survey Tomography based on Micromegas detector for Unreachable Sites Technology (MUST^2) to address a societal challenge of increasing importance: sustainable water management. This muon tracker, conceived and developed by the *Laboratoire souterrain à bas bruit* (LSBB), relies on a Micromegas readout plane with a thin time projection chamber (TPC). A network of new generation muon trackers is being deployed to both survey groundwater in aquifers near the LSBB and enhance the safety and operational efficiency of large structures, such as dams. The resulting compact, high field-of-view detector is able to operate in harsh environments with challenging access and operational conditions. MUST^2 is currently being deployed on a double dam system to both characterize the detector and monitor the building and its surroundings. In parallel, the combined use of photogrammetry and LIDAR is tested coupled with muography for the modeling of mid-sized targets. This publication details the upgrade of the MUST^2 technology, with its new and improved features. It presents the experimental configuration of the detector in a dam monitoring context, and an example of LIDAR and photogrammetry support for muographic analyses.

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1. INTRODUCTION

As the world's population increases, access to freshwater becomes a global societal challenge. Underground reservoirs play an important role in the storage of water, as an estimated 20% of the world's population relies on groundwater from karstic reservoirs [1]. Even though they have reached the end of their expected lifespan, 85% of dams are still in use, especially in developed countries, lowering their performance, increasing the costs of maintenance, and the risk of dam failure [2]. Sustainable groundwater management, close infrastructure monitoring, and technological innovation are key to addressing the growing needs linked to water resources.

In this context, a rising technique based on the measurement of naturally occurring cosmic rays, muography [3], might contribute to mapping inner density heterogeneities. The TRUST-ME project presents muon tomography as a tool to complement the existing well-established techniques for the survey of underground water and the monitoring of large hydraulic structures [4, 5].

2. EVOLUTION OF THE MUST^2 DETECTOR

Intended for geophysical applications, the muon tracker requires a wide acquisition field of view, a high sampling frequency and records each event time while being compact and portable, suited for confined spaces or underground operation. The lack of a technological solution combining all these requirements at the time motivated the design of a new detector. The technology used in the project is an updated version of the MUST^2 muon tracker, a bulk-Micromegas-based detector with a thin time projection chamber [6]. The potential for industrial applications of the project motivated its protection with a patent since 2015.

The former version of the detectors used the Scalable Readout System (SRS) APV25 front-end hybrid acquisition cards, able to record single events during 675 ns with a 25 ns time resolution and a maximum sampling rate of 7 kHz [7]. The digital gain of the cards is also fixed, making its performance variable depending on each track capacity. APV25 does not allow *in situ* data filtering, which requires the use of large bandwidth and consequent storage space. APV25s are analog hybrids, and the digitalization takes place in the Front-End Concentrator (FEC); hence, the quality of the transmitted data depends strongly on the cable length (limited to 25 m). The triggering of the detector requires an external pulse, done via two external scintillators in coincidence, which provides a robust trigger signal but adds cost, volume, and complexity to the setup [8]. Furthermore, different standalone devices cannot share a common clock, complicating multidevice reconstruction due to the different time drifts between detectors.

To reduce the aforementioned limitations, the muon tracker acquisition system has been updated with SRS VMM 3A hybrids [9]. Each hybrid can process a total of 128 acquisition tracks with a time resolution of 1 ns and a higher rate capability of 3.6 MHz.

This enhances the accuracy of track reconstruction, and particularly reduces the incertitude of the calculated zenithal coordinates; hence, improving the angular resolution of the detector. However, the effect on acquisition efficiency is negligible. They feature an adjustable gain and allow the automatic suppression of below-threshold data during acquisition, resulting in a better signal-to-noise (S/N) ratio and more efficient data management. The data are now digitalized in situ by the hybrids, improving the data pipeline and extending the deployment range. VMM also allows self-triggering; external scintillators are now optional. With this configuration, up to 8 VMM hybrids can be connected to a DVM, corresponding to the $512X$ and $512Y$ channels on a MUST^2 detector. This major update, summarized in Table 1, allows the synchronization of several FECs on the same network with a single acquisition system and enables 4D tomography.

Characteristics	Previous version (APV 25)	TRUST-ME version	
Time resolution	25 ns	1 ns	Improved angular resolution
Adjustable amplification gain	No	Yes	Programmable, better signal/noise
Automatic zero-suppression	No	Yes	Less data traffic, improved storage
Self-triggering	No	Yes	Simplified setup
Gain compensation	No	Yes	Constant performance
Maximum sampling frequency	7 kHz	4 MHz	High-rate measures
Networked detectors	No	Yes	4D tomography possible

TABLE 1: Comparison between 2015 and current MUST^2 detectors.

The new system currently being tested at LSBB measures $60 \times 70 \times 10\,\text{cm}^3$ without the peripherals (seen in Figure 1), weighs $\sim$20 kg, and has a wide field of view ($\sim$170° zenith and 360° azimuth, represented in Figure 2) and has a $512 \times 512\,\text{mm}^2$ sensitive area. Coupled with the gaseous detector and its front-end electronics, the system includes an inline close-circuit gas analyzer and filter, a high-voltage power supply, a deployable data acquisition system, and a network switch.

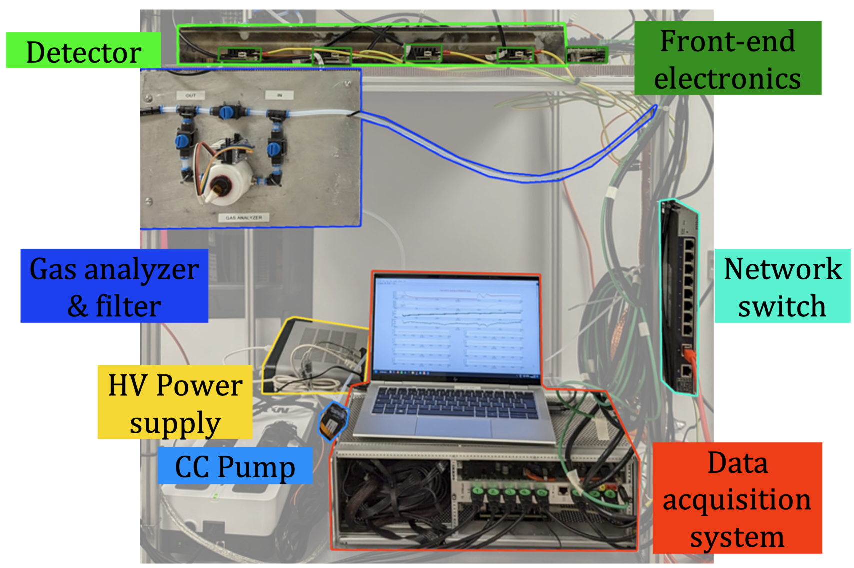

FIGURE 1: Image of the new version of the MUST^2 detector and peripherals.

The data acquisition software operates on both Linux and Windows OS but requires custom network configurations. This software has been developed by CERN's RD51 [10] for fundamental research purposes and adapted to the project applications. It contains a suite for data acquisition and real-time monitoring of the data, and slow control/automatic calibration software [11]. It allows real-time data analysis and electronics drift corrections.

3. MODELING TARGETS USING PHOTOGRAMMETRY COMBINED WITH LIDAR

A proof-of-concept test to apply muography to monitor water dams was carried out in 2017 in *Saint-Saturnin-lès-Apt* (France) [8]. The water reservoir, located above the village, is held by two dams: (i) the decommissioned one from 1763, usually drowned, and (ii) the one in service from 1855. This pilot site presents favorable characteristics due to the relatively well-known topology, dimensions, the stone and mortar double dam structure, and the possibility of simultaneously monitoring its geological framework. In addition, the valve cabin, beside the dam and below the ground level, provides an optimal location for the detector. Two digital models (DMs) were considered: one with the geology and infrastructures, based on 2006 plans, and another with water at the service level. The DMs were used to simulate the muon flux received by the detector depending on the water level. The modeling

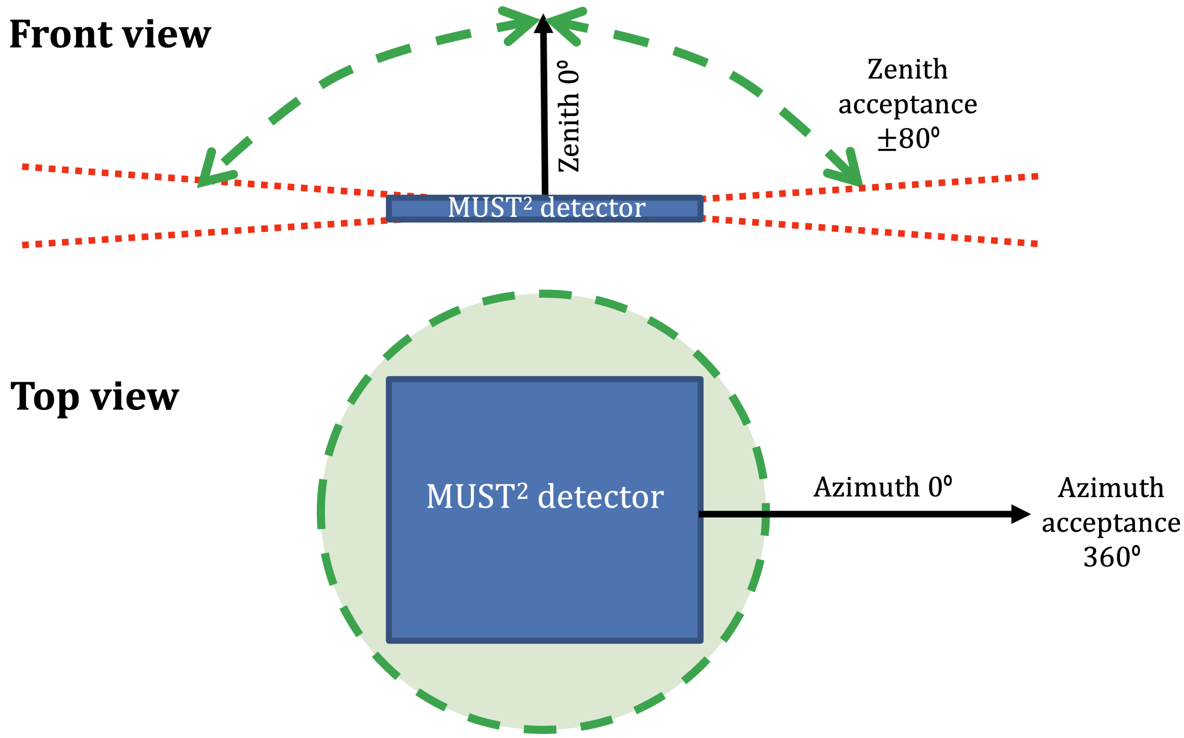

FIGURE 2: Diagram of the zenithal and azimuthal acceptance angles of MUST^2 detector.

of the geometry and material properties during simulations plays a key role in the accuracy of the results. The analysis of expected versus measured muon fluxes allows creating a map of apparent density.

This preliminary work was not meant to provide a detailed image of the dam, but these promising results motivated a dedicated study to confirm the applicability of muography for dynamic dam diagnosis. A complementary campaign was scheduled with the new detector reproducing the original conditions. However, the reservoir had to be manually emergency-emptied out in early 2023 due to the sudden appearance of water leaks in the downstream face of the dam [12].

We carried out an airborne photogrammetry campaign, leading to a 1 cm resolution model of the dams and emptied reservoir. In addition, the French National Geographic Institute (IGN) has provided high-definition LIDAR (10 points per m^2) data from 2021 for the area above the water level [13]. The photogrammetric data was used to cover the gaps of the IGN LIDAR dataset at the bottom of the reservoir, as well as to enhance the detail level of the structure. The inner parts of the structure were completed with handheld LIDAR measurements. This updated DM has been compared to the one based on 2006 data to assess the presence of sediments not considered during the modeling of 2017 (Figure 3).

Figure 3(A) shows a top view from the DM comparison. Colored dotted lines represent the isoheight, and their values correspond to the orthometric height in meters (labeled as Coord. Z in the leftmost color scale). The depth of sediments in meters has been calculated with CloudCompare as the difference in height between the DMs of 2006 and 2023 (labeled as C2M signed distance in the rightmost color scale) [14, 15]. The real capacity of the reservoir has gone from 11,000,m^3 (nominal capacity in 2006) to 9,735 m^3 (calculated from the photogrammetry model in 2023), a storage loss of over 12% in 17 years.

Figure 3(B) shows the cross section of the dam, where the deposit of sediments reached over 2.5 m above the drain intake, causing its blockage. The location of the detector and its lower field-of-view (FOV) limit are also displayed in the image. The detector monitors muons coming through different media: rock, sediment, dam, and open sky. The events are acquired simultaneously and discriminated by their region of origin. By comparing the data in the direction of the dam against open sky, the effect of natural muon flux fluctuations can be minimized and enhances the identification of dynamic changes within the dam.

4. CONCLUSION

In the context of climate change and sustainable water management, the TRUST-ME project aims to test in field conditions and validate the MUST^2 technology for groundwater and large infrastructure monitoring. The updated version of the detector has improvements in transportability, detection efficiency, data processing, and network capability that enables scattering or 4D tomography. The MUST^2 detector can be built on large-scale production and deployed in confined environments.

Parallel to these developments, LIDAR combined with photogrammetry can be used to enhance the performance of muography when applied to the characterization of mid-sized volumes with heterogenous compositions or complex shapes.

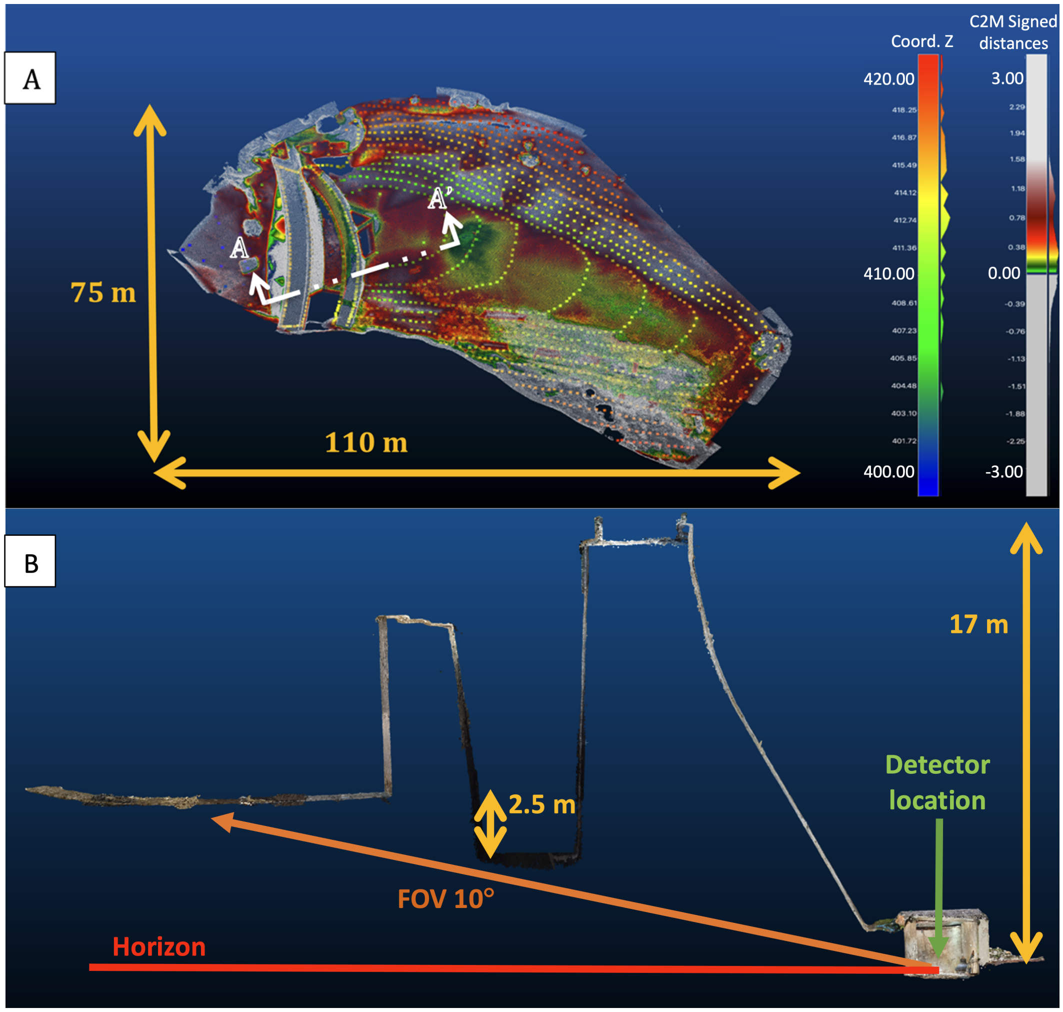

FIGURE 3: Model of the *Saint-Saturnin-lès-Apt* dam system, (A) top view and (B) detail of section A-A' with the location and field of view of the detector.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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