# A Decade of 3D Laser Scanning for Design Information Verification: Lessons Learned from Onkalo

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## Abstract

*Since 2014, 3D laser scanning has been utilized for Design Information Verification (DIV) activities at the Onkalo disposal facility for spent nuclear fuel in Finland. High-precision static laser scanners are used for initial verification of tunnel sections following excavation, with the 3D model being incrementally updated as construction progresses. Mobile laser scanning is subsequently used for re-verification, enabling efficient detection of changes in the tunnel's current status relative to the reference model acquired using static scanning. This paper presents a comprehensive overview of the past decade of DIV activities, outlining the generation of the final 3D model and discussing key results, implications, and recommendations for future applications.*

## 1 Introduction

Onkalo is a final disposal facility for spent nuclear fuel constructed deep into granite bedrock in Finland. Nuclear safeguards inspectors from the European Commission (DG-ENER) and the International Atomic Energy Agency (IAEA) periodically perform Basic Technical Characteristics (BTC) verifications, as termed by Euratom, or Design Information Verification (DIV), as termed by the IAEA. During these verifications, the inspectors confirm the design information provided by the operator, which primarily consists of a set of 2D CAD drawings, each covering a section of the underground tunnel. To verify the declarations, inspectors create an as-built 3D map of the disposal repository using 3D laser scanning techniques and compare it to the declared 2D drawings.

The use of 3D laser scanners allows for a quick and accurate way to map large and complex areas such as the Onkalo site, enabling inspectors to (1) visualize the "as-built" 3D maps and compare them with the design information declared by the operator, and (2) compare the maps against those from previous verifications to identify potential changes.

The verification activities are divided into several parts, including the verification of new excavations declared by the operator, the verification of the absence of undeclared changes in areas where no construction activities have taken place since the last time, and the update of the 3D reference model of the entire facility, which is crucial for ensuring the accuracy and completeness of the DIV/BTC.

The rest of this document is structured as follows: Section 2 briefly describes the Onkalo site, and Section 3 provides an overview of the scanning technologies used during the verifications. Section 4 details the scanning activities carried out over the years, whereas Section 5 explains the methods used for processing the scan data. Section 6 explains how the 3D map was used to verify the operator declarations, and finally, Section 7 draws conclusions.

## 2 The Onkalo site

The Onkalo disposal facility is a pioneering deep geological site located on Olkiluoto Island in southwest Finland, near the Olkiluoto Nuclear Power Plant in Eurajoki municipality. Developed and operated by Posiva Oy, the project is carried out under the framework of Finland's Nuclear Energy Act. It is currently under construction and is expected to be the world's first permanent geological repository for spent nuclear fuel and high-level radioactive waste of civil origin. The disposal facility extends to a depth of about 455 meters into granite bedrock, providing a safe and stable environment for the long-term storage of nuclear waste. Construction of the Onkalo repository began in June 2004, and it is designed to store approximately 6,500 tons of spent nuclear fuel from Finland's five nuclear reactors.

The Onkalo disposal facility is a complex site divided into five zones (TU1 to TU5), as illustrated in Figure 1, that consists of a spiral-shaped access tunnel, four vertical shafts, and various tunnels and technical rooms. It utilizes the KBS-3 disposal concept developed in collaboration with Sweden, which involves placing the spent fuel in copper canisters surrounded by bentonite clay to prevent leakage and contamination. The disposal facility also includes an above-ground encapsulation plant for preparing the spent fuel for disposal.

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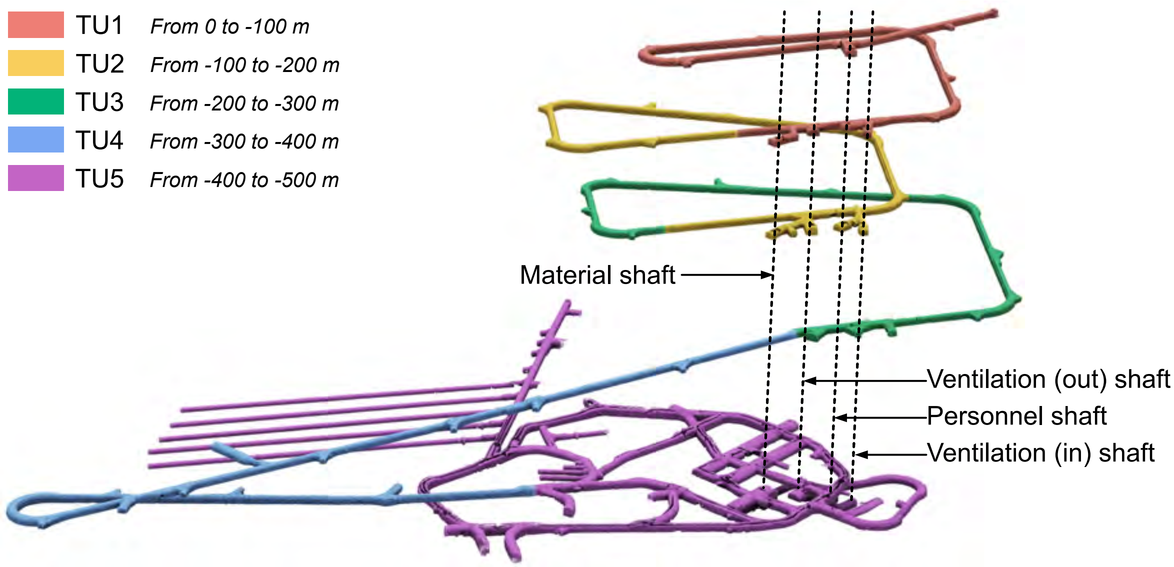


**Figure 1.** The Onkalo disposal facility as of the acquisition campaign of 2024, with the 5 different areas (TU1 to TU5) shaded with different colors and the four vertical shafts displayed as dotted lines.

This paper focuses exclusively on the underground facility, as data from the above-ground installations is classified and cannot be disclosed.

The site is designed to operate for an expected 100 years, with the start of operations scheduled for 2026. Currently, the disposal facility is in a trial run phase, demonstrating the disposal process with non-radioactive test elements.

## 3 3D laser scanning technologies

Two main 3D laser scanning technologies have been used for creating the reference model of the facility and for performing the DIV/BTC: static scanners and mobile scanners. Table 1 summarizes all the different laser scanners that have been used since the first proof-of-concept in 2007 to the latest verification in 2024, together with their main specifications.

The systems used by inspectors for 3D scanning has evolved over time, leading to more accurate instruments and more powerful processing software. The next two subsections outline the different scanners that have been used in the last decade and their main features.

### 3.1 Static scanners

Static scanners operate from fixed positions, typically mounted on tripods, providing highly detailed and accurate point clouds with a coverage close to 360 degrees. Single acquisitions take between one to five minutes and, depending on the environment, the spacing between two consecutive scans varies to ensure a proper overlap.

They have been used in two different setups over the years: car-mounted and tripod-mounted. In both cases, the scanning procedure has always consisted in a stop-and-go approach: the scanner remains static while scanning and, once finished, is moved to the next position. Depending on the areas of the facility, consecutive scan spacing ranged from 12 metres in the large access tunnels to 5 metres, or even less, in the narrow deposition tunnels or cluttered areas. This, combined with the acquisition time, makes the task time-consuming for such a large facility, rendering unfeasible to perform a full acquisition per verification due to time and resources limitations.

As detailed in Table 1, verifications over the years have relied in different models of commercial static scanners. Variations in sensor technology, point density, and proprietary output formats across devices can influence downstream data processing workflows and require careful harmonization to ensure consistency and comparability. Figure 2 shows some examples of the static scanner setups over the years.

### 3.2 Mobile scanner

Mobile scanners acquire data while in motion, either carried by an operator or mounted on a moving platform like a robot or vehicle. This allows for faster data collection at the expense of providing less detail and accuracy when compared to static scanning. The field of view and range of mobile scanners is also more reduced. However, since the acquisition is performed while moving the environment is observed from many different points of view and, consequently, the overall coverage of mobile acquisitions is more complete and with less occlusions than the static ones.

| | Z+F Imager 5003 | Z+F Imager 5006 | Faro Focus3D | Z+F Imager 5010 | Z+F Imager 5016 | HDL-32 | VLP-16 |
|---|---|---|---|---|---|---|---|
| Type | Static | Static | Static | Static | Static | Mobile | Mobile |
| First year used | 2007 | 2007 | 2014 | 2014 | 2020 | 2014 | 2019 |
| Last year used | 2007 | 2007 | 2019 | 2019 | 2024 | 2024 | 2024 |
| Laser class | 3R | 3R | 3R | 1 eye-safe | 1 eye-safe | 1 eye-safe | 1 eye-safe |
| Range (m) | 53.5 | 79 | 120 | 187.3 | 365 | 100 | 100 |
| Accuracy (mm) | 5 | 1 | 2 | 1 | 0.5 | 20 | 30 |
| FOV (VxH deg) | 310x360 | 310x360 | 305x360 | 320x360 | 320x360 | 30x360 | 20x360 |
| Speed (points/sec) | 500,000 | 1,016,727 | 976,000 | 1,016,727 | 1,100,000 | 700,000 | 350,000 |

**Table 1.** Different laser scanners used since 2007 to 2024 together with their main vendor specifications

To address the main issue related to static scanners, i.e. the long acquisition time, the JRC developed a dedicated mobile scanner for the Onkalo facility: the Mobile Laser Scanning Platform (MLSP). It is based on 3D SLAM (Simultaneous Localization and Mapping) technology: the laser scanner acquires several 3D scans per second; by aligning consecutive scans to each other, it is possible to build a 3D map as the sensor moves through the environment. In addition to the 3D map, SLAM generates the trajectory of the sensor, which allows to location-tag any auxiliary information collected during the acquisition. The MLSP operates in two modes: the Mapping mode is used to generate a 3D map of a previously unknown environment. In Tracking mode, the acquired data is aligned in-real time with a pre-loaded reference map; any geometrical changes with respect to the reference are highlighted to the user. One of the key benefits of the system is that it does not rely on global positioning sensors, so it can work in GPS-denied areas, like indoor or underground environments.

In the standard configuration, one or more laser sensors are mounted on a backpack and the data is acquired while the user walks through the environment. A 360 panoramic camera captures colour information which is geometrically and temporally aligned with the 3D data. An Inertial Measurement Unit (IMU) supports the data processing.

The earliest version of the MLSP was firstly used Onkalo during the 2014 verification in hybrid mode: it was mounted on the top of a car, together with a static scanner, to perform stop-and-go acquisitions. In this setup the mobile scanner was used only for tracking the motion of the car in between static scans. The goal was to ensure that a fixed spacing of eight metres between scans was satisfied. Figure 3 shows the system used during the verification.

The MLSP backpack was demonstrated during the 2014 verification. However, it was in the 2015 verification when the full system was firstly used to verify the absence of undeclared changes in the areas that were mapped the year before using static scanners. Both, in the 2015 and the 2017 verifications, the MLSP mounted a single Velodyne HDL-32E laser sensor, a high-definition lidar designed for 3D mapping and navigation applications. This compact and lightweight sensor uses 32 laser beams to create a 360-degree 3D point cloud of its surroundings, providing detailed and accurate data with a resolution of up to 700,000 points per second. With a range of up to 100 meters and an accuracy of ±2 cm, the HDL-32E is capable of capturing 3D data while moving at a speed of up to 10 point clouds/s.

Since the 2019 verification, the single-scanner MLSP system was gradually replaced by a dual-scanner one that mounted two Velodyne VLP-16 sensors at different angles. The main reason for such upgrade was related to the benefits of increasing the vertical field of view: by having a second sensor tilted vertically, the overall coverage of the system improves considerably as the floors and ceiling become visible at shorter ranges and with more perpendicular incidence angles. Unlike

**Figure 2.** Static scanner setups. (left) Z+F Imager 5003 mounted on top of a car during the 2007 proof-of-concept. (centre) Faro Focus3D mounted on a tripod during the 2014 verification. (right) Z+F Imager 5006 mounted on top of a car during the 2007 proof-of-concept.

**Figure 3.** Hybrid setup for the MLSP in the 2014 verification. (left) detail of the mobile laser mounting on top of the car. (right) full hybrid system used during the verification.


**Figure 4.** MLSP systems used for the verifications. (left) single-head backpack with one Velodyne HDL-32E laser sensor, demonstrated in the 2014 verification and used in the 2015 and 2017 verifications. (right) dual-head backpack with two Velodyne VLP-16 sensors configured in a tilted position, used from the 2019 verification.

the HDL-32E, the VLP-16 offers half of the laser beams (16 instead of 32) and half of the data rate (350,000 points per second instead of 700,000). Also, the vertical field of view of a single sensor is lower (20 degrees instead of 30). However, by mounting two sensors in the same system, the overall data rate and computational requirements remain unchanged while the coverage increases significantly, providing more complete and robust results. Figure 4 shows the two variants of the system used during the verifications.

## 4 Verifications

Since the first verification in 2014, nine joint verifications have been carried out in the Onkalo facility by DG ENER and IAEA. However, the first acquisition campaign dates back from 2007 when a proof-of-concept was performed. In July 2007, the length of the access tunnel was 2,194 metres, reaching a depth of 207 metres. Within the framework of collaboration between the JRC, European Commission's Research Centre and STUK, Finnish Radiation and Nuclear Safety Authority, it was decided to make a field trial of JRC's 3D Reconstruction and Verification laser technologies to accurately model the Onkalo tunnel. The exercise aimed at sharing information and practices concerning measurement equipment and methodologies including data processing and visualisation software. The full details of such campaign can be found in [1].

Over the coming verifications, the scanning strategy relied on stop-and-go static scanners for mapping newly excavated areas in order to ensure the global consistency and accuracy of the reference 3D model, see Figure 5. The mobile system was used for fast verification in previously mapped areas where no new excavations were declared. Static scanners were also used to perform random control scans in previously mapped areas. Table 2 summarizes all the verifications and the scanners used.

### 4.1 2014 Verification

In November 2014 the tunnel had a length of almost 5,000 metres, including technical facilities and demonstration tunnels. During this verification, four teams of two inspectors (one IAEA, one DG ENER) scanned during five days all TU1 to TU4 and the part that was already excavated of TU5. During this verification only static scanners were used (two Faro Focus3D and two Z+F Imager 5010) on both setups (tripod and car mounted). The mobile scanner was only used in a hybrid setup to ensure the spacing of the scans taken by the cars.

All data processing, i.e. 3D scan alignment and verification against the CAD designs, was carried out simultaneously from the offices and the inspector conclusions were taken at the end of the campaign. Data was kept in the facility under common IAEA and ENER seals.

| Year | New excavations | Static scan | Static scanner model | Scan count | MLSP | Comments |
|---|---|---|---|---|---|---|
| 2014 | 5,000m | YES | Focus3D - Z+F 5010 | 901 | YES | MLSP for spacing static scans |
| 2015 | ∼250m | YES | Focus3D - Z+F 5010 | 56 | YES | First use of MLSP for verification |
| 2017 | ∼500m | YES | Focus3D - Z+F 5010 | 165 | YES | - |
| 2019 | ∼500m | YES | Focus3D - Z+F 5016 | 200 | YES | First use of the MLSP dual head |
| 2020 | 350m | NO | - | - | YES | First time with only MLSP |
| 2021 | 800m | YES | Z+F 5016 | 84 | YES | - |
| 2022 | 0 | NO | - | - | NO | Visual inspection |
| 2023 | 1,600m | YES | Z+F 5016 | 278 | YES | New information security policy |
| 2024 | 0 | NO | - | - | YES | Full re-mapping |

**Table 2.** Summary of the verifications over the years

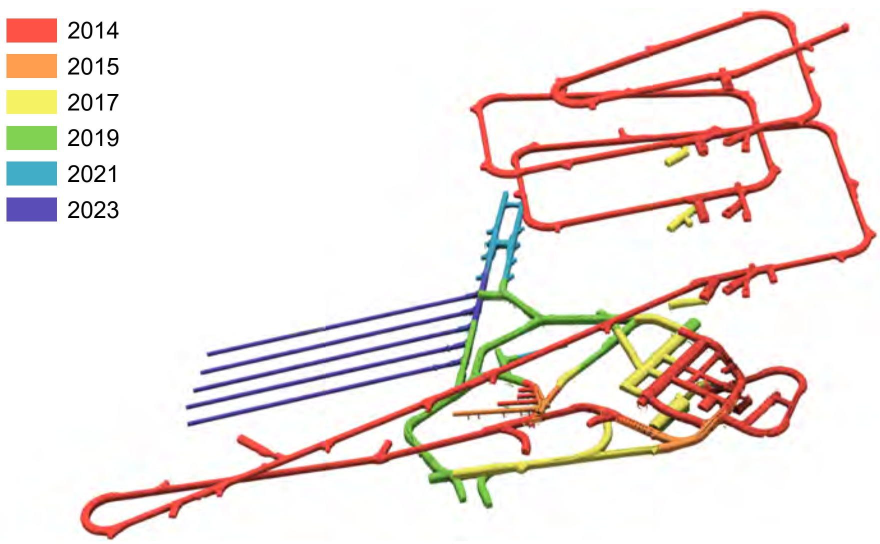


**Figure 5.** 3D reference model of Onkalo over the years. The shading of the tunnels corresponds with the year of the verification in which such areas where mapped with the static scanner.

### 4.2 2015 Verification

In November 2015, the Onkalo DIV was the first in-field use of the MLSP, which allowed to significantly reduce the effort for the activity with respect to the previous year. Both IAEA and Euratom inspectors were very satisfied with the performance and agreed to use the same approach for future DIV/BTC verifications in Onkalo. After the verification, IAEA started the process for approving MLSP for safeguards use.

The verification methodology consisted in using the MLSP in areas where no changes were declared since November 2014, combined with static scanners in a predefined number of random locations. For the new excavations, static scanners where used to extend the reference 3D model of the facility.

### 4.3 2017 Verification

Similarly to the previous verification, in July 2017 the MLSP was used to verify that no undeclared, safeguards-relevant changes were made in the areas that existed already in November 2015, together with 17 additional re-verification static scans. For the new excavations 148 static scans where acquired and incorporated to the reference model.

### 4.4 2019 Verification

The 2019 yearly verification included the verification of the Encapsulation Plant together with the verification of the vertical air-inlet shaft and the above-ground hoist buildings with the same technology as the tunnels. To increase performance during the verifications, two main changes were introduced: (1) a new MLSP backpack was used with a dual laser head that enabled for creating mobile blueprints that could be used in the verification process against the operator-declared CAD drawings. (2) The 3D processing software (3DLVS) was replaced with a newer one (STeAM Desktop), both developed by JRC, that allowed to align scans in a faster and more robust way and to combine mobile and static data. For the verification of the absence of undeclared changes the MLSP was used with six static scans. For TU5, 200 new scans were acquired.

### 4.5 2020 Verification

The verification of October 2020 was the first one in which the MLSP was the only scanner used: as the new excavation since 2019 were only about 350 metres, it was decided to postpone the static laser scanning to 2021. Mobile acquisitions were performed in the new areas to document the current state of the excavations and as a potential reference for future static scans. The absence of undeclared changes was verified with the MLSP and additional verifications of the inlet air shaft connections were performed: inspectors exited the lift at random levels and used the MLSP to localize themselves in the 2019 reference maps, thus verifying that the shaft connections corresponded to the expected locations.

### 4.6 2021 Verification

For the verification of October 2021, approximately 800m of new tunnels had been excavated since the last static scanning in 2019: central tunnels 5 and 6, and a test tunnel in TU5. Excavation of the depositioning tunnels 5.1 to 5.5 had started, but the areas could not yet be accessed for verification. These areas were acquired with static scanners (first in-field use of the Z+F Imager 5016) and the resulting 84 scans were incorporated to the reference model. The MLSP was used to verify the absence of undeclared changes in TU5 and the shaft connections in TU2 (approximately 3 hours of data) and the ventilation hoist building was verified against the operator design by using MLSP-generated blueprints.

### 4.7 2022 Verification

In 2022 three inspectors, one from Euratom and two from IAEA, performed the verification by means of visual observation. No 3D laser scanning was performed, but the activities relied exclusively on the scans available from previous verifications.

### 4.8 2023 Verification

During the verification of November 2023, the depositioning tunnels 5.1 to 5.5 were scanned with the static scanner (1.6km). The first two, 5.1 and 5.2, were declared since the campaign of 2021 but could not be accessed by then. In total, 278 scans were acquired, taking each tunnel half a day per team (one Euratom and one IAEA inspector). The resulting 3D model was used to generate a blueprint, which was overlaid on top of the operator's provided maps to confirm that the execution of the excavations was according to the original planning.

The mobile system was used to confirm the absence of undeclared changes in the areas that were scanned until 2021. Most of the verification activities focused on TU5, as several infrastructure changes were present, e.g. new equipment and civil works carried out since the acquisition of the reference model. The system clearly identified such changes, while confirming that no additional excavations had been made. The net MLSP scanning time was approximately one hour distributed over two half days. Additionally, the MLSP was also used to perform a random re-verification of the ventilation hoist building, focusing on the access to the personnel shaft.

In 2023 the facility operator POSIVA modified its information security policy: data acquired above ground, i.e. the encapsulation plant, remained classified as confidential and should not leave the site. Data acquired below ground, i.e. the disposal facility, got re-classified as restricted and was released to be taken off-site, provided that the security procedures were followed. This allowed to perform additional data analysis and cleaning for the disposal facility model that could be used in the next verifications, as detailed in the following sections.

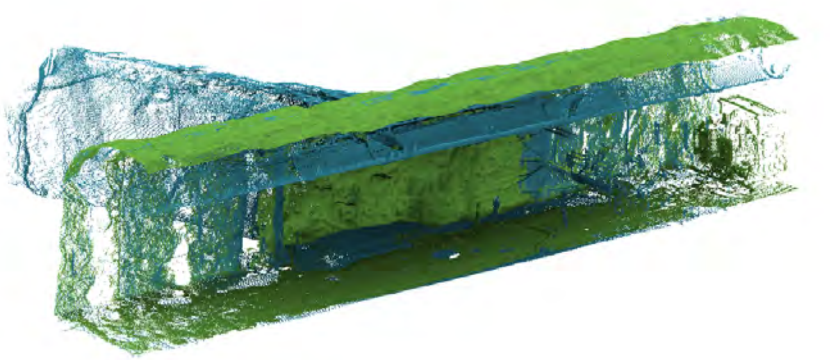

**Figure 6.** Temporal inconsistencies in the reference model generated incrementally over the years with the static scanner. Section of a tunnel acquired twice in two different verifications: 2019 (green) and 2023 (blue). Notice how the model in 2019 did not include the ventilation pipes on the top of the main tunnel and how the side tunnel was not yet excavated.

### 4.9 2024 Verification

Since no new excavations were declared for the verification of November 2024, the full activity relied exclusively on the MLSP system. The main goal was confirming the absence of safeguards-relevant changes during the previous year and to generate a new full 3D model of the disposal facility using exclusively mobile data. Additionally, the Encapsulation Plant (EP) and the hoist building were also verified with the MLSP.

The generation of a new map was motivated by two main reasons: (1) integrate in the reference model the small changes that took place over the last ten years, like the levelling of the floors and construction of infrastructure inside the existing tunnels, e.g. ventilation pipes, and (2) generate a new full 3D model of the facility, as-built in 2024, without temporal inconsistencies. Figure 6 shows an example of such inconsistencies in one section of the tunnel.

In total, the full mapping of the site with the mobile system took four and a half hours, distributed in two teams with two MLSP systems and covering a total distance of about 16 kilometres. The data processing was performed on site, using the original 3D model (the one acquired with the static scanner over the previous years) as a reference. The new model was generated using the mobile system in tracking mode to ensure that the global consistency of the previous model was preserved and that the two models were in the same reference frame.

## 5 Data processing

The measurements performed with 3D scanners, both with static and mobile, are always expressed in local coordinates around the optical center of the device. Consequently, after performing multiple acquisitions of the same environment from different positions, the data has to be aligned to generate a single model that integrates all the measurements in a consistent way.

Scan alignment is a two-stage process, as detailed in the next two sub-sections and illustrated in Figure 7: first, scans need to be pairwise aligned, i.e. consecutive and overlapping scans get aligned between themselves (Section 5.1). Once all scans have been connected through pairwise alignments (also called *matches*), the relative pose of any scan w.r.t. any other scan can be estimated through the set of matches that connect the intermediate scans between themselves. Notice from Figure 7-left how the positions of the scans are fully compatible with the matches, i.e. the arrow of each match always falls in the centre of the second scan.

The second stage consists on ensuring the global consistency of the final model (Section 5.2), as each pairwise alignment introduces small errors. Such errors are a consequence of three main factors: the accuracy of the measurements provided by the scanner, the partial overlap between the two scans and the small errors introduced during the estimation of the alignment. This is particularly critical for the mobile data, as the scan frequency is higher (10 scans per second), the overlap is lower due to the limited field of view of the sensors and the accuracy of the measurements is one order of magnitude worse.

Even though pairwise errors can be considered negligible, such errors propagate over distance as all the scans get incrementally connected. Notice from Figure 7-centre how, even though $S^1$ and $S^6$ were indirectly connected, calculating their pairwise alignment (dashed arrow) would require $S^1$ to be in the position illustrated as $S^{1*}$, which contradicts the original position calculated when no redundant matches existed. The global optimization process exploits redundant matches, i.e. matches between pairs of scans that are not necessary for connecting all the scans between themselves (also called *loop closures*), to distribute the errors uniformly across the model and, thus, ensure global consistency, see Figure 7-right.

### 5.1 Pairwise alignment

Pairwise alignment between scans is divided into two steps: (1) a global initialization needs to be estimated to roughly align both scans with no prior knowledge of their relative poses and (2) given such global initialization, a local refinement needs to be performed aiming to minimize the distances between neighbour points from both scans.

For the global alignment, our approach works under the assumption that places can be recognized by analyzing the projection of the observed 3D points along the gravity direction. Relative poses between pairs of scans are estimated by aligning their 2D projective representations and benefiting from the corresponding dimensional reduction. Then, our global matcher retrieves the associated relative 3D transformation between scans by estimating their alignment over the $Z$ axis. Full details of the technique can be found in [2] and [3].

When using the mobile system, the measurements of the inertial sensor are used to estimate the gravity direction. With the static scanner, we assume that the mounting (either in a tripod or a vehicle) aligns the vertical axis, $Z$, with the gravity direction.

Global alignment plays a critical role in the MLSP when working in tracking mode: during the initialization the position of the inspector needs to be estimated in order to start tracking his motion within the reference map. Either with a manual procedure or with an automatic approach, the system needs to align the live 3D data coming from the laser with the reference model. This is done with a dedicated global matching algorithm described in [4] and [5].

Once the relative pose of two scans has been estimated, the refinement of the alignment is performed by using the Iterative

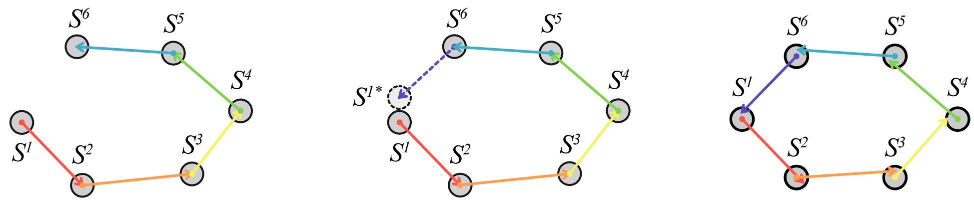


**Figure 7.** Scan alignment. (left) pairwise alignment of a set of six consecutive scans ($S^1$ to $S^6$), where the scan position is represented as a circle and the match between scans is represented as an arrow that starts from the center of one scan and ends in the position where the other scan should be, according to the alignment calculated. (centre) loop closure. (right) result after the global optimization.

Closest Point (ICP) algorithm [6]. Our technique computes the alignment of two scans by minimizing the point-plane distances [7] between compatible pairs of points in both scans. To approximate these distances, we fit locally optimal planes centered at each point in one scan, estimating a surface normal that captures the local geometry.

Given one fixed scan, $\mathcal{P} = \{\langle \mathsf{p}_0, \bar{\mathsf{n}}_0\rangle, \langle \mathsf{p}_1, \bar{\mathsf{n}}_1\rangle, \ldots \langle \mathsf{p}_n, \bar{\mathsf{n}}_n\rangle\}$ and a moving one $\mathcal{Q} = \{\mathsf{q}_0, \mathsf{q}_1 \ldots \mathsf{q}_m\}$, where $\langle \mathsf{p}_i, \bar{\mathsf{n}}_i\rangle$ are the pairs of points and normal vectors from the fixed scan $\mathcal{P}$, respectively, and where $\mathsf{q}_j$ are the points from the moving scan $\mathcal{Q}$, and given the relative pose estimated by the global matcher, $\tilde{\Gamma}_P^Q$, that roughly aligns $\mathcal{Q}$ w.r.t. $\mathcal{P}$, we proceed in three steps:

1. Select a random set of points and normals from $\mathcal{P}$ and retrieve their nearest neighbours from $\mathcal{Q}$ after applying the $\tilde{\Gamma}_P^Q$ transformation, which gives us $\{\langle \mathsf{p}_i, \bar{\mathsf{n}}_i, \mathsf{nn}_i\rangle\}$, where $\mathsf{nn}_i \in \mathcal{Q}$ is the nearest neighbour of $\mathsf{p}_i$ and where $\left\|\mathsf{p}_i - \tilde{\Gamma}_P^Q \mathsf{nn}_i\right\| < \theta_d$, being $\theta_d$ a maximum distance for considering two points compatible.
2. Given the set of compatible points selected in the previous step (also known as *correspondences*), estimate a new relative transformation, $\tilde{\Gamma}_P^Q$, that minimizes their point-plane distance errors, $e = \left[\left(\tilde{\Gamma}_P^Q \mathsf{nn}_i - \mathsf{p}_i\right) \cdot \bar{\mathsf{n}}_i\right]^2$, where $\cdot$ is the dot product.
3. Check for termination, i.e. error function not decreasing or maximum number of iterations reached. If so, the new $\tilde{\Gamma}_P^Q$ is the relative pose that better aligns both scans. If not, repeat from step 1 (collect new correspondences and update the alignment) with the new $\tilde{\Gamma}_P^Q$.

During the local refinement of the poses the most computationally demanding task is retrieving nearest neighbours. For ensuring real-time in the MLSP when working in tracking mode, custom acceleration data structures had to be developed. Thanks to a pre-calculated gradient map the overall computational requirements where considerably reduced. More details can be found in [4] and [8].

## 5.2 Global optimization

The global optimization problem is modeled as a sparse graph, where scan poses (nodes) are connected through matches (edges). The graph structure allows formulating a sparse global problem that optimizes scan poses, considering simultaneously all the compatible correspondences retrieved during the pairwise alignment. A sparse graph solver [9] is used to perform the calculations and to benefit from the intrinsic sparse nature of the problem (typically a scan is not connected to all the others). Full details of the technique can be found in [2], [3] and [10].

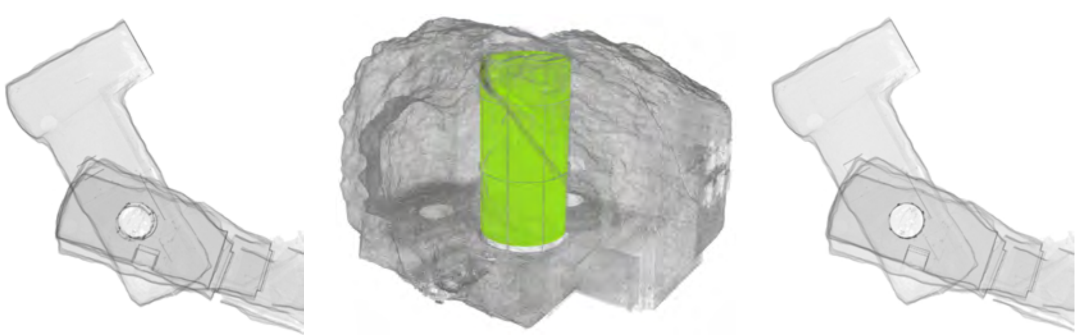

**Figure 8.** Ventilation (in) shaft alignment. (left) top-down projection of the ventilation shaft before performing the global optimization. Notice how the circular sections of the four access tunnels that connect the shaft as it goes from ground level to -500 metres are slightly misaligned due to the incremental drift propagated along the access tunnel. (centre) cylinder fitted from the scan data used for the global optimization. (right) top-down projection of the ventilation shaft after performing the global optimization. Notice how the drift has been significantly mitigated, improving the vertical alignment of the data.

In the specific case of Onkalo the presence of loops could only be found in TU5, as the access tunnel is a continuous road that spirals down and where only one scanning path is possible. However, since the tunnel is several kilometres long and the spacing between consecutive scans is around ten metres some accumulated drift was expected. This became evident when analysing the four vertical shafts, after the data was released by the operator in 2023.

As illustrated in Figure 8 (left), the absence of loops leads to the propagation of minor pairwise alignment errors along the tunnel, compromising the overall consistency of the model. The top-down projections of the shafts, which connect to the main tunnel at varying depths (from ground level to -500 metres), revealed inconsistencies in the data. These shafts were never directly scanned; only the sections visible from the access tunnels were captured, preventing the possibility of defining the loop closures necessary to mitigate drift.

To address this issue, we adopted the approach depicted in Figure 8 (centre): for each shaft, we isolated all the access tunnels that connect it with the rest of the facility. For each access tunnel, we used a Random Sample Consensus (RANSAC) algorithm [11] to fit an optimal cylinder around the shaft. Then, for each cylinder we computed the rigid transformation required to align it vertically with the other cylinders along the Z-axis, while maintaining its relative height. These transformations were then integrated into the global optimization problem. After optimizing with these new constraints, the final model preserved local pairwise accuracy and significantly enhanced global consistency, as demonstrated in Figure 8 (right). Notice how the circular sections of the shaft along the entire facility (500 metres long) align perfectly in the vertical direction.

## 6 Verification tools

Several software tools have been implemented over the past decade to support the verification of operator-declared CAD drawings using the as-built 3D maps derived from the scan data. During the verifications of 2014, 2015 and 2017 the software used for aligning the data and performing the analysis was 3DLVS, which supported 3D change analysis and blueprint verifications with static scanner data. From 2015 the MLSP system was introduced, providing a live change analysis, but with no integration to 3DLVS, i.e. mobile and static scanner data could not be aligned and analysed simultaneously. From 2019, 3DLVS was replaced by STeAM Desktop and, gradually, new verification modules were implemented and included in the on-site verifications. This section provides a detailed overview of these tools.

### 6.1 Blueprints verification

Blueprints verification consists on creating a top-down view of the scanned data, i.e. an as-built floor plan of a part of the facility, and performing a visual comparison against the CAD drawings provided by the operator. The goal is to confirm that the construction works have been executed according to the original designs.

To generate the as-built 2D drawing, the 3D data (or a slice in a range of heights) is projected in the gravity direction to produce an image. Later, this image is aligned using an interactive tool against the CAD drawing provided by the operator and overlaid on top of it to perform a visual verification. With 3DLVS only slices of static scanner data could be used. Later, with the development of STeAM Desktop both, static and mobile data (or a combination of both), could be projected without the need of creating slices. This allowed for a considerable increase of efficiency, as mapping with the MLSP is considerably faster than with the static scanner and the final accuracy of the mobile 2D maps is sufficient for such verifications. Figure 9 shows one example of blueprints verification where the as-built image (red) has been generated using mobile data and overlaid on top of the CAD drawing provided by the operator (black).

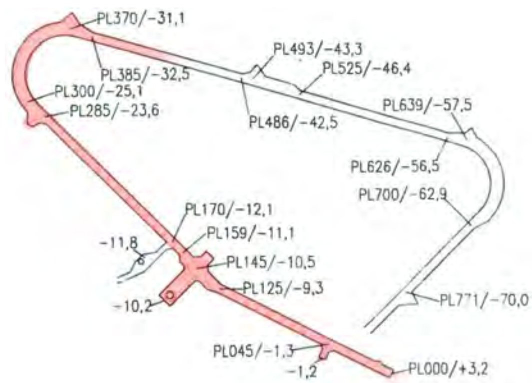


**Figure 9.** Blueprints verification. As-built top-down projection of the 3D data acquired with the mobile system (red), aligned and overlaid on top of the CAD drawing provided by the operator. Note that the CAD drawing shown in this images serves only for illustration and provides less details than the real operator declaration.

### 6.2 3D change analysis

The 3D change analysis verification consists on comparing two 3D scans, acquired with the static scanner, and visualizing the geometrical changes that have occurred between the acquisitions. To perform this analysis the two compared scans need to overlap as much as possible, i.e. they must be acquired from (roughly) the same position. However, the placement of the scanner does not require high precision, as both scans are aligned before performing the analysis.

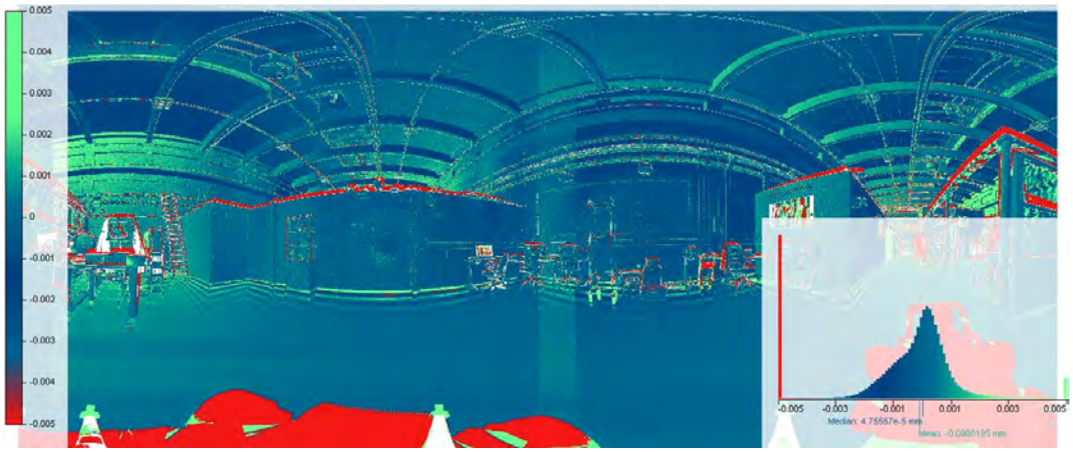


**Figure 10.** 3D change analysis results. Visualization of the geometric differences between a reference and a query scan, taken from the same position. The color coding indicates the point-plane distances (in metres) between nearest neighbors from both scans after alignment. Red areas correspond to objects that have been removed, i.e. present in the reference scan but not in the query one, whilst green areas correspond to newly added objects, i.e. present in the query scan but not in the reference one, Notice from the histogram (bottom-right) how the average distances between unchanged points are sub-milimetric, which is consistent with the scanner specifications (Z+F Imager 5016, $\leq$ 0.5mm) and confirms its correct calibration.

During the Onkalo verifications, there are two main use cases for this tool: (1) verifying the absence of changes in sensitive (or randomly selected) locations and (2) cross-validating the static scanners from both inspectorates. For the first one, inspectors select every year places of interest that were scanned in previous verifications and perform new scans from the same positions where the references were acquired. For the second one, at the beginning of a joint verification both inspectorates perform a scan with each scanner from the same position. All scans get cross-validated, i.e. the data from one scan gets compared against the data of all the other scans. If no significant differences are observed between devices, the data acquired from both inspectorates is shared and fused into the single reference model.

To highlight the geometrical differences between aligned scans, point-plane distances between nearest neighbors are computed, similarly to Section 5.1. The resulting distances are then displayed by projecting them into the structured view of the scans, which allows for a fast and intuitive 2D visualization, as illustrated in Figure 10.

### 6.3 Mobile change analysis

Change analysis using the MLSP data can be performed in two ways: live and offline. In the first case, the system performs all the calculations in real-time, providing the inspectors an immediate feedback on both, their position inside the facility and the

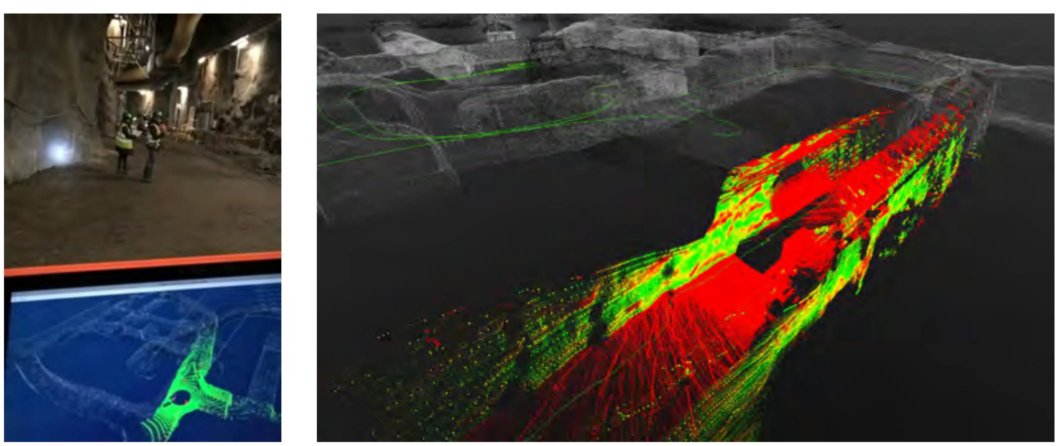

**Figure 11.** Mobile change analysis. Grey points correspond to the reference model, green points correspond to unchanged areas, whilst red points correspond to changes above 5cm. (left) picture of one inspector performing a live mobile change analysis in TU5 during the verification of 2018. (right) offline mobile change analysis of TU5 during the 2024 verification. The green line represents the trajectory that the inspector followed during the verification. This trajectory was estimated in tracking mode against the previous reference model (created with the static scanner) and was later used to generate the new updated model with MLSP data.

results of the change analysis. This is particularly useful from an efficiency point of view: in areas where no changes have been made since the last verification, the inspector only needs to walk around to confirm the declaration without the need of re-processing everything later from the office. On the other hand, in case of finding undeclared changes, the inspector can react immediately and clarify them while inside the facility.

When performing a live mobile change analysis, all data coming from the sensors is recorded. This allows to repeat the verification from the office, i.e. offline, and to get a more detailed/complete view of the results. Moreover, since for performing the change analysis it is necessary to estimate the trajectory of the MLSP within the coordinate system of the reference map (tracking), the measurements collected by the laser can be used in STeAM Desktop to produce an updated version of the reference map that maintains the global accuracy of the original model. This was done for the first time during the 2024 verification: all the facility was re-scanned with the MLSP and aligned against the reference map created with the static scanners and globally optimized. The outcome was a new updated reference model aligned with the previous one, that only took four and a half hours to acquire.

### 6.4 Global change analysis

The global change analysis tool facilitates comprehensive 3D change analysis across entire facilities. Unlike the 3D change analysis described before, which operates on individual scans acquired with the static scanner, the global change analysis compares a full 3D model of a facility, the query, against another full 3D model, the reference, and computes the differences between the two, as point-plane distances. To visualize the results, the global change analysis creates a map with the original points of the query, colour-coded with the resulting distances. Figure 12 shows an example of this tool.

### 6.5 Other applications

The hardware and software tools developed for the Onkalo verifications have had a significant impact beyond their original intended use. The MLSP device was patented in 2016 [12] and a technology transfer agreement was signed with a private company to commercialise the system for non-nuclear applications. In 2015 it won the Microsoft Indoor Localization Competition [8] and it was used as a reference system for the competitions of 2016, 2017 and 2018.

Together with its associated 3D processing software, STeAM Desktop, the MLSP has been used to develop a 3D Information Management System (3DIMS) to support decommisioning activities, to map radiation levels in nuclear facilities where no GPS signal is available, to develop Virtual Reality visualization techniques [13], or to mine training data for other AI-based nuclear safeguards applications [14, 15, 16], amongst others. Figure 13 shows some examples of other applications.

## 7 Conclusion

The use of 3D laser scanning has proven to be a valuable tool for carrying out Design Information Verification (DIV) in the Onkalo disposal facility. Over the past decade, several software and hardware tools have been custom-built for this purpose, allowing inspectors to carry out verifications efficiently and effectively. The scanning hardware and software will con-

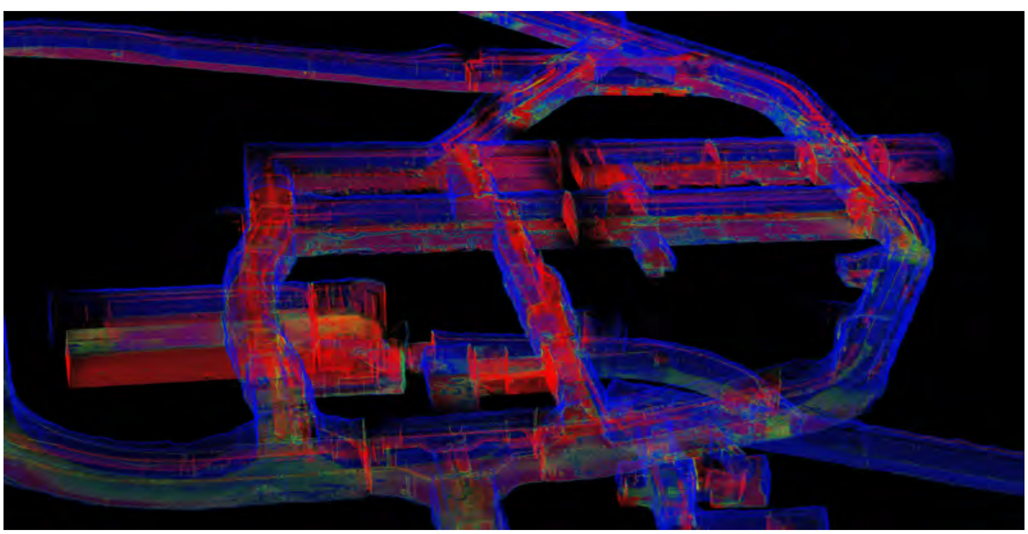

**Figure 12.** Results of the global change analysis of the 2024 verification for a section of TU5. Blue points represent no changes and red points represent areas that changed more than 5 cm. Notice how leveling of the floors and the construction of infrastructure, e.g. ventilation pipes, introduced major changes in the reference model, which are easy to spot in a global analysis.

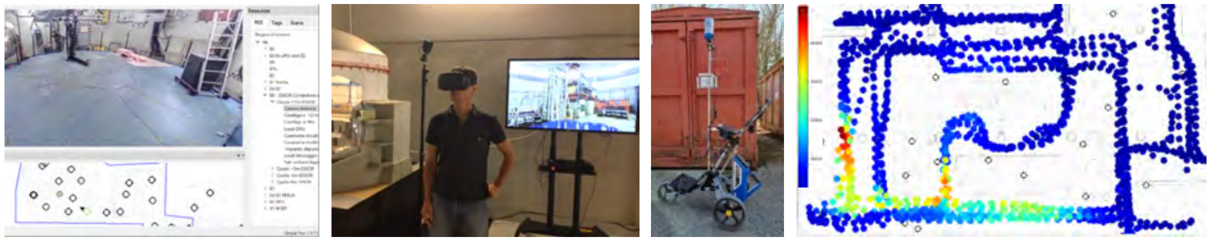

**Figure 13.** Other applications. From left to right: (1) decommissioning 3D database (3DIMS), (2) VR visualization tool, (3) radiation mapping device with the MLSP and (4) radiation mapping results in 3DIMS.

tinue to be the principal tools for DIV verifications during the Onkalo operation, enabling the accurate verification of the facility's design information. Furthermore, these tools are also been applied to other nuclear safeguards applications, including both DIV and Physical Inventory Verification (PIV), where accurate 3D scanning is used to verify that nuclear material containers have not moved between verifications, demonstrating the versatility and potential of this technology in supporting nuclear safeguards activities.

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