USING A LASER SCANNER FOR THE CONTROL OF ACCELERATOR INFRASTRUCTURE DURING THE MACHINE INTEGRATION

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Abstract

In response to increasing demands for 3D as-built control for installations and infrastructure at CERN, a laser scanner was identified to be the ideal instrument for these types of measurements and a Leica HDS3000 purchased. Examples of scans in the LHC tunnel and elsewhere that have been made with this instrument will be presented, together with the registration and geo-referencing of the point clouds into the CERN coordinate system. Subsequent interference checking against CAD design models has been made by both importing the model and exporting the point clouds. The advantages and disadvantages of each method will be shown.

1. INTRODUCTION AND MOTIVATION

At the beginning of the installation work of the LHC machine, after the dismantling phase of LEP, the Survey Group was asked to make control measurements of civil engineering work, and subsequently to provide as-built documentation of the infrastructure installed in the tunnel.

This had to be done for those parts of the tunnel with tight installation tolerances and for modified and newly constructed areas. This included the enormous experimental caverns where some critical points had been defined where controls of the civil engineering work should be undertaken by geometric measurements.

This work was initially done using a total station (TCRA 1100), measuring to a reflector or to auto-reflective strips, with an integrated software package allowing profile measurements. TCRA measurements were also undertaken to natural surfaces, like concrete walls.

These kinds of measurements allowed us to deliver coordinates of a certain number of points to be compared with the CAD model. However, this method could only give an answer for a particular and well defined request. Other details of the tunnel zone were not measured due to lack of time and knowledge about what dimensions could be important at a later date. Therefore, we found ourselves returning to the same area on several occasions to measure different points of interest.

To be able to provide a more complete service our attention focussed on the 3D laser scanners that were proving their worth in determining as-built information in numerous different domains (e.g. civil engineering and industrial plant). These instruments offered the opportunity to gather detailed 3D information of a complete zone and the acquired data would allow the integration team to interrogate the point cloud database in response to specific queries as and when required.

2. LASER SCANNER TEST AND PURCHASE

Prior to setting up an official price enquiry a list was compiled of all the laser scanner manufacturers that produced an instrument capable of precise measurements in a range between 1 m and 100 m (A good website providing an extensive list of available laser scanners may be found at [XXXX]). A demonstration was organised of the Mensi GS100 that ably showed the possibilities of the technology, but the integration team, who would have to invest time and effort into the exploitation of the data, remained to be convinced.

At this time a request was received to provide as-built information in the new Atlas experiment hall and it was decided to invite firms to scan the cavern and demonstrate more fully the benefits of the technology. A very long day of scans and some comprehensive processing provided CERN with a dense point cloud of the civil engineering works, and an as-built model that were rapidly put to good use.

This helped show the full potential of laser scanners, but also revealed not only the large amount of time required to produce as-built models, but also the problems encountered by CAD programs in handling the large sets of measured points. In view of this it was decided to push forward with the purchase of an instrument however, the initial use of any data would have to concentrate on simply checking the point cloud against design models for potential interference problems.

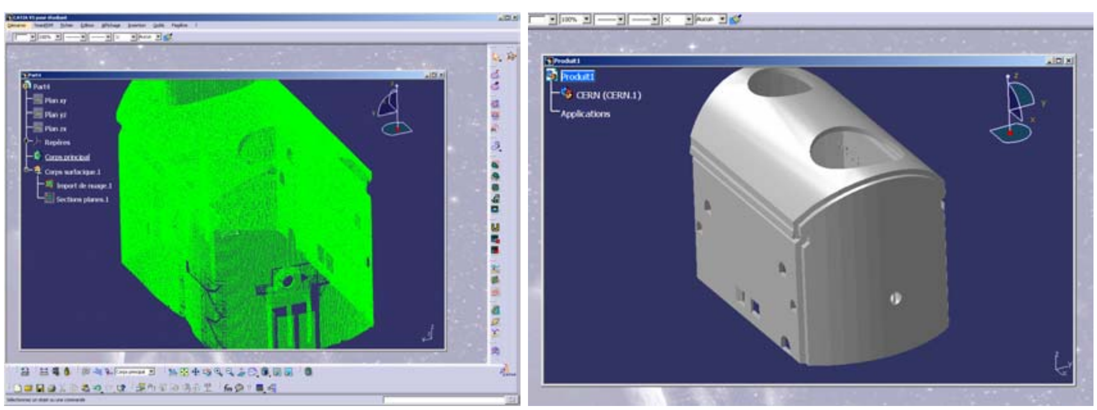


Figure 1: Point cloud and model of the ATLAS scan

The result of the price enquiry and the verification of the instrument against the technical specifications resulted in the purchase of the HDS3000.

2.1. Specifications

After the test scans in the ATLAS cavern, specifications for a price enquiry were established. Due to the peculiarities of the LHC tunnel, the location of network points and the accuracy demands of the integration group, the following principal instrument parameters were defined, see [1].

Minimum Range:	≤ 1.5 m
Maximum Range:	≥ 60.0 m
Single Scan Field of View, Horizontal:	≥ 360^G (gradians)
Single Scan Field of View, Vertical:	≥ 60^G
Minimum Data Acquisition Rate:	≥1000 points per second
Minimum Scan Increment, Horizontal:	≤ 0.003^G
Minimum Scan Increment, Vertical:	≤ 0.003^G
Point Position Accuracy at 60 m, at 1σ:	≤ 6 mm
Integrated camera, for aiming & scan zone definition	

Table 1: Main specification parameters for a 3D Laser Scanner

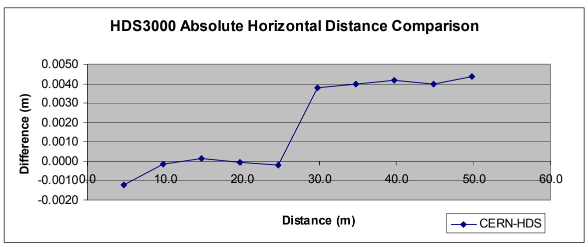
The instrument was to be able to measure 54m of tunnel from a single station, the tunnel diameter being 3.8m, and the station 1.75m from the wall. This determined –with a maximal density of 20mm- the minimum scan increment.

As part of this instrument specification, the system was also to be operational in an autonomous way during a whole working day and use target points adaptable to our geodetic reference network. On the software side, the system was to be able to connect together the numerous point clouds coming from different stations and to geo-reference them into the CERN coordinate system. It was also to be possible to create models of parts of the point cloud and import from and export to those CAD programs in use at CERN for comparison of point clouds with models.

Figure 2: LEICA HDS3000 with accessories

2.2. Instrument Testing

As part of the price enquiry tests were carried out including a scan of a section of the LHC tunnel, and the export of the acquired data to Catia. Tests were also carried out using the CERN calibration bench to verify the instrument met the specifications given for the accuracy of points. This was done by comparing the scanned points with data from a TDA5005 for the horizontal and vertical angle comparison, and the bench interferometer for the distance measurement comparison. For these tests, measurements were made with a TDA5005 -mounted on the rail of the calibration bench- to a prism on the calibration bench chariot. Points were measured every 3m in the range of 0 to 50m. The same points were scanned, a HDS target replacing the prism, from the HDS3000 stationed on its tripod near the rail (mounting at the same place as the TDA was not possible due to lack of space). By means of a transformation of the two measurement lines (the eccentricity between the two stations having been measured), we obtained differences between TDA and HDS measurements for the distances as well as for the horizontal and vertical angles. Figure 3 gives the results of these measurements, which are within the specification given for the instrument



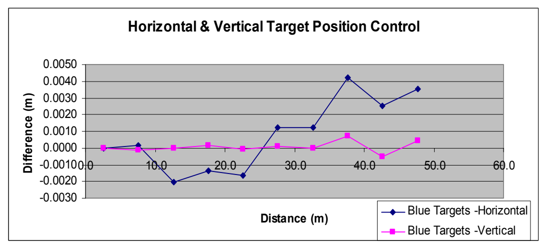


Figure 3: Results of test measurements on the CERN calibration bench

3. USING THE HDS3000

Once installed in place the scanner takes several minutes to initialise its systems and run through a number of internal calibration checks. The choice of the station of the scanner is dependant of the objects to be scanned but also of the reference points available.

Using the Survey module of the Cyclone application (the HDS software package) to control the instrument, a database is configured and the connection to the instrument established. A spherical grid centred on the instrument position is used to define the images (made with an integrated video camera) and the scans to be taken. The user can orient this view in any direction and continuous area of the 360° horizontal and -45°….+90° vertical range may be defined and scanned or the images captured. Any number of such areas may be defined.

The area selection, for both images and scans, can be done by fencing interactively in the grid or directly by introducing numbers into a form. There is also a possibility to define the density of the points in horizontal and vertical direction separately. As a result, the number of points and the time necessary for a scan is given. Furthermore, detailed information on the station and on the atmosphere can be introduced. A script can be written and executed to automate the image capture and/or scan of one or more areas. Once the scan executed, it can be viewed in a separate viewer, with the same view facilities as for the images. For the targets in the measured scene, there is a special acquisition mode. The targets are selected, numbered, then automatically measured with high precision two step scanning algorithm.

3.1. Target Network and Orientation problems

With the Laser Scanner it is theoretically possible to scan a certain region of the tunnel (or another object) without any target points set out. The point cloud would then be saved in the local coordinate system of the scanner. If one or more instrument set-ups are used it is necessary to introduce targets that are measured from each station. In the case of the LHC integration, however, it is also important to be able to transform the point clouds into the CERN coordinate system. Targets placed on the geodetic network points in the LHC tunnel provide the solution but all the points are in the floor roughly in a line running parallel to the axis of the tunnel. Consequently they provide a poor determination of the system which is able to rotate around the line of control points. Adding additional “free” points helps tie stations together but does not help with the under constrained system, a known point off the line is needed. To overcome this problem, at least one reference point measured from a given station is equipped with a twin target pole (see Figure 1) for which the coordinates of both targets can be determined.

3.2. Registration and Geo-referencing (hardware and software)

Once the field work is done, the point cloud has to be prepared for comparison with the CAD model. The target centre positions are calculated from the coordinates of the floor points, taking into account the vertical at a given location. These coordinates are imported into Cyclone and treated as an additional station.

With the registration tool, a least squares adjustment is performed using the target points to determine the transformation parameters necessary to bring all the point clouds into the reference frame of one of the stations, in our case the CERN coordinate system (CCS) represented by the calculated points. The R.M.S of this calculation has typically not been greater than ±3mm for a single point, and the result of which is a model space with all the points in the CCS.

4. APPLICATIONS OF THE HDS3000

Since the purchase of the instrument, end of March 2004, about 30 scan projects of varying size have been carried out. A few examples are mentioned below. These give an overview of the various underground areas that have been scanned for the infrastructure installation in the LHC tunnel, and other applications.

4.1. Tunnel areas and infrastructure

The first tunnel sections to be scanned were mainly situated near the interaction points. These are regions where different tunnels join, and the diameter of the tunnel sections changes. The zones of interest were the intersections and edges of the different tunnels with the floor, and the positions of pipes and cable trays which could interfere with other equipment to be installed later. The aim of these measurements was the comparison of the as-built data obtained by the scans against design information in the form of CAD models.

By visual control during the scan, we verify that the density of the measured points is high enough (the values defining a scan are only valid for a right angle between laser and the measured surface). A second denser scan is sometimes necessary on the walls where the angle of incidence of the laser is small. With low resolution scans (e.g. for civil engineering installations) additional scans are also occasionally required to allow the target points to be identified and selected.

The result of a typical scan of this type is shown in Figure 4. The colours shown are a function of the intensity of the returned signal. The targets plugged into geodetic floor points (in blue with white circle) or distributed elsewhere in the object area can be recognized in the point cloud.

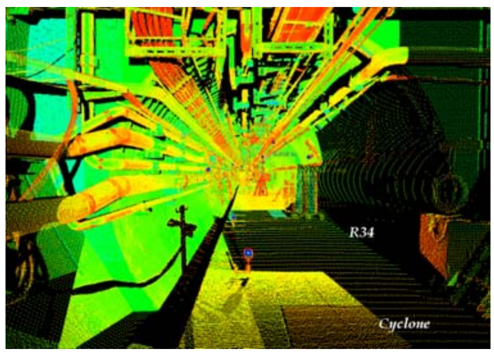


Figure 4: Point cloud scanned in R34

4.2. LHC Cryogenic Line

Another important project was to determine the position of the Helium Distribution Line (QRL), which will feed the superconducting magnets around the LHC tunnel. As the mounting of this line will take place before the magnet installation, it is important to be sure that there will be enough space between the QRL and the magnets. After a test scan, where only a service module (part to be connected to a quadrupole, about every 100m) was scanned, 800m of tunnel were scanned in two working days, with the density of the points between 1.5….90cm; the latter being in the region furthest from the station at about 50m. These scans were made with the help of a script, dividing the scan in five parts with different point densities depending on the distance between instrument and the tunnel section being measured.

4.3. CNGS crane support plates

For the future Neutrino-to-Grand-Sasso project, a crane had to be installed in an underground cavern. To fix it to the ceiling, some thirty plates form the reference surface for the rail mounting. In order to check the position of the plates, in addition to a conventional measurement (by total station), a scan of these plates was performed. A jig with a HDS-Target in the middle was built that would attach to the bolts holding the reference plates in place. The idea was to test the angle and precision with which these targets could be measured. The requested precision was ±6mm. Spurious reflections from the metal jig initially prevented measurements at acute angles, but the problem was resolved by painting the jig black!

After the registration and geo-referencing of the point clouds, the comparison of two points measured from consecutive stations showed that their coordinates were only different by ±2mm; this is in fact the same precision you can reach in the precision of the network of the scan stations done in the tunnel, when the geodetic network points are used as references.

The comparison with the TCRA measurement showed greater differences between the determined coordinates; it is important to mention however, that the TCRA measurements were not made in an optimal configuration either (small angles between station and reflective strips) for some points. The time taken by for each set of measurements was equivalent.

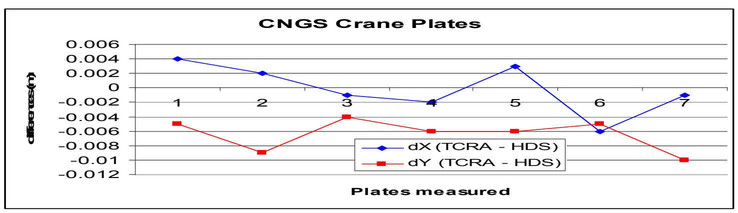


Figure 5: Results of comparison measurements TCRA and HDS

5. EXPLOITATION OF THE POINT CLOUD DATA

As mentioned previously it was decided at an early stage that time constraints would prevent the creation of as-built models from the leaser scanner measurements; although it may be carried out in certain cases and will be re-considered once the LHC Project is completed. The decision was therefore taken to check for interferences using the measured points and the design models for the various installations.

5.1. Interference Checking against Design Models

The CAD tool for the LHC project is Euclid; however it will be phased out and replaced by Catia for all new projects at CERN. AutoCAD is also used for some specific applications at CERN and Cyclone has a module (CloudWorx) to integrate seamlessly with it, including tools to import AutoCAD models. The interference checking between the point clouds and the design models could therefore be done in any of four applications: Euclid, Catia, AutoCAD, and Cyclone.

Constraints on the number of points that could be handled by Euclid (800,000 maximum, 300,000 for good response times) meant that in the end only the other three options were considered.

5.1.1. Comparison with models in Cyclone

In Cyclone the point clouds are stored in a database optimised for their 3D presentation on the screen. With the CloudWorx module AutoCAD accesses this same database directly and the response times in handling these very large point clouds are again very good. Cyclone also has an in-built tool for interference checking between the measured points and a CAD model, and CloudWorx extends this tool even further.

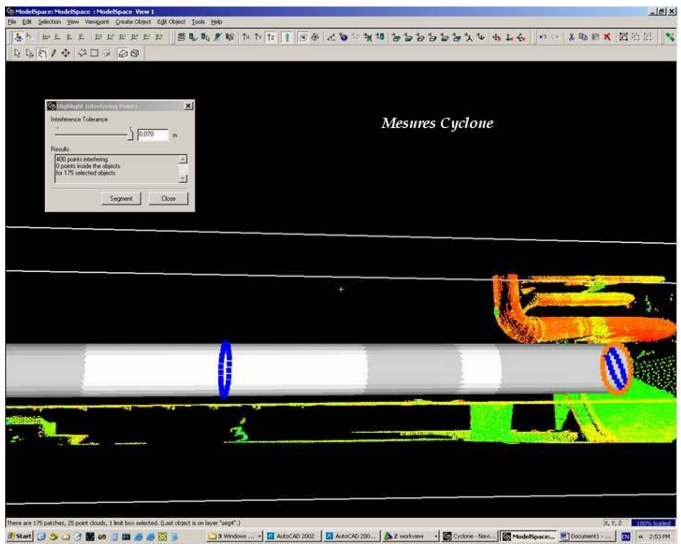


Figure 6: Interference checking between tunnel floor and QRL

Initial tests were made by exporting a Euclid model into AutoCAD and then exporting the same model again into a format specific to Cyclone. Although able to handle enormous point clouds with apparent ease, even relatively simple CAD models imported through the chain described above proved to be too much for Cyclone. Figure 4 shows the interference checking tool being used to find the minimum distance between the tunnel floor and a model of part of the LHC cryogenic line. This simple model has been decomposed into ~120 facets in passing from Euclid to Cyclone, and the interference checking required the point cloud to be reduced to a minimum in order to retain any level of performance.

Further brief tests were carried out using CloudWorx and AutoCAD, but once again the process was time consuming, and each imported model was broken down into a large number of facets all of which had to be selected in order to carry out the process.

5.1.2. Comparison with models in CATIA

In order to do interference checking in Catia, the point clouds were exported from Cyclone as an ASCII file and imported in directly. Catia has a module in its package that is designed for handling and manipulating point clouds, although this is very limited when compared to Cyclone. Although more capable than Euclid, Catia also has a limit on the number of points it can deal with: this has proved to be in the ~1 M points if application performance is to be maintained (~10 M points maximum).

Due to the point limitations we are obliged with this method to split up the point clouds and export individual sections of tunnel. All information other than the point coordinates is lost.

The design model from Euclid is translated into a format compatible with Catia (*.wrl), but as with the point clouds some information is lost along the way.

With both the point clouds and the design model in Catia, the interference checking is performed visually. To do this it is necessary to first create a mesh over the point clouds; for the applications in the LHC tunnel a system is then established to enable a section through the mesh and the models to be moved along the tunnel axis and inspected in a separate window, see Figure 7a. When required the minimum distance between the mesh and the objects in the model can also be determined, see Figure 7b. In both figures the orange coloured surface is the mesh over the point clouds.

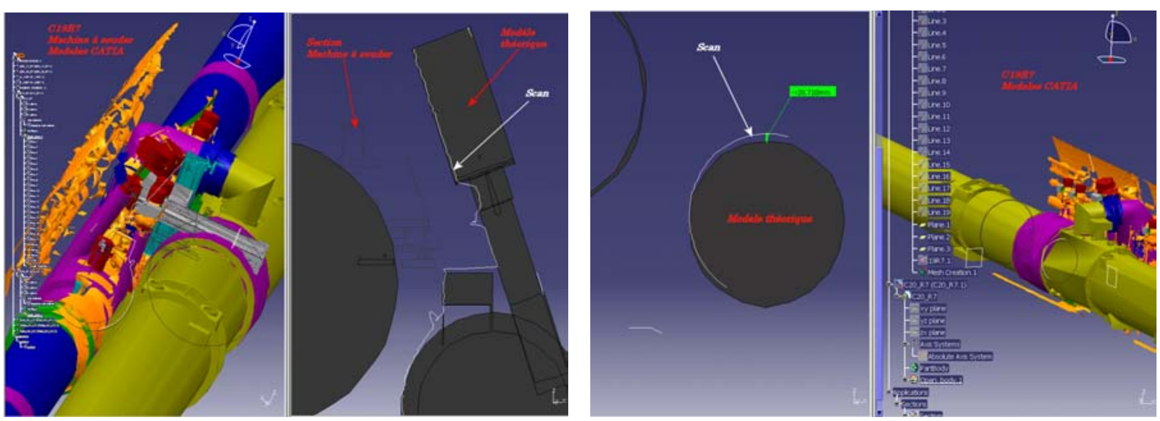


Figure 5a and b: Interference check with CATIA

This has proved to be quite an effect technique, although the loss of the intensity values associated with the points can sometimes make it more difficult to identify the different elements in the tunnel: even for someone working with them on a daily basis. Having a view of the original point cloud open at the same time helps remedy this problem.

As an aside, it was found that the 3D mesh tool available in Catia is much more appropriate than that available in Cyclone for 3D objects, since the Cyclone mesh tool is optimised for creating digital terrain model type meshes always tied to the vertical. Figures 6 and 7 shows the original point cloud of a measured statue together with a mesh created by Catia.

Figure 6: Point cloud statue **Figure 7: Mesh in Catia for the statue**

6. MODELLING

6.1. Simple models in Cyclone

In Cyclone it is also possible to do more extensive data processing: measure distances between points, model surfaces and simple forms e.g. cylinders. This can be done by selecting points in the point cloud and using in-built algorithms, for example to find the best fit surface or circle, to determine the parameters. In well defined objects, it can

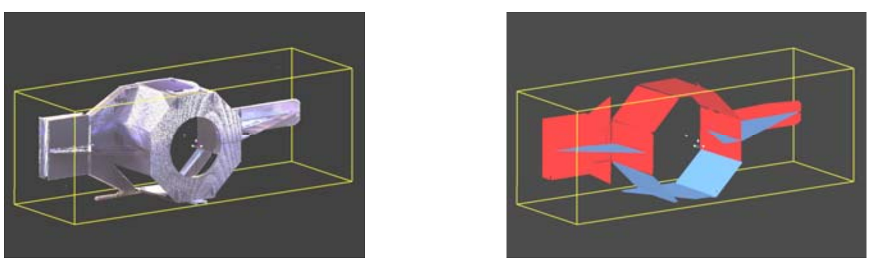


Figure 8: Point cloud and surface modelling of FAS

also be done with a "region grow" function, where an initial selected area is used and then extended to determine the best fit object. This is mostly applied for surfaces with well defined edges or corners, like in buildings. An example of some basic modelling is the FAS (Front Absorber Support) of the ALICE Experiment (Figure 8). This object was first measured by conventional methods (reflectorless total station) to be able to determine the position of surfaces and cylinders. Scans were also made and the point cloud transformed into the same system as the original measurements. Our experience with the modelling of cylinders was not entirely satisfactory; for the points inside a hole or the inner surface of a cylinder the selection of the points was not simple, and for the large central opening of the FAS the orientation of the modelled cylinder was not that of the real cylinder.

A comparison of edge coordinates and centre coordinates of two small holes (all points were selected manually out of the point cloud) of a number of surfaces showed differences between the total station measurement and the result of the scan of about ±6mm.

7. CONCLUSION

The present paper shows examples of scanning at CERN, the post processing of the data, and the exploitation of the data in concert with CAD models as a control for the LHC machine integration. These scans give the Installation Coordination group (TS/IC) the opportunity to have complete as-built data of CERN underground areas and infrastructure at a given moment in time, contributing thereby to the quality control of the LHC installation. With a reliable record of the position of the different elements and installations in the tunnel the point cloud data from the laser scanner provides an assurance regarding any potential interference.

It has not all be plain sailing; our HDS3000 was possibly the first to be delivered in Europe and there have been teething problems. These included a firmware patch applied on site and a return to the USA for the replacement of a faulty chip that controlled the video camera. However, with the proven worth of the data obtained with the instrument and the ability of TS/IC group to integrate that data into their other controls, the demand for scans is slowly increasing all the time.

A scan of the whole QRL line (~27 km) after its installation in each of the eight sectors of the LHC tunnel is now foreseen. Using a modified scan script (a higher density of points is now required, forcing the necessity of an additional station between two successive service modules) we hope to be able to scan at least 200m of the QRL each working day and then process and analyse the results within 2 days. At present there is still considerable work to be done to be sure of achieving this goal, not just to meet the challenge of measuring the QRL in that short period of time but also to automate as much as possible the processing and analysis.

Most demands so far have been for the machine integration although we do expect to scan the second big underground LHC cavern (for the CMS experiment) once the civil engineering work is finished. There may well be other scans carried out for the experiments; the HDS3000 is now an integral part of our equipment, when it is deemed to be the most appropriate instrument for a given job it will be used.

We would like to thank all our colleagues from the TS/SU, TS/IC, and TS/CSE groups, and from our Industrial Contract team who participated in the field work, with the post-processing and with the integration of the data.

8. REFERENCES

[1] Mark JONES, "Technical Specification for the supply of a Portable 3D Measuring System to provide as-built dimensional information of the infrastructure in the LHC Tunnel".