

Precise Long Tunnel Survey using the *Riegl VMX-250* Mobile Laser Scanning System

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ABSTRACT

Our company has been using the *RIEGL VMX-250* since July 2010 in diverse scenarios, especially where data acquisition productivity is pertinent. In this presentation, we will be describing a long tunnel survey project.

Spain has the longest high speed rail network in Europe. Recently, two parallel 25 km long tunnels were built and an accurate 3D survey was demanded by the Spanish authorities. *Artescan* accomplished this survey using the *RIEGL VMX-250*. The integrated INS-GNSS is specified for 1 minute GPS outages; however, in this case, each survey project was realized with approximately 1 hour of total GPS outage in the mobile receiver. An absolute accuracy of 2 cm was achieved by using a combination of well acquired exterior GPS positioning, INS and odometer measures inside the tunnel and use of control points. For trajectory adjustment, *RiProcess* powerful tools were successfully used.

KEYWORDS: mobile laser scanning, long tunnel survey

INTRODUCTION

Tunnels for transport have existed for centuries. They have been developed both in urban environments for mass traffic transports and in interurban environments mainly to cross mountains, both for roads and railways.

The recent worldwide development of high speed railway lines has stimulated the construction of a large amount of new tunnels. These tunnels are longer and deeper, especially in mountainous regions, where base tunnels need to be built in order to obtain railway lines with minimum gradients connected with the valley level.

Surveying represents an important role within these tunnels' lifecycles by applying different technologies and methodologies, for different purposes, from the construction of new ones to the monitoring of old ones. Several tunnel surveying technologies are well known and documented. Mobile Laser Scanning, in spite of being relatively new, has already had several reference projects that are normally presented as application examples; very long tunnels have not been a part of those applications. This paper will describe a very long tunnel survey project by using *RIEGL's VMX-250* Mobile Laser Scanning and a specific methodology developed to answer this challenge.

TUNNEL SURVEYING

Tunnel surveying can be divided in three major application tasks: the set-out of the project positioning, alignment, dimensions and shape during its construction and excavation works, the tunnel monitoring/condition survey, and the as-built survey.

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All these tasks rely on the application of surveying technology, which due to the underground environment and confines of space, is a unique challenge in itself.

The development of computerized total stations with increased functionality such as automatic target recognition, automatic target tracking and remote control has provided the hardware for increasingly accurate traditional survey tasks, such as the base survey over land for the start and end reference points of the tunnel and the establishment of reference stations within the tunnel.

Another less traditional survey technology that is very well suited to as-built tunnel surveying is 3D laser scanning. It is able to combine sets of scan positions of measured panorama 3D point clouds (x,y,z), which provide high resolution of the tunnel inner dimensions and geometry/shape. Recently, it has made available more robust solutions to integrate laser scanners in moving platforms, as long as its trajectory can be precisely defined.

MOBILE LASER SCANNING SYSTEM

Mobile Laser Scanning Systems (MLS) have been successfully implemented in the surveying market in recent years. These systems take advantage of the latest INS/GNSS navigation technology with good performance and results in open sky environments where GNSS observables are available. Artescan has owned and operated, since 2010, the RIEGL VMX-250 MLS system, which integrates at its core, 2 RIEGL VQ-250 profile laser scanners, an Applanix GNSS-inertial system of grade POS LV 5 series and one DMI (odometer). These systems perform mobile laser scanning in motion installed road vehicles, rail and also in vessels.

Some Artescan results in linear corridors applications

In the last 18 months, Artescan has been operating the *RIEGL VMX-250* MLS with success in several projects.

A group from our company went to the Swiss Gottardt region for a cooperation project with ETH University of Zurich applying MLS to a 270 km long project. A combination of MLS data of national roads, highways and tunnels, including the existing 16 km long Gottardt tunnel, were acquired for visualization and landscape proposes.

A large construction company with a national road rehabilitation project spanning a length of 37 km in southern Portugal asked for the entire road surface survey and demanded height accuracy better than 1 cm. The survey referential was based on the implemented high accuracy topographic network along the side of the road with a bench mark every 500m. Based on the topographic network, a set of control points were conveniently marked on the asphalt every 100 m and was surveyed by a robotic total-station. Based on these control points, trajectory adjustment was conducted in *RIEGL's* RiProcess software and as a result, a RMS error of 6mm was accomplished for the MLS survey data. This result was determined by comparing a sample of 155 points spread on 7 areas along the road measured by the client's survey team with a total-station. The MLS data acquisition took 5 hours during one night to avoid traffic and minimize GNSS ionosphere noise on the observables.

Similar projects have been carried out in different road projects and geographies where the asked accuracy varied from 1 to 5 cm. The desired results were in all cases accomplished by using the same control point methodology, accordingly to each project aim, and in some cases, not even needing to use any kind of adjustment.

THE PAJARES TUNNEL SURVEY PROJECT

Pajares Tunnels

The new high speed railway line León – Asturias, includes the construction of the Pajares tunnels, beneath the Cantabrian Mountains. These tunnels are the second longest railway tunnels in Spain, the sixth in Europe and the seventh in the world. Some important characteristics of these twin tunnels are listed below:

- 2 single-track tunnels
- Distance: 25 km
- Continuous longitudinal gradient of 16.8 thousandths, downward towards north
- Circular section: 8.5 m diameter
- Surface area: 52 m²
- Connecting galleries: every 400 m
- Distance between the axes of both passages: 50 metres in the interior of the massif

For construction purposes, the tunnels were divided in different sections with physical separation between them. To simplify, we can consider two main divisions: Pajares North with approximately 15 km long and Pajares South with 10 km long. Besides the main tunnel, an auxiliary access tunnel was also built with 2 km, named the Folledo Tunnel.

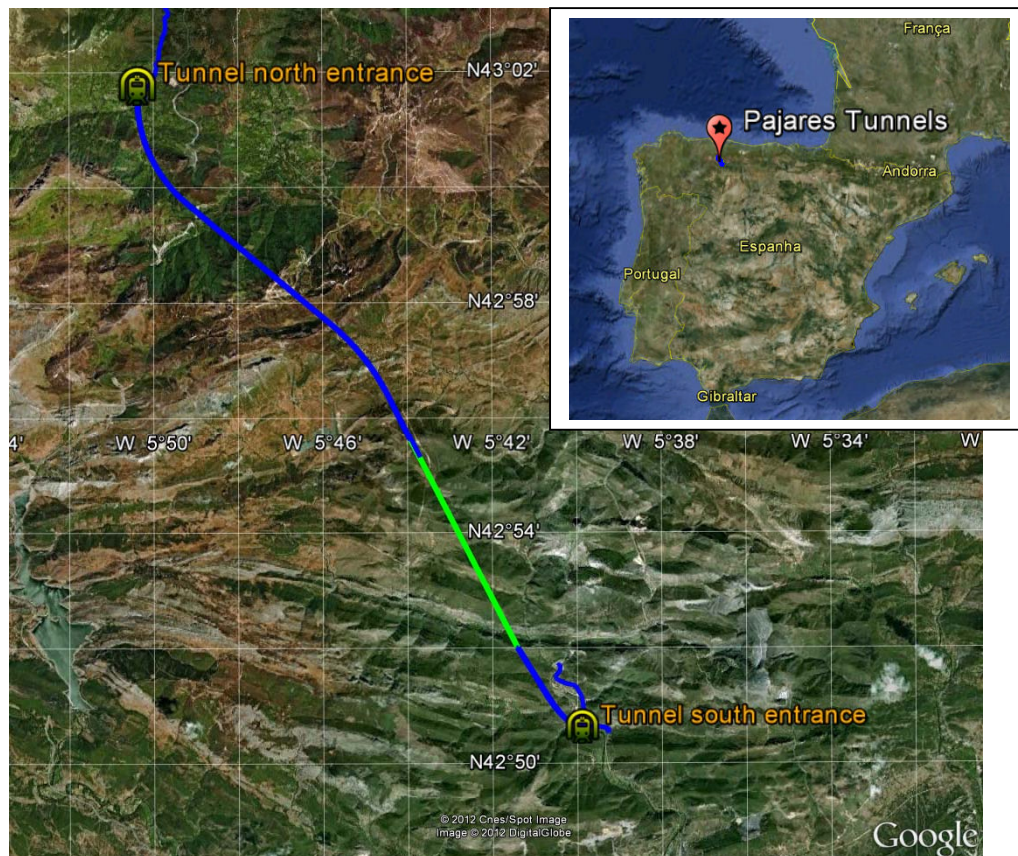


Figure 1 – Google Earth plot mapping of the Pajares tunnels in the Cantabrian Mountains in northern Spain.

Project approach

Our client asked for this survey project to be carried out by Terrestrial Laser Scanning (TLS). After a quick analysis of this job and how it would be performed with the survey approach for 50km of tunnels with TLS, it was quite clear that this mission would take months of very hard work in a difficult environment and unhealthy conditions for our surveyors.

Due to the tunnel's construction work being not yet finished and with teams working in some cases with heavy machinery, the low quality of the air inside and safety rules, the availability of these tunnels for the job had also frequent restrictions.

The question of using our MLS system came as a possible solution, concerning not only the time but the cost and possibly the results.

The Applanix INS-GNSS navigation system, integrated on the *RIEGL VMX-250*, it is only specified for outages up to 1 minute / 1 Km. In spite of its state-of-the-art performance, great challenges are to be expected when applied on several kilometers of complete GPS outages along such tunnel lengths.

Our main concern/question with applying our MLS, in this context, was how we could define a successful methodology that would allow rectifying the incremental drift of the trajectory within the absolute accuracy better than the 2 cm demanded. A careful project preparation was made including some field tests.

Control Point Frequency Analysis

Knowing the availability of new tools in RiPROCESS software to correct for trajectory induced errors and enable a higher degree of flexibility in the trajectory/LiDAR data geometry manipulation, as well as the use of regular control points well visible on the LiDAR data, a test/evaluation project was carried out to simulate the conditions of a several kilometer long tunnel MLS survey.

Artescan defined a road test near our offices in Coimbra that consisted of a twin double lane road 2.5km long with roundabouts on both ends, allowing a full round of approximately 5km of length and continuous cycle passes.

A survey team materialized a set of regular control points (some every 25m) accurately marked and surveyed by a precise total-station and high precision level. The MLS long tunnel simulation project took the usual proceedings, set-up and initialization in motion with good GNSS observables. With a good initialization and the desired INS parameters threshold achieved, a very short stop was taken to disconnect the GNSS antenna cable from the GNSS receiver (simulating the tunnel entrance). With the GNSS cable disconnected, the mission went on with several test road loops until a data length of 25 km was accomplished. At the mission finish, the GNSS antenna cable was connected again (simulation of tunnel exit) and the 5 minute stop of GNSS observables was recorded.

This test was repeated hours later the same day (with other GNSS constellation) with the aim to provide more assurance of the results and conclusions.

In order to evaluate the expected accuracies with different frequencies (distances) of the control points' availability, the trajectory was processed several times using incremented amounts (and frequency) of control points. This procedure helped to evaluate the different absolute accuracies of the trajectory and MLS data in comparison with MLS data from the same test road acquired in ideal GNSS conditions (assuming this data as the correct result).

After the mandatory analysis and evaluations, the conclusion was that with a good start, initialization, project finishing and applying trajectory corrections with control points every 25m, it would be possible to achieve the demanded absolute 2 cm RMS error accuracy.

Control Point Materialization

Besides control point frequency or distance, it was necessary that there was a prior evaluation of the ideal size, form and physical materialization for the control points, in a tunnel context. Based on Artescan's experience and the tunnel's characteristics, it was decided to use squares painted white on the tunnel's wall surface, considering the existence of water on the ground. The size of the square was calculated in 30 cm sides, considering a survey speed of 25 km/h and a surface distance of 3.5 meters to assure a minimum of 9 scan lines hitting each square target. After the first experience of materializing the control points, Inzamac survey engineers noted the existence of water infiltration on the walls and that the painting method could not be applied in wet surfaces. Because of this, white square stickers were used instead. The northern lower corner of the square was used as the control point (see Figure 2).

The initial field procedures included traverse operations along the tunnel, followed by adjustment on the coordinates of traverse stations. From these stations, all of the coordinates of the control points were determined within the demanded accuracies by using precise total-stations. Inzamac was responsible for these operations.

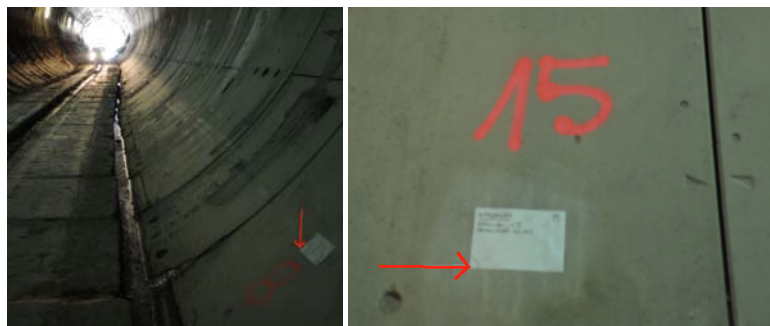


Figure 2 – photos of two of the implemented 2080 Control Point marks

The Survey

During project preparation, we realized that the Pajares Tunnels were actually divided in four different tunnel sections, as both East and West tunnels were physically divided approximately at the middle. This fact prevented entering by one side and leaving by the other one, and obliged to leave the tunnel by the same entrance. Besides this division, we had also to consider the auxiliary Folledo Tunnel. Five different survey projects were planned accordingly. Both the South Tunnels, as well as the Folledo Tunnel, were surveyed in one day in August 2011, and the North Tunnels were surveyed in two trips, due to tunnel availability for survey. The east North tunnel survey was held in one day in September 2011 and the west North tunnel latter in January 2012. Besides the *RIEGL* VMX-250, two GNSS receivers and a 4x4 pick up, two technicians were necessary for the survey, both of them for mounting the equipment, and afterwards, one for driving and one for controlling the survey.

The GNSS receiver was mounted as a base station on a known point of the traverse network outside the tunnel. The VMX-250 was mounted on the top of Artescan's 4x4 pick-up truck and after that the *RIEGL* RiAcquire software was initialized in the Control Unit and used as the software to control all acquisition processes. The GNSS initializations of the projects were made by at least 5 minutes of static adequate GNSS constellation observables with 6 to 9 satellites and PDOP's lower than 2.0. The initialization of the inertial system parameters was carried out by driving the vehicle for an average distance of 8 km, with speed and acceleration variations, until roll, pitch and yaw were below 0.018, 0.018 and 0.044 respectively. The entrances in the tunnel were made at 20 km/h, the defined acquisition speed. Using a Laser Configuration of 300 kHz for each of the VQ-250 scanners with an acquisition speed of 20km/h at an average tunnel surface distance of 3 to 5 meters, point density was 1672 pt/m² (5 x 1 cm line and point distance, respectively). After starting the scanners, logs of the data were acquired

and saved in “records”. For data storage and processing issues, records of 1 km long were saved and for each record, the associated values of X,Y,Z or Roll,Pitch,Yaw were written down by the system operator. Typically, after driving 4 kms, the Yaw accuracy parameter started to get higher and led to trajectory drifting. At the end of each tunnel portion and after stopping data acquisition, it was necessary to conduct driving maneuvers in order to invert direction and return to the entrance point. The finalization procedure was made by a similar procedure to the one of the GNSS initialization, and at the same place.

The main constraints to be considered in this survey were obviously the GPS signal outage, the short time window for the operation, the driving conditions inside the tunnel and the matter of not having a way out at the end of the linear data acquisition.

The condition of the existing “pavement” led many times to speed variations and bumps, what consequently led to Yaw parameter degradation. The infiltrations and water leakage inside the tunnel led to speed and trajectory variations and also to problems in detecting intensity variation on the control point LiDAR data that were dirty with unclean water.

The longest GPS signal outage was that of 80 minutes in the project of the East tunnel, by North entrance. The GPS signal outage, and the trajectory drifting associated to it, was assumed to be solved by trajectory adjustment using the control points every 25 meters in the data processing phase, as long as the trajectory had good initialization, good finalization and good inertial and DMI measurements during tunnel data acquisition.

As a good practice procedure, random records of each project are processed on the field, immediately after the survey and before demobilizing, so the acquired data could be evaluated on its completeness and correctness.



Figure 3 – RIEGL VMX-250 surveying the Pajares tunnel

Data Processing

This chapter will first focus on the software tools and methodologies used to achieve the tunnel point cloud within the absolute accuracy demanded for this project, and then provide just an overview of the profile extraction process, as the latter can be easily accomplished by several software packages.

The flowchart of the tunnel data processing to obtain the precise point cloud from the MLS survey is divided into three principal stages. The first stage uses MMS POSPac software from Applanix to process the trajectory. The second stage uses RiProcess software to extract, georeference, and adjust the point clouds. Finally, in the third stage, RiScan Pro software is used to filter and clean the point clouds from those points not belonging to the tunnel structure. A schematic flow diagram is added (Figure 5) to better present the work flow.

The stages presented on the Figure 5 diagram will be further explained as follows:

Within the POSPac MMS project preparation phase, trajectory and GNSS base station data was imported. The following task were the DMI variables verification and updating,

statistical standard deviations reduction to minimal, as well as assigning the correct coordinates to the point of the GNSS base station point.

With the parameterization completed, the trajectory post-processing was carried out to acquire a first temporary result. This process integrates all information from the INS-GNSS navigation system and from the DMI and applies differential corrections to the navigation, producing a new processed trajectory. To validate these results, it is mandatory that there is a RMS error analysis of the processed North, East and Down Position. At this stage, considering the context of this work, values as high as 20 m for the RMS error for the stretch of the trajectory that is inside the tunnel and smaller than 2cm for the stretch outside the tunnel were admissible. Figure 6 shows the values of the RMS error for the results on the Northing, Easting and Down Position (Height) coordinates. The units on the vertical axes are in meters and on the horizontal axes are in seconds.

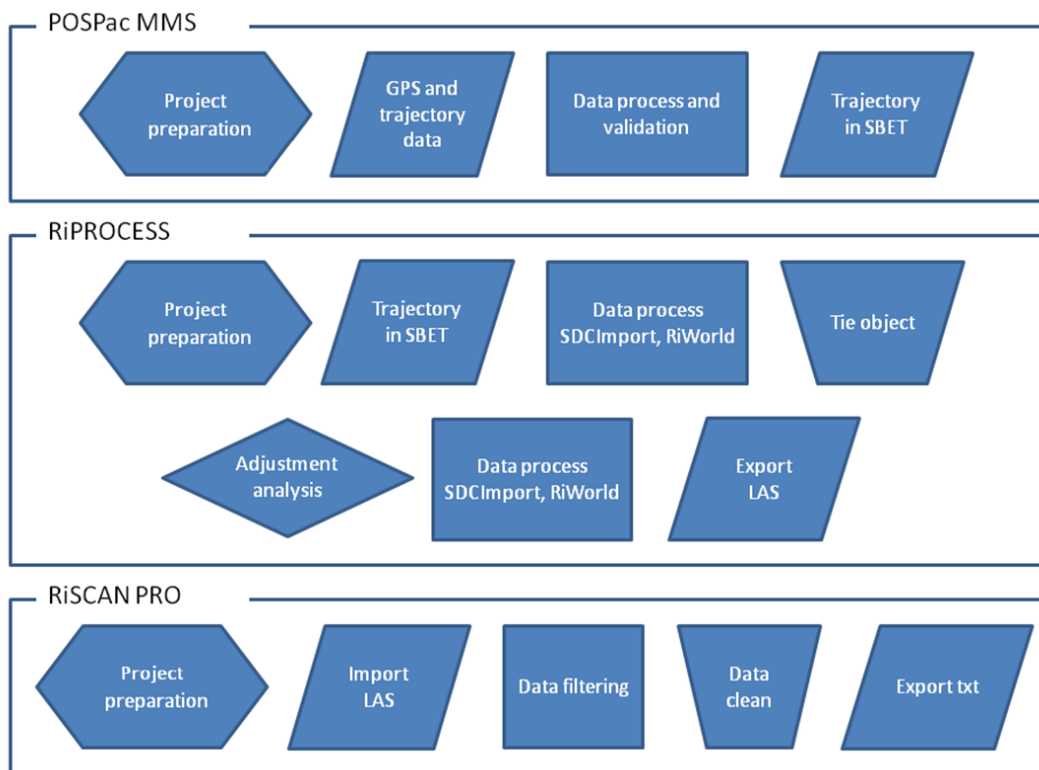


Figure 5 – Trajectory and point cloud processing in schematic flow diagram

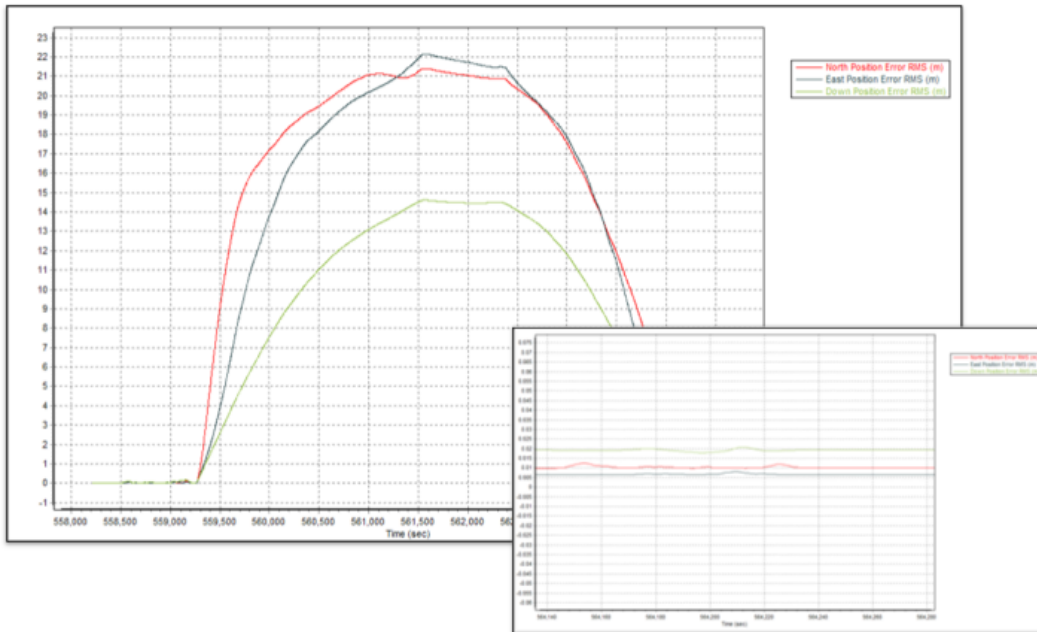


Figure 6 – Values of the RMS error for the results on the coordinates of the trajectory.

After validating the result of the post processed trajectory, this was exported in the SBET format.

The second stage of the process contemplates the use of RiProcess software, as it allows the verification and validation of the offsets and calibration matrices for the INS-GNSS and scanners, as well as the definition of the coordinate system and cartographic projection to be used and in which the point cloud data of the project should be exported.

The new trajectory was then imported in RiProcess where it was associated to the recorded data by redirecting the correspondent links. After this assignment, the data processing tasks were performed on the several records, namely Target Extraction using the SDCImport, Global Registration using RiWorld and View Preparation. A consistency validation was done between the two scanners' point clouds. With this validation accomplished, the next stage consisted in identifying over the point cloud the square stickers, to mark them as tie points and link them to the correspondent control point with well determined coordinates. The square stickers placed on the tunnels walls to mark and identify the control points had precisely 30 x 30 cm². Figure 7 presents the tie point on the point cloud over a control point and the photograph.

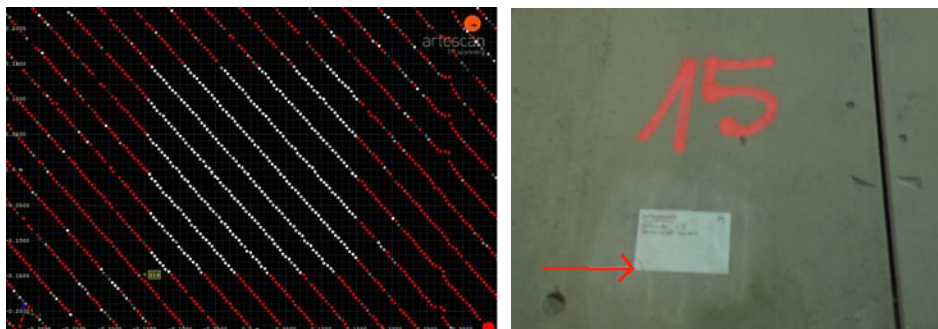


Figure 7 – Point cloud and photograph over a Control Point

In the entire project, more than 2080 Tie Objects were identified over the two tunnels and the Folledo gallery. As a reference value, an experienced user took about 2 minutes to identify

each Tie Object. The standard deviations of calculated adjustment values were always below 1 cm.

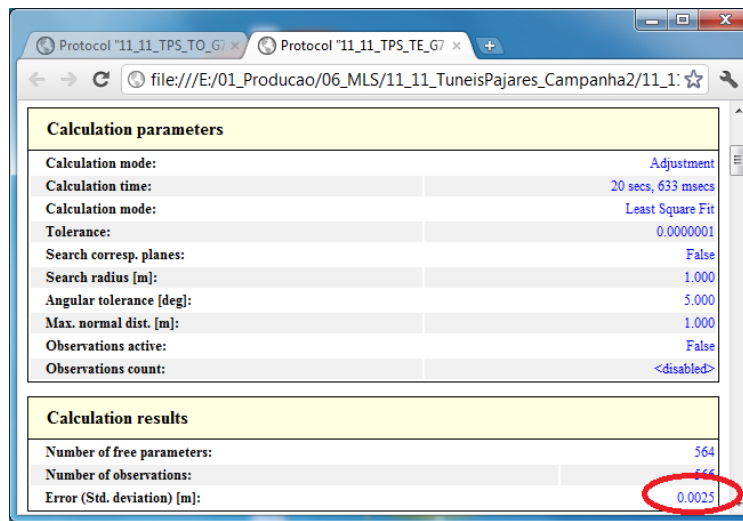


Figure 8 – Standard deviation of the adjustment calculation results

The validation of the consistency between the point clouds of the two scanners can be done through the RiProcess display mode, Height / Difference / Laserdata, applying the option Maximum Height Difference between all LASDATA objects.

Figure 9 illustrates the process on validating the position of the cloud and the consistency between them. It is noted that the points represented here are roughly within 1 band of 1cm for the two scanners and differ less than 0.5cm with respect to the Control Points.

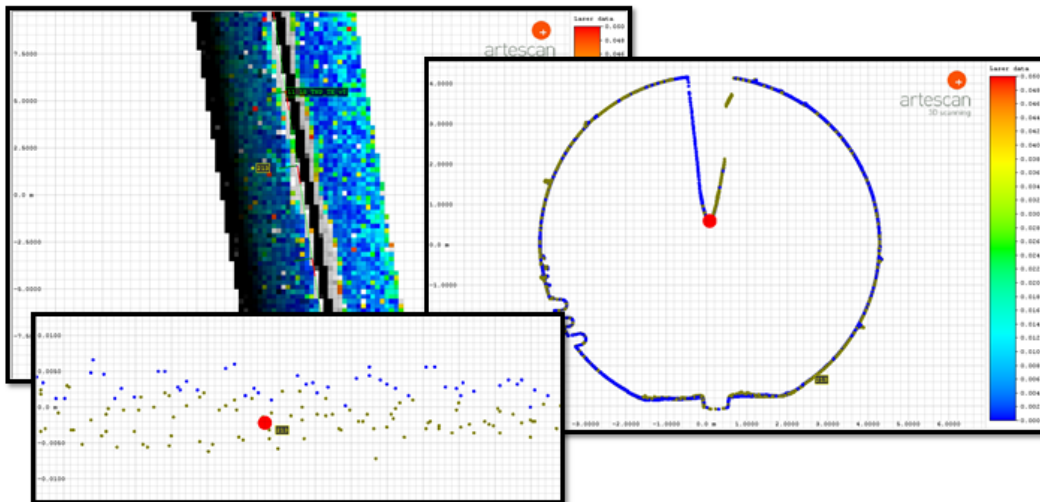


Figure 9 – RiProcess print screens on the validation process of 2 point cloud adjustments

After finalizing the point clouds validation in RiProcess, they can be exported in LAS format to be further processed in RiScan Pro.

The third phase uses RiScan Pro to filter and clean point clouds. Recalling that the final object of this work is a clean point cloud (only with points representing the walls of the tunnels) and points with a spacing of 10 cm, an Octree filter of 10 cm was applied after what manual

clean up was performed to eliminate non-tunnel wall points. As a standard procedure, we defined ranges of 20 meters where the point cloud was placed in a frontal orthogonal view to enable the selection of the points to delete (selection in red). Figure 10 illustrates the selected points to be deleted.

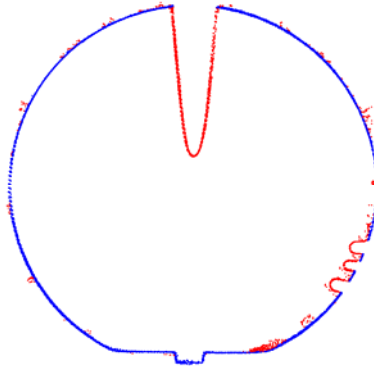


Figure 10 – Non-structural tunnel point selection (red) for deleting.

A technician took on average about 7 minutes to clean a stretch of 20 meters. After the point clouds are “cleaned” of non-structural points, they are exported into ASCII format.

Profile generation

This survey work aim was to verify the geometry of the tunnel construction to check if the clear way and the catenaries fit or if, on the contrary, some geometric adjustment must be done. Other valuable information taken from the data was the concrete volume determination used.

To answer these questions, the client asked for detailed profile extraction each 2m along the tunnels. This data processing was carried-out by the partner Spanish company Inzamac, as they had the adequate software and were interested in this processing task.

For the tunnel LiDAR data profile generation/extraction, Inzamac used the CLIP software. Using this software, the CAD tunnel construction project could be inserted, along with its defined CAD project primitives as tunnel axis and tunnel theoretical profile. These primitives were used to extract the LiDAR data profiles along the axis poly-line, and to evaluate by comparison the theoretical profiles against the LiDAR profiles, as shown in Figure 11.

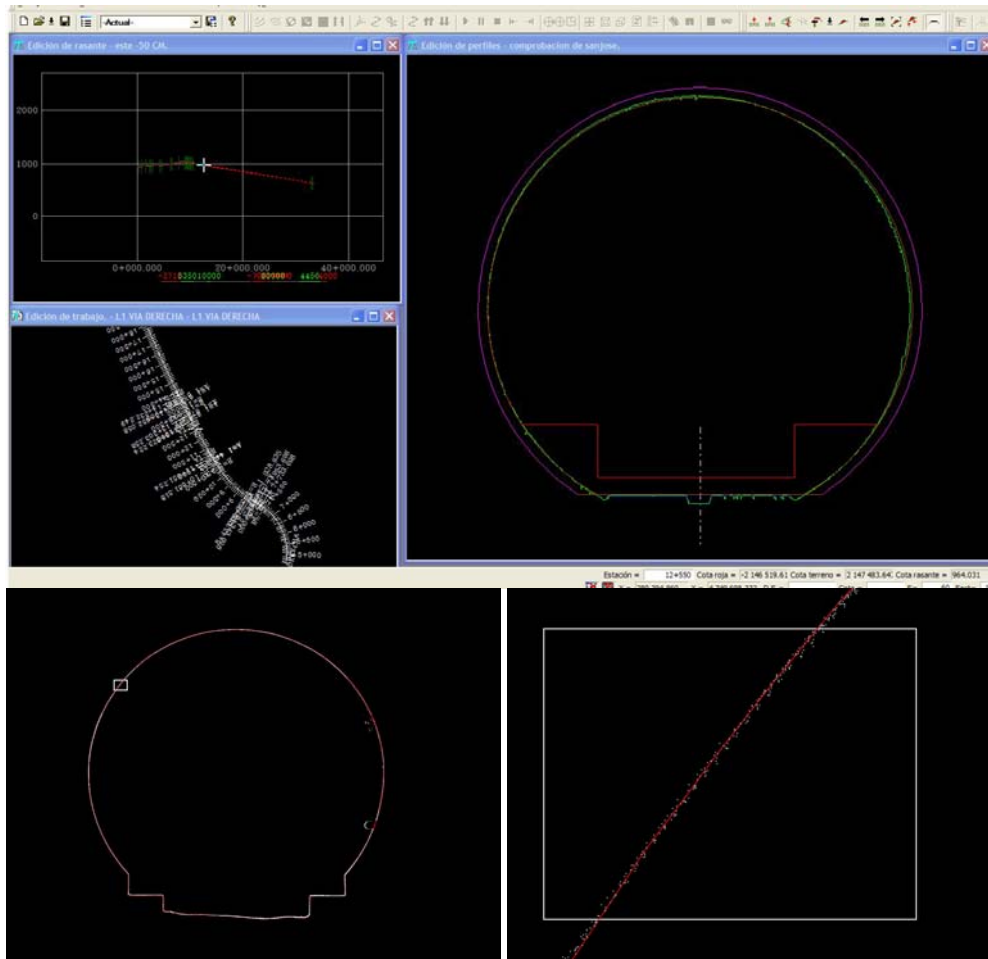


Figure 11 – Screenshot of CLIP software combining the construction CAD tunnel project with LiDAR generated profiles.

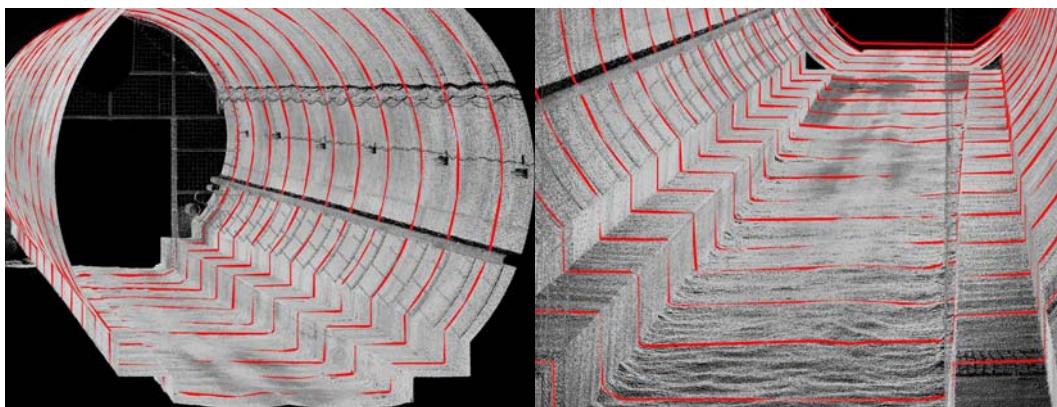


Figure 12 – MLS point cloud data combined with CAD profile along the Pajares tunnel section

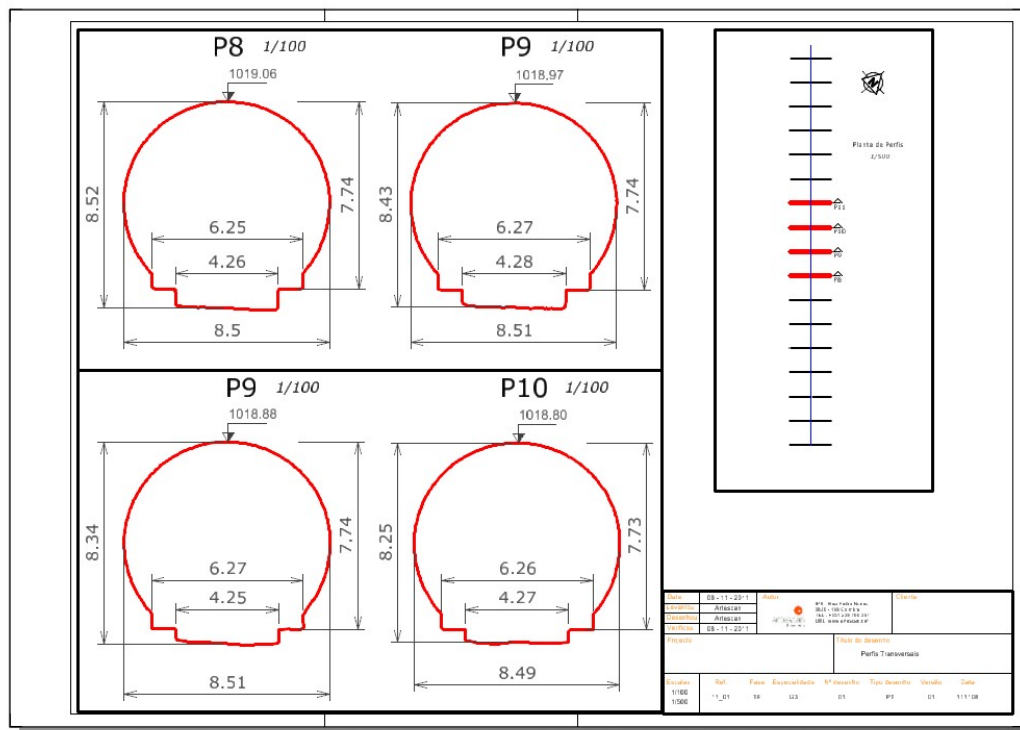


Figure 13 – Some point cloud generated profiles and evaluation of critical measurements for the tunnel project.

Results and accuracy evaluation

A quality control survey was performed to evaluate the provided profiles generated by the MLS. A random conventional total-station profile survey was carried out by the client in several sections of the tunnels. As a result, not totally disclosed to Artescan, the client informed that a majority of the differences were in the 1 to 2cm interval and maximum differences of up to 3 cm were found.

Regarding the quality of the data and tunnel coverage the results were very satisfactory. The LiDAR data acquired by the *RIEGL VMX-250* was dense enough to identify most of the existing structures, the intensity and reflectance data allowed for a perfect identification of the control points, even in unfavorable conditions, and the combination of the two *VQ-250* scanners allowed for an almost complete coverage of the tunnel, even when there were obstructions.

CONCLUSIONS

This project opened a new promising perspective for as-built long tunnel surveying. In spite of the fact that the classic traverse network and control point implementation and survey is mandatory, the survey itself of the tunnel geometry/shape can be accomplished in a much shorter time interval with almost constant LiDAR data high resolution density. This allows significant shortening of time and costs in long tunnel as-built surveying and with a higher and more valuable amount of information and quality.

The shortened time of on-site surveying can be, by itself, a major advantage in most cases, and can also be a decision issue. The tunnel availability for survey works can be difficult to manage, especially when this task is to be accomplished for long distances and when in presence of other operations inside the tunnel that shorten the time allowed or lower the condition's availability.

In this particular project, the on-site time reduction comparing MLS to TLS would have been of a factor within less 10 to 15 times, this allowing a cost reduction of approximately 70 to 80%.

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