THE CONNECTION MEASUREMENT PROCESS OF TWO NEW GALLERIES TO THE LHC TUNNEL

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Abstract

Surveying is needed at all stages of most civil engineering projects, such as the connection measurements of tunnels. In that case, the accuracy required is higher than for any other surveying application. Two long new galleries of 350 m have been excavated (around ATLAS and CMS experiments) and are connected to existing LHC tunnel by four shafts of 15 m depth. The accuracy required for this transfer of coordinates needed to be better than 5 mm. The operation was demanding due to the peculiar form of the construction and the lack of space to pass the laser beam from the total station to the targets. Thus, and because of the organisation numerous difficulties affected our results and obliged us to repeat the operation several times. During the measurement operations the worksite was not at the expected condition. The measurements had to be adapted to the conditions being. Unpredicted difficulties such as a thunderstorm of dust and air coming from the worksite affected the measurement. Safety reasons and human error posed obstacles to the project completion as well. Finally, the measurements were terminated when the site passed in CERN’s authority. The paper will present the change of strategies and methodologies due to the civil engineering conditions as well as the beforehand studies based on simulations and the results finally obtained.

INTRODUCTION

The LHC is designed to provide proton beams of 7 TeV and nominal luminosity of $10^{34} \text{cm}^{-2}\text{s}^{-1}$. This objective will be achieved by upgrading the existing CERN accelerators and infrastructure [1]. For this purpose, the High-Luminosity Large Hadron Collider (HL-LHC) project aims to crank up the performance of the LHC in order to increase the potential for discoveries after 2029 [3]. The HL-LHC is LHC’s successor, and the goal is to achieve 5 to 10 times more data/luminosities. More precisely the objective is to increase the integrated luminosity by a factor of 10 beyond the LHC’s design value.

Two diametrically opposite insertion regions in Point 1 (P1) and 5 (P5), housing the high-luminosity multipurpose experiments ATLAS and CMS 100m underground the surface, will be affected by huge civil engineering. Works started in 2018 and last until 2022. A shaft of around 80 meters was bored on each site, as well as an underground cavern and a 300-metre-long service tunnel. This service tunnel was linked to the LHC tunnel by four connecting identical tunnels (2 in each side: UPR13, UPR17 for P1 and UPR53, UPR57 for P5).

Figure 1: A schematic layout [3] showing the sections of the HL-LHC to experiments and utilities. The points referred to in the text are the top and bottom, hence ATLAS at P1, CMS at P5.

During such big projects and constructions surveying intervention is needed. For the connection of the two long new galleries of 350 m to the existing LHC tunnel through 15 m depth’s shafts, the accuracy required was higher than for any other surveying application. More precisely for the coordinates transfer the accuracy needed had to be better than 5 mm. The peculiar form of the construction and the unpredictable site situations caused by multiple factors, affected our measurements.

Figure 2: A schematic layout showing the LHC and the new inserted tunnels on the right and the left side of each Point.
STRATEGY

The HL-LHC project is a tremendous technical challenge in many technological domains, not the least in surveying operation. In order to reduce the difficulties during the measurements, multiple simulations were done. The initial strategy was to perform the measurements during the construction time, at a time where the works had progressed enough and as less obstacles as possible are present in order to have good lines of sights. Therefore, the simulations involved different point positions, heights, instruments, tripods. The goal was to ensure very high reliability and the best possible results.

To deal with the different construction stages at every operation, different possible adaptations had to be done on site such as openings in the walls, the doors or the staircase.

The equipment was prepared at the office before the operations, and some equipment was specially ordered and made at the section’s workshop to fit the sites conditions.

The simulations were done with the Logiciel général de compensation (LGC) [4][5] software that is a generic software of 3D compensation which calculates the coordinates adjustment based on the Ordinary least squares theory. The necessary input for the simulation is:

- the points considered as referenced and therefore considered as fixed, the variable ones and their approximate coordinates
- the position of the instrument
- the sequence of the measurements foreseen
- the a priori errors of the instruments

Figure 3: Example of some point coordinates’ compensation simulation. The standard deviation of some coordinates on the y-axe are slightly beyond the limits. Only the SY deviation for the GGPSO1 is bigger than in a range of 5 mm.

Many simulations were performed, with various positions of points and instruments. Plumb lines and nadir-zenithal telescope measurements were simulated as well as total stations ones. The coordinates transfer was based on known existing network points on the magnets and on the floor. Almost all the simulations were generating results with the requested accuracy, it seems that LGC simulations are perhaps a bit too optimistic. But at the end, the best configuration appeared to be with a high accuracy total station and points at different levels in the staircase.

Figure 4: Position of the stations, the bracket foreseen as well as (right) the stations and the foreseen points to be measured (GGPSO).

OPERATIONS IN UA17

1st measurement

- The measurement conditions were the ones of a civil engineering work and can be described as follows:

  - huge difference of pressure between LHC tunnel and HL-LHC, small window to ensure the measurements
  - no final concrete on walls
very few obstacles (no shielding, no concrete stairs but temporary scaffolding)
points to determined installed and fixed
no stable floor and ironing at bottom of the shaft
The measurements were performed with the LEICA TS60.

The results were not as good as expected: the accuracy criteria was exceeding a bit the limits, even tough the deviation ($1\sigma$) of the new determined points was below the 5 mm expected as shown on fig 6.

Figure 6: Results of the second operation. The standard deviation of some coordinates on the y-axe are beyond limits especially on the SY deviation for the GGPSO1 and GGPSO2.

The reasons of the poor quality of the measurements could be due to the environmental conditions (strong air current, no stable floor) or/and technical problem with the total station.

Moreover, a comparison with the coordinates issued by the civil engineering company surveyor gave deviations of more than 2 cm mainly in the x direction.

2nd measurement

A 2nd trial was made at the end of February 2020 using this time a LEICADA5005. The measurements conditions were a bit better as:
- final concrete on the floor and walls was done
- concrete stairs not installed but a scaffolding

- some shielding installed
- the new points (GGPSO) to be measured were not accessible, the idea was to leave 4 new temporary points in the final concrete at the top of the shaft and connect them to the GGPSO at a later stage

We had some problem with the TDA5005 to perform the measurements, even at very small distance, at the top of the shaft because of the presence of dust or humidity. We therefore used the TCRA2003, but as there is no ATR system, the differences between face 1 and 2 were not satisfactory. Finally, the absolute tracker AT402 was used with great success.

Nevertheless, the results were very good as the accuracy criteria was inside the limits and the deviations ($1\sigma$) of the four new points were below one mm.
temporary points had been covered by the coating and the points were lost. As a result, the measurements had to be redone.

**FINAL MEASUREMENT OF UA17**

The site passed under CERN’s authority and the measurements where not finished yet. By that time the final concrete was placed, the shielding as well as the stairs and the final floor in the UPR17 were installed. All the GGPSOs where installed, too.

The stairs’ presence complicated the operation. The idea was to take measurements, vertically, through two holes in the corners of the stairs and the gap of 15 cm between the stairs. A suggestion was to perform measurements with an absolute tracker, compensator on and off [2] mode to connect the top with the bottom of the shaft. This technique, with compensator off and instrument slightly inclined from horizontal, ensures a better accuracy of the horizontal angle when the instrument measures close to the zenith.

### Test

Before the measurements took place, a simulation test was done aiming to find what is the accuracy difference between measurements of points on the vertical of the instrument.

The test consists in measuring with the AT402 already known coordinate points in the lab. The AT402 was set up almost at the vertical of a nest. All the points were measured with the compensator on mode and this specific point with the compensator mode on and off as well. The difference between the results was insignificant, under 15dmgon.

### New simulation

In the shaft four sockets were foreseen, two under the gap in the middle of the stairs and two in the corners were there are holes. Also, there was a bracket to measure from different view the same common points.

On the top, a station would be done for the connection between the points of the shaft and the UA gallery. The two stations at the UA gallery would make the connection through the end of the gallery. Four GGPSO’s are used as well for the measurement, two of them were used as stations, too.

The results given by the simulation had a small deviation from the sigma 0, but as there were no alternative solutions at this stage, there was no other option but accept them and apply them in real conditions.

Table 1: The results of the simulations are the following:

| SIGMA 0 A POSTERIORI | (0.88334, 1.11649) |

**Figure 8:** Position of the equipment in site according to the simulation.

**Figure 9:** Position of the equipment in site derived from the conditions.
Results

During the data analysis, four different options were done, to end up in the best measurement results talking into account:

1. All the points and stations (compensator on/off)
2. All the points and stations apart the bracket stations with compensators off
3. All the points and stations apart the bracket stations with compensators on
4. All the points and stations apart the brackets (compensator on/off)

Table 2: Accuracy criteria comparison

<table>
<thead>
<tr>
<th></th>
<th>SIGMA 0 A POSTERIORI</th>
<th>VALEUR CRITIQUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.88620</td>
<td>(0.90721, 1.09268)</td>
</tr>
<tr>
<td>2</td>
<td>2.30375</td>
<td>(0.89711, 1.10675)</td>
</tr>
<tr>
<td>3</td>
<td>4.16539</td>
<td>(0.89615, 1.10371)</td>
</tr>
<tr>
<td>4</td>
<td>2.29689</td>
<td>(0.87511, 1.12470)</td>
</tr>
</tbody>
</table>

Table 3: Analytical deviations for the GGPSOs’ coordinates:

<table>
<thead>
<tr>
<th></th>
<th>SX (mm)</th>
<th>SY (mm)</th>
<th>SZ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. All measurements and stations</td>
<td>UA17.GGPSO.1</td>
<td>0.52</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>UA17.GGPSO.2</td>
<td>0.76</td>
<td>3.07</td>
</tr>
<tr>
<td></td>
<td>UA17.GGPSO.3</td>
<td>0.65</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>UA17.GGPSO.4</td>
<td>0.42</td>
<td>0.81</td>
</tr>
<tr>
<td>2. All the points and stations apart the brackets stations with compensator off</td>
<td>UA17.GGPSO.1</td>
<td>1.3</td>
<td>6.47</td>
</tr>
<tr>
<td></td>
<td>UA17.GGPSO.2</td>
<td>1.5</td>
<td>12.3</td>
</tr>
<tr>
<td></td>
<td>UA17.GGPSO.3</td>
<td>2</td>
<td>4.58</td>
</tr>
<tr>
<td></td>
<td>UA17.GGPSO.4</td>
<td>1.5</td>
<td>3.76</td>
</tr>
<tr>
<td>3. All the points and stations apart the brackets stations with compensator on</td>
<td>UA17.GGPSO.1</td>
<td>0.5</td>
<td>1.29</td>
</tr>
<tr>
<td></td>
<td>UA17.GGPSO.2</td>
<td>0.46</td>
<td>2.71</td>
</tr>
<tr>
<td></td>
<td>UA17.GGPSO.3</td>
<td>0.66</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>UA17.GGPSO.4</td>
<td>0.28</td>
<td>0.65</td>
</tr>
</tbody>
</table>

4. All the points and stations apart the brackets (compensator on/off)

|   | UA17.GGPSO.1 | 6.49 | 23.67 | 0.2 |
|   | UA17.GGPSO.2 | 3.73 | 46.72 | 0.33 |
|   | UA17.GGPSO.3 | 9.57 | 16.29 | 0.21 |
|   | UA17.GGPSO.4 | 4.27 | 13.1 | 0.19 |

The measurements with the compensator off in real conditions did not give as trustworthy results as the simulation-test had indicated.

The first combination gives a quite big SIGMA0 but not the biggest one, and the SX, SY, SZ deviations are below 1mm.

The second combination, that takes off the measurements with the compensator off but includes the measurements with the compensator on, still gives us big deviations at the SY coordinates.

The third combination, that does not consider the measurements with the compensator on, gives us much better results concerning the GGPSO’s coordinates deviations enforcing the hypothesis that something affected the results. We could accept this measurement if the SIGMA0 had a smallest deviation.

The fourth and last deviation, in which we do not take at all into account the measurements from the brackets, gives us the biggest coordinates deviations. It is reasonable as there is not a good connection between the bottom and the top of the UPR.

Finally, the most advantageous results are of the 1st case that include all the points and all the measurements. The SIGMA0 does not present the biggest deviation and the GGPSO’s deviation coordinates are less than 1mm

**CONNECTION OF THE OTHER AREAS**

The three other areas have been connected using the same technique as the final one used for the UA17.
Table 4 The results of all the campaigns are presented in the table below.

<table>
<thead>
<tr>
<th>Area</th>
<th>Date</th>
<th>Max deviation (mm)</th>
<th>Conditions</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>UA17</td>
<td>17-01-2020</td>
<td>4</td>
<td>Civil engineering</td>
<td>TS60</td>
</tr>
<tr>
<td>UA17</td>
<td>26-02-2020</td>
<td>0.25</td>
<td>Civil engineering</td>
<td>TDA5005, TCRA2003, AT403</td>
</tr>
<tr>
<td>UA17</td>
<td>30-06-2020</td>
<td>0.76</td>
<td>CERN reception</td>
<td>AT40x</td>
</tr>
<tr>
<td>UA57</td>
<td>26-08.2020</td>
<td>2.2</td>
<td>CERN reception</td>
<td>AT40x</td>
</tr>
<tr>
<td>UA13</td>
<td>30-09-2020</td>
<td>2.5</td>
<td>CERN reception</td>
<td>AT40x</td>
</tr>
<tr>
<td>UA53</td>
<td>10-11-2020</td>
<td>0.5</td>
<td>CERN reception</td>
<td>AT40x</td>
</tr>
</tbody>
</table>

REFERENCES


CONCLUSIONS

The operations took place in very complicated conditions. It is always very difficult to include complementary topographical activities at a time the works are still under the responsibility of the civil engineering company. The co-activities with many workers, the environmental conditions, thunderstorm of dust/humidity, involved many difficulties that lead to a waste of time and at poor quality work. That is why the whole procedure was repeated several times until the golden mean was found.

The risk factors that appeared during the operation measurements, could not have been predicted during the simulations’ phase. The factors identified are natural, technical, and human.

As far as it concerns the technical factors, several instruments were used. Surprisingly, the TDA5005 was not able to measure in dust and humidity conditions, but the absolute tracker AT402 was the best one to perform in all conditions, and was very efficient to measure almost at the zenith taking advantage of the powerful ATR system.

One of the most frequent problems identified on site are due to human factors, especially when on site exist several working groups. One of the major problems was that the site conditions were not as predicted and agreed before the operations. Regardless of whether a human error is voluntary or non-voluntary, they can cause frustration, loss of time and poor precision. Coactivity can turn things even worse, especially when it comes to multicultural and multi-language environments.