Published by IOP Publishing for Sissa Medialab

Received: *September 30, 2022*
Accepted: *October 3, 2022*
Published: *November 29, 2022*

Geodetic deformation measurement and analysis of the ATLAS experimental cavern at CERN

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Abstract: Caverns for large physics detectors, such as the one for the Large Hadron Collider experiments, sit nearly 100 m underground and measure several tens of meters in length, width and height. The deformation of the cavern base slab over decades has a direct influence on the relative alignment of detectors with respect to the accelerator. The expected long-term movements are larger than the fine adjustment of detectors and accelerators. In this paper, the measured deformations of the ATLAS experiment's main cavern floor and lateral walls over nearly 20 years have been analysed. The measurement series have been performed in various time intervals getting down to half a year. The used measurement techniques, such as the polar method (total station and laser tracker) and precise levelling, allow to obtain sub-millimetre precision. Even if the deformations are significantly (four times) lower compared to the predictions of the civil engineering consultants at the moment of the cavern construction, the measured ones reach values up to 5.0 mm for the base slab and up to 14.7 mm for the lateral walls.

Keywords: Overall mechanics design (support structures and materials, vibration analysis etc); Detector alignment and calibration methods (lasers, sources, particle-beams)

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https://doi.org/10.1088/1748-0221/17/11/P11041

Contents

1 Introduction

1.1 Stability of underground facilities

The construction and maintenance of underground facilities remain one of the most challenging assignments in many industries such as mining, power engineering and transport [1]. The stability of caverns below ground level is affected by the construction approach, excavation technique, geology, and in-situ stress [2]. The precise forecasting of the underground deformation is commonly discussed as part of the design, planning and construction [3]. The monitoring of constructed underground facilities is equally important in the context of forecast verification. A variety of methods and sensors allow the displacements and deformations of underground facilities to be monitored. In most cases, monitoring is used to assure the stability of a construction and thereby confirm the safety of a structure. However, when such constructions are combined with high-precision technology, even the smallest movement of walls or the floor can have a negative impact on the performance of a facility [4, 5].

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1.2 Accelerators and experiments at CERN

Particle accelerators are sensitive and demanding machines. In addition, they have often a considerable size, occupying up to several square kilometres. The scientific experiments are therefore erected underground taking advantage of the isolated environment and reducing the necessary space on the surface. The Large Hadron Collider (LHC) at CERN is currently the world's most powerful tool for particle physics research [6]. The LHC was constructed based on the same tunnel as the previous Large Electron-Positron Collider (LEP) reusing most of the existing underground infrastructure. It was still necessary to construct two new, large experimental caverns along with several adjacent technical caverns and galleries [7]. The monitoring of the LEP experiments revealed vertical movements limited to a few millimetres with respect to the smoothed accelerator during its installation and operation. The observed initial sag after cavern construction and installation of the detectors was at the level of 2.5 m for the ALEPH and DELPHI experiments [8]. Regular, long-term monitoring of the LEP experimental caverns was not required. On the other hand, understanding the stability of the civil engineering structure was a driving factor for the re-adjustment of LHC and its physics experiments. This is due to the higher alignment requirements of the different parts of the LHC detectors and of their alignment with respect to the nominal beamline of the accelerator.

ATLAS (A Toroidal LHC ApparatuS) is a general-purpose detector used to exploit the potential of the LHC accelerator. It is the largest of the LHC detectors with a length of 44 m, a diameter of 25 m and a weight of 7000 t. Eighteen ATLAS feet, which cover an area of 25 m $\times$ 9 m, support the main part of the detector [9, 10]. Accuracy at the sub-millimetre level is demanded for the measurement of ATLAS detector parts with respect to the nominal LHC beamline. In this context, it should be noted that the civil engineering specification of the ATLAS experimental cavern (known as UX15) did not include any limits for the movement of the cavern [11].

The expected operation time of the LHC at more than 25 years is significantly longer than for the LEP, which implies a different consideration of deformation for any upgrade of the accelerator and experiments. Preparations for the upgrade of the LHC to the High Luminosity LHC (HL-LHC) [12] are already ongoing, with the HL-LHC foreseen to be operational in 2029. CERN is also tabling plans for completely new facilities such as the Compact Linear Collider (CLIC) [13] and Future Circular Collider (FCC) [14]. Their construction will be based on the experience gained from the civil engineering of the LHC project and the subsequent analysis of geometric deformation.

1.3 Civil engineering

A major geological investigation was executed in 1981/82 in view of the LEP construction [15], with an even more detailed study undertaken for the construction of the ATLAS cavern in the period 1995-97. The drilling of boreholes allowed the structure of the moraine and molasses to be determined along with their geological properties, showing multiple layers of variable thickness from a few centimetres to several meters consisting mainly of sandstones and marls, as well as some transitional rock types [16]. It was also possible to get an insight into the hydrogeology of the area. The construction of the ATLAS cavern complex was challenging due to the different shafts, caverns and galleries that had to be excavated around the LEP accelerator structures and remained operational during the first years of the civil engineering works [17], see figure 1.

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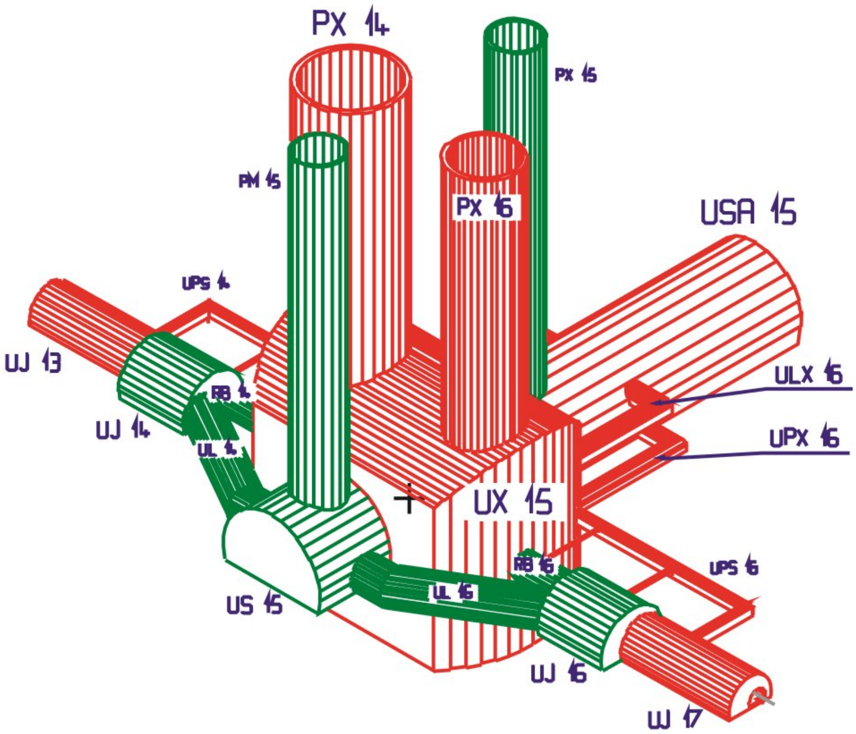

Figure 1. Layout of ATLAS underground facility [13].

The experimental cavern for the ATLAS detector has a length of 53 m, a width of 30 m and a height of the cavern vault of 35 m. The cavern base slab, situated 100 m underground, has a thickness of 5 m and is constructed using an invert to advantageously transfer the forces. It is built of highly reinforced concrete to resist the earth's pressure. The different walls and the vault of the cavern are 1–2 m thick. The USA15 is the largest adjacent technical cavern, reaching 62 m in length and with a diameter of 20 m.

Prior to the start of the civil engineering works for the LHC, simulations were performed to estimate the induced deformations of the LEP tunnel during the continued operation of the accelerator. They were based on the detailed analysis of the geological properties of the area around access Point 1 of the LHC that houses the ATLAS experiment. The predictions indicated a maximum vertical displacement of 23 mm for this area. The influence of constructions preceding the definitive stop of the LEP accelerator is limited to a region of ± 40 m with respect to the ATLAS interaction point [5].

The civil engineering consultants have provided different predictions for the vertical movements of the base slab of the completed ATLAS experimental cavern [18]:

1. Settlement of the cavern base slab by 2 mm prior to the detector installation

2. Settlement by an additional 5.5 mm consequent to the detector and infrastructure installation (8000 t)

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3. Heave of the base slab 1mm/year up to 12 mm due to pressure of the underlying ground close to the detector support (central part of the cavern)

4. Stability (defined as movements lower than 1 mm per year) not achieved even after 15 years

The calculation that provides these values by the civil engineering consultants are considered conservative and could be interpreted as a worst-case scenario.

1.4 Detector positioning requirements

The requested measurement accuracy for the assembly of the parts ranges from a few hundredths of millimetres for the pixel detector to several tenths of millimetres for the outer layer of the Muon chambers. Besides the measurement accuracy, the detector positioning accuracy includes the construction accuracy but also the placement accuracy of elements of up to 1800 t such as the TILE/Liquid Argon barrel calorimeter.

The relative alignment of the ATLAS detector to the accelerator is estimated to be 0.5–1.0 mm at the level of one standard deviation. The measurement accuracy needs to be achieved in each of the regular experimental maintenance periods to ensure a smooth restart of the equipment. The relative accuracy for the repositioning of the moving detector parts is detailed in the specification of the ATLAS Detector Positioning System (ADEPO) system [19].

1.5 Study motivation

This paper treats the geodetic measurement of the ATLAS cavern deformations on the base slab and the lateral walls. This is the first time the behaviour of such a large underground construction is studied at a sub-millimetre level of accuracy over almost 20 years. The main objective is to determine the magnitude and characteristics of the cavern deformation since its construction. In addition, the results of the base slab measurement are compared to the prediction of the civil engineering consultants.

The geometrical network in the ATLAS cavern has been regularly measured to ensure the accurate placement of the detector components with respect to the nominal accelerator beamline. Such regular measurements have also been mandatory for the maintenance and upgrade work on the experiment. This has allowed us to get a deeper understanding of the cavern deformation, with the analysis precious for the design of any future detector upgrades.

2 Methodology and materials

2.1 Deep references

CERN has two deep references installed ± 60 m on either side of the ATLAS interaction point (cavern centre). These are extensometers in vertical boreholes executed from the main accelerator tunnel. The installation took place in the period 2002–2004 during the civil engineering works of the LHC project with the references at a depth of between 8 m and 23 m below the tunnel floor, taking into account the geological situation. They have a steel anchorage of 0.5 m at their ends that have been fixed using cement grout in a layer of sandstone. This gives them the major advantage of being independent of local tunnel movements [20]. A mechanical interface has been fixed on top of the 10 mm stainless steel bar of the extensometer, which allows regular measurement with optical levelling equipment.

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2.2 Coordinate system

For the calculation of the measured coordinates and the analysis, two different coordinate systems have been used: the CERN Coordinate System (CCS) [21] for the least squares adjustment in CERN's LGC2 software [22] and the ATLAS survey coordinate system for the analysis.

The CCS is a right-handed Cartesian coordinate system synonymous with its reference frame. It is used to define the relative position of all accelerators and experiments at CERN. The adjustment software LGC2 takes into account the parameters of the CERN Geodetic Reference Frame (CGRF) [23] that is based on a densified geoid and an ellipsoid.

For the analysis of the results, the ATLAS survey coordinate system has been used as it is nearly parallel to the cavern walls and to the floor in order to ease the interpretation of the results. The ATLAS survey coordinate system is also used for the installation works in the cavern. The relation between the CCS and ATLAS system is described in [24, 25] and the ATLAS survey coordinate system is a right-handed Cartesian coordinate system defined as follows, see figure 2 [26]:

1. The origin is the nominal ATLAS interaction point.
2. The X_{SU}-axis is horizontal, in the vertical plane containing the beamline and is positive towards A-side.
3. The Y_{SU}-axis is horizontal and perpendicular to the XZ-plane and is positive towards the centre of the LHC.
4. The Z_{SU}-axis is along the local vertical line as defined by gravity, perpendicular to the XY-plane and positive to the top.

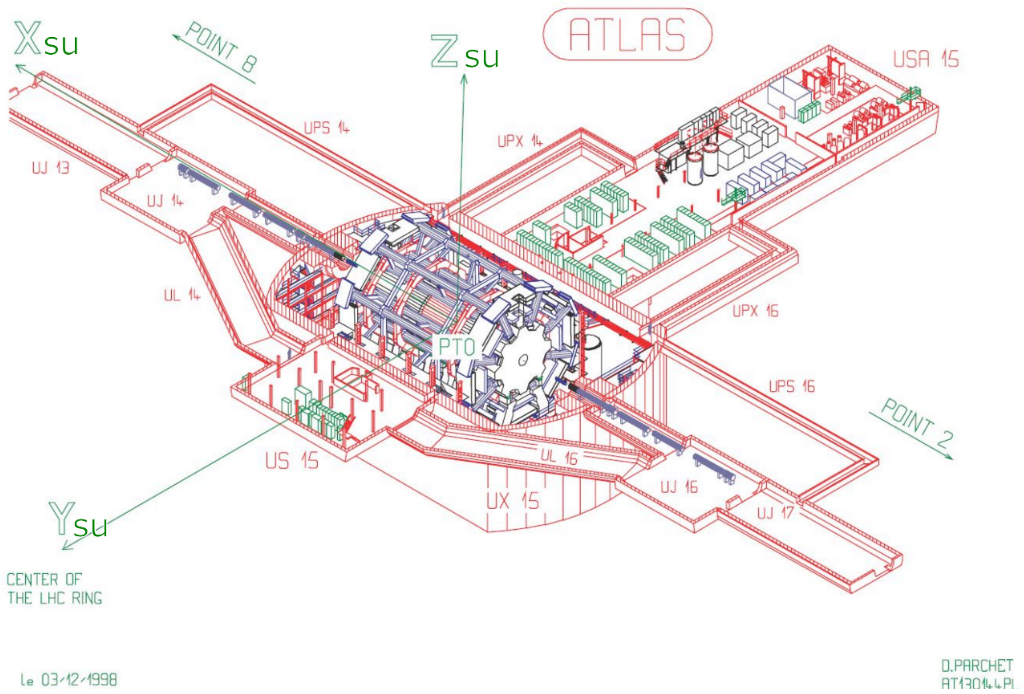

Figure 2. Definition of the ATLAS survey coordinate system.

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2.3 Measurement and equipment

The assembly and installation of the ATLAS detector was a highly complex process performed with different surveying techniques for each specific task. Due to advances in technology, the instrumentation has been upgraded from total stations to laser trackers during the monitoring period. This upgrade increased the measurement speed as well as the precision of the results. Moreover, the work could be achieved with less manpower.

Direct optical levelling has been the preferred method for measuring vertical stability up to 2013 using the Wild NA2 and N3 instruments. The specification of these instruments gives an accuracy of 0.2–0.3 mm per kilometre of double levelling, a clear advantage when measuring in the tunnel areas at up to ± 600 m on either side of the interaction point [27, 28].

For the planar and 3D measurements, manual total stations such as the Wild TC2002 were used up to 2013. The specifications of the TC2002 give an angular precision of 1.5 mgon and a distance precision of 1 mm [29]. With a calibration of the integrated opto-electronic distance meter on CERN's geodetic base, the precision could be improved by at least a factor of five with respect to these specifications, reaching 0.2 mm. Since 2013 Leica AT401/2 Laser Trackers [30, 31] have replaced the total stations and optical levels. These lightweight laser trackers are compatible with the existing reference points and have been a significant step forward for both measurement accuracy and measurement speed. The change of instrumentation increased the in-field angular accuracy by a factor of two and the accuracy of the measured distances by a factor of five. The high-precision metrology network is measured and entirely adjusted in a single 3D calculation.

2.4 Survey monuments

The definition of precise and reproducible reference points is essential for any monitoring task. In the ATLAS cavern, foldable or plug-in brackets directly connected to the concrete walls, see figure 3, are used both to support the survey instrumentation and as reference points. Their solidity makes them less prone to accidental damage from the many co-activities that take place during maintenance periods. For the base slab, holes have been drilled to install reference points sealed in the floor, protected by a cover to avoid damage. The majority of the reference points are designed to use 3.5-inch balls and prisms, based on the same concept as nests with a conical contact surface for a spherical target. The floor monuments are generally more robust than the foldable brackets on the walls.

2.5 Layout of the metrology network

The metrology network has been designed and continually adapted to meet the requirements of the different metrology works executed during the construction and maintenance of the ATLAS experiment. In total, around 100 reference points of the primary metrology network were installed mainly on the cavern base slab (30×), on the lateral walls (55×) and in the technical galleries UPS14/16 (10×), see figure 4. For short to medium-term stability, most of the survey monuments are fixed to concrete. The cavern network extends to a volume of 46 m × 30 m × 22 m with additional 40 m lengths for each of the galleries. All points are accessible using common platforms and access structures. The main height references in the experimental cavern come from two sensors of the Hydrostatic Levelling System (HLS) installed in the cavern that is regularly linked to the deep

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Figure 3. Examples of different types of survey reference monuments.

references in the LHC tunnel. A direct line of sight from the accelerator tunnel to the experimental cavern was possible in the first years of construction but it has been obstructed since 2004 when the ATLAS forward shielding was installed. The reference in the radial direction comes from the furthest sensors of the wire positioning system (WPS) in the UPS14/16 galleries that run parallel to the tunnel at a distance of 16 m. This guarantees a high-quality geometrical link between the experiment and the accelerator tunnel on either side of the cavern. As the WPS sensors are located in relatively small galleries at around 60 m from the cavern centre, they are impacted less by deformations and therefore are used as the common reference for the alignment of both the accelerator and the experiment [32].

2.6 Datum definition and data adjustment

The raw measurement data have been adjusted based on a common datum to ensure the same conditions for all epochs. Different reference points were chosen for the vertical measurement and the 3D approach. The datum for the vertical measurements is based on the height of the deep references. For multiple reasons, the height of these deep references has needed updating to ensure continuity in the monitoring. Especially during the first years after cavern construction, it was necessary to use the adjacent tunnel areas to keep the heights consistent. Reference points in the

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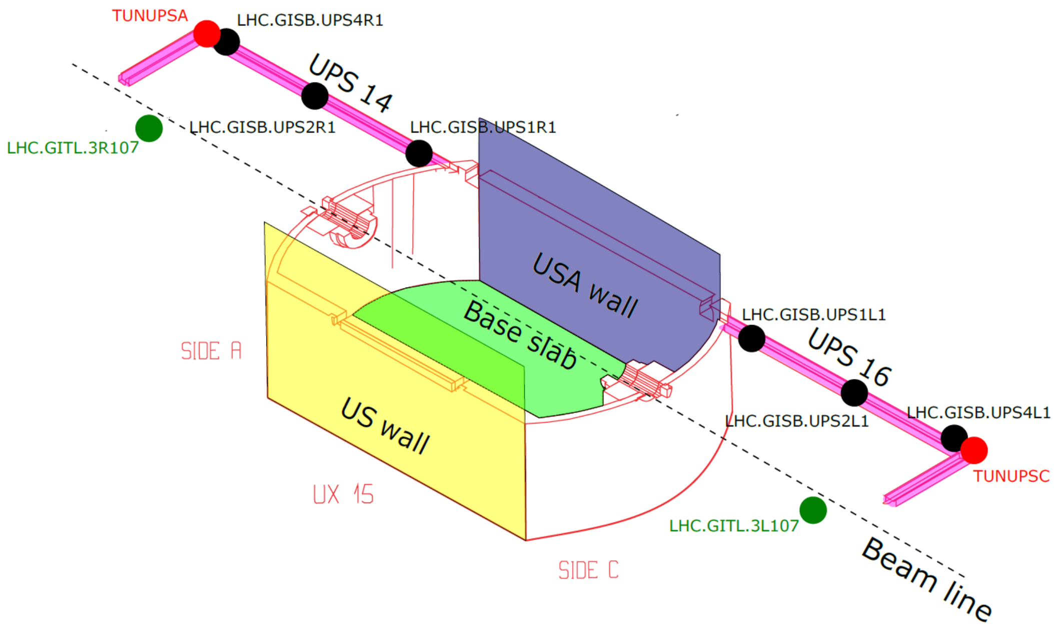

Figure 4. Layout of the measurement area and datum.

LHC tunnel, up to a distance of ± 350 m with respect to the ATLAS cavern, were taken into account in case of inconsistencies in the deep references.

The three-dimensional data have been adjusted with respect to point pairs located in the corner of the survey galleries UPS14/16, see figure 4. The points (LHC.GISB.UPS4#1), forming part of the newly installed HLS/WPS measurement system, are used as the datum since 2008, while before, the closest symmetrical pair of points (TUNUPS) was used. Due to their distance of more than 60 m to the cavern centre and their location in the small volume of the survey galleries, these points are assumed to be relatively stable over time. The observed movements after almost 20 years of monitoring have confirmed this assumption. As a datum, the coordinates of the A-side point (LHC.GISB.UPS4R1 or TUNUPSA) have been kept fixed in all three directions. The second point has been used as orientation, fixing its X-coordinate in the survey coordinate system.

The choice of datum points in such an underground environment is non-trivial. The selection of points considered as the datum for the analysis is therefore mainly based on the mechanical design, as for the deep references, or on the distance to the zones of expected movements identified by the civil engineering predictions. In both cases, regular measurements have been executed to confirm these assumptions. As the deep references give a kind of pseudo-absolute position, the approach to ATLAS surveying is based on the relative position of the ATLAS cavern with respect to the LHC tunnel.

2.7 Data extend and sorting

The archived data contain measurements since August 2003. Figure 5 shows the chronology of all epochs containing measured points on the floor and on the walls. The vertical measurements have been treated separately from the three-dimensional ones, due to the differences in the measurement technology in the first years and the fact that the measurement times did not overlap. Occasionally during calculation, measurement periods were merged to ensure a datum connection, such that all epochs had sufficient measurements and could be analysed using a common datum.

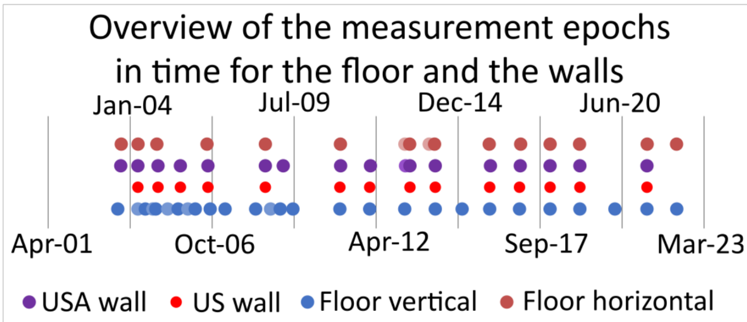

Figure 5. Overview of the measurement epochs in time for the floor and the walls.

The differences in coordinates have been calculated with respect to the most recent available epoch. The 1D data cover a representative part of the ATLAS cavern floor, while the 3D measurements contain information concerning the horizontal displacements of floor points and the movements of points located on the US and USA walls. The time interval between epochs varies depending on the accessibility and visibility of the points and the operation schedule of the LHC. However, even if the measurements did not take place at regular intervals and the number of measured points differs between epochs, the data characterizes the yearly change of the cavern geometry over a 20-year period.

The other two walls located on the A-side and C-side of the cavern (see figure 4) as well as the cavern vault have not been measured with high precision and in intervals that would allow these observations to be included in this analysis.

2.8 Mathematical observation model

The acquired observations have been used to calculate the estimates of the point coordinates and the precision of those coordinates. To find these estimates, the least square model describes the relationship between the observation acquired in the defined reference frame. Any parameter of that model can be represented by the following function (2.1) [33].

$$F_1(\overline{X}, \overline{L}) = 0, \tag{2.1}$$

where F_1 is a vector function of unknown parameters of observation, $\overline{X}$ is a vector of the unknown parameters and $\overline{L}$ is a vector of true values of observations. In addition, the vector of unknown parameters being estimated by the model is described in equation (2.2).

$$\overline{X} = X_0 + dX, \tag{2.2}$$

where X_0 is the initial estimates of the unknown parameters and dX are errors in the estimates of the unknown parameters. The observation equations are not linear in angular networks, thus a linearization is necessary. The linearization of the model is performed through a Taylor series expansion given in the form (2.3).

$$F_1(\overline{X},\overline{L}) = F_1(X_0, L) + \left.\frac{\partial F_1(\overline{X},\overline{L})}{\partial \overline{X}}\right|_{X_0,L} dX + \left.\frac{\partial F_1(\overline{X},\overline{L})}{\partial \overline{L}}\right|_{X_0,L} V = 0, \tag{2.3}$$

where L is the observed measurement values and V is the residuals in the observed measurement values. The partial derivatives, $\frac{\partial F_1(\overline{X},\overline{L})}{\partial \overline{X}}$ and $\frac{\partial F_1(\overline{X},\overline{L})}{\partial \overline{L}}$, are evaluated with the values X_0 and L for $\overline{X}$ and $\overline{L}$. The least square estimates can be presented in the matrix form as the $d\hat{X}$ vector of increments to coordinate estimates (2.4) and $\hat{V}$ vector of estimates of residual in observed measured values (2.5).

$$d\hat{X} = -(A^T(BP^{-1}B^T)^{-1}A)^{-1}A^T(BP^{-1}B^T)^{-1}W, \tag{2.4}$$

$$\hat{V} = -P^{-1}B^T(BP^{-1}B^T)^{-1}(Ad\hat{X} + W_1), \tag{2.5}$$

where P is a weight matrix that should be assigned before the least square solution, $W = F_1(X_0, L)$, $A = \frac{\partial F_1(\overline{X},\overline{L})}{\partial \overline{X}}$ and $B = \frac{\partial F_1(\overline{X},\overline{L})}{\partial \overline{L}}$. The uncertainty of estimated parameters can be derived from covariant matrix (2.6) and (2.7).

$$\sum\nolimits_{d\hat{X}} = \sigma_0^2(A^T(BP^{-1}B^T)^{-1}A)^{-1}, \tag{2.6}$$

$$\sum\nolimits_{\hat{V}} = \sigma_0^2 P^{-1}B^T(BP^{-1}B^T)^{-1}[BP^{-1} - A(A^T(BP^{-1}B^T)^{-1}A)^{-1}A^T(BP^{-1}B^T)^{-1}BP^{-1}], \tag{2.7}$$

where σ_0^2, is given by the unbiased estimate. To estimate the precision of point displacements between epochs the following formula was used (2.8).

$$\hat{\sigma_D^2} = \sigma_p^2 + \sigma_n^2, \tag{2.8}$$

where σ_p^2 is the precision of a coordinate in a primary epoch and σ_n^2 is the precision of a coordinate in a new epoch.

3 Results and discussion

3.1 Floor vertical stability

Figures 6, 7, 8 and 9 illustrate the vertical deformation of the floor. A heave has been detected for the majority of the 26 epochs since construction. The exceptions are certain periods mainly during the initial ATLAS construction phase (2003–2009). The total deformation between July 2003 and March 2022 adds up to a maximum of 5.0 mm. The initial measurements in July 2003 had a relatively poor accuracy, with a mean standard deviation of 0.35 mm, as they were based on polar trigonometry rather than precise levelling or laser tracker measurements. This improved to a standard deviation of 0.18 mm between 2003 and 2005, and since August 2005 the average accuracy of this height measurement has remained unchanged with a standard deviation of 0.09 mm. The largest deformations of the base slab are seen in the central part and in particular close to the ATLAS feet on the USA side. The more stable parts of the floor are seen to be found close to the corners of the cavern.

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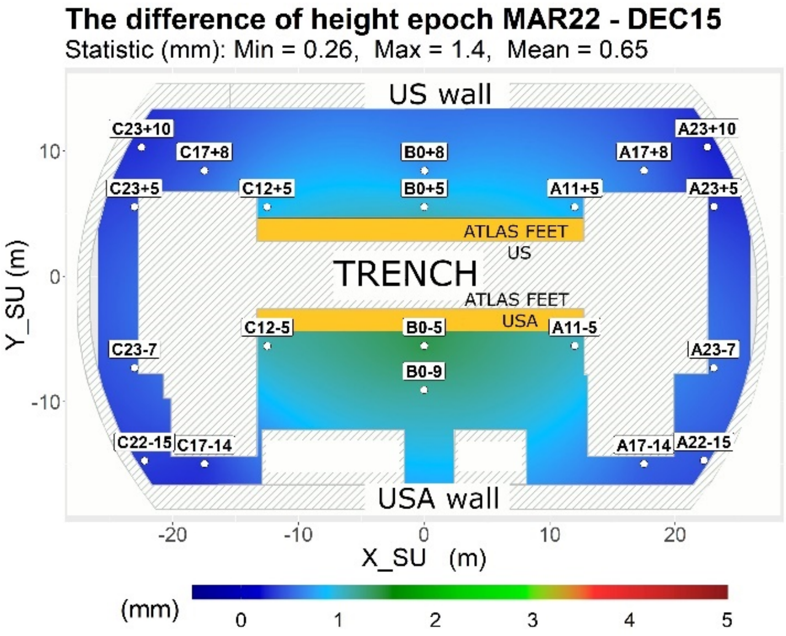

Figure 6. The vertical deformation of the ATLAS cavern floor comparing measurements from December 2015 with those from March 2022.

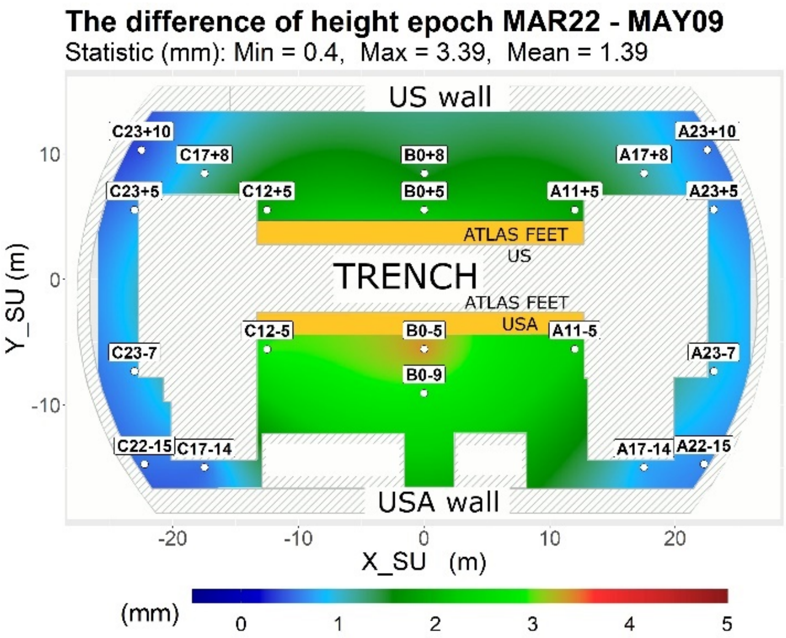

Figure 7. The vertical deformation of the ATLAS cavern floor comparing measurements from May 2009 with those from March 2022.

Knowledge of the floor deformation is critical for the ATLAS experiment as it affects the position of the detector and hence its alignment with respect to the accelerator. For that reason, the floor points have been measured more frequently than the wall points.

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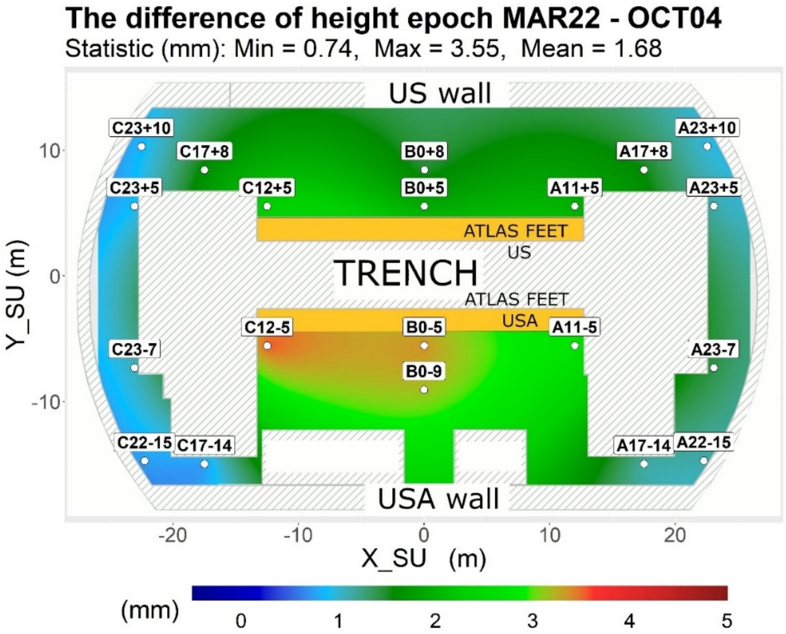

Figure 8. The vertical deformation of the ATLAS cavern floor comparing measurements from October 2004 with those from March 2022.

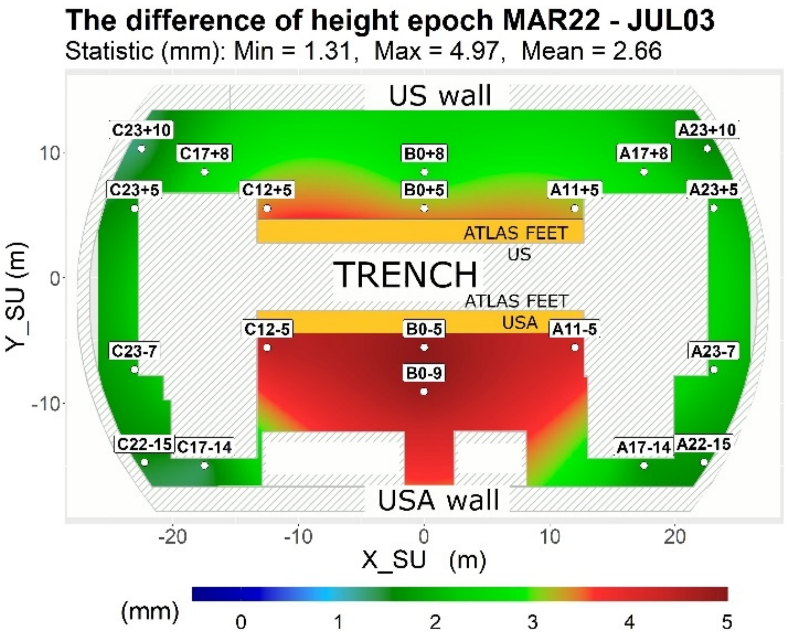

Figure 9. The vertical deformation of the ATLAS cavern floor comparing measurements from July 2003 with those from March 2022.

The measurement is focused on the cavern base slab and particular interest has been paid to the central part of the floor at the location of the ATLAS feet. Although the central area of the cavern is crucial, it has not been available for measurements in several epochs as it was obstructed by ATLAS

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construction and upgrade works. As a consequence, the reliability of the measured points varies from epoch to epoch. The measurement configuration has been adapted for each epoch to keep a similar statistical output.

The ATLAS detector axis is laterally shifted with respect to the cavern axis, creating an unbalanced distribution of the detector weight on the cavern floor. In addition, the base slab includes several asymmetrically shaped trenches as shown in figure 9. These facts could cause differences in floor rigidity and explain the stronger heave of the cavern floor next to the ATLAS feet on the USA side.

3.2 Regional comparison of the base slab

Figure 10 shows the average vertical movement of the cavern centre, defined as the average of the 8 points close to the area of the ATLAS feet. The movement of the cavern corners is presented as an average of 4 points. Both centre and corners move up by around 1 mm during the first period after the handover of the cavern by the civil engineers. The deformations of the cavern centre became negative between 2005 and 2008 when the ATLAS experiment installation entered its final phase, and since the start of LHC operation in 2009, the displacement speed has stabilised at an average value of 0.15 mm/year with respect to the cavern corners.

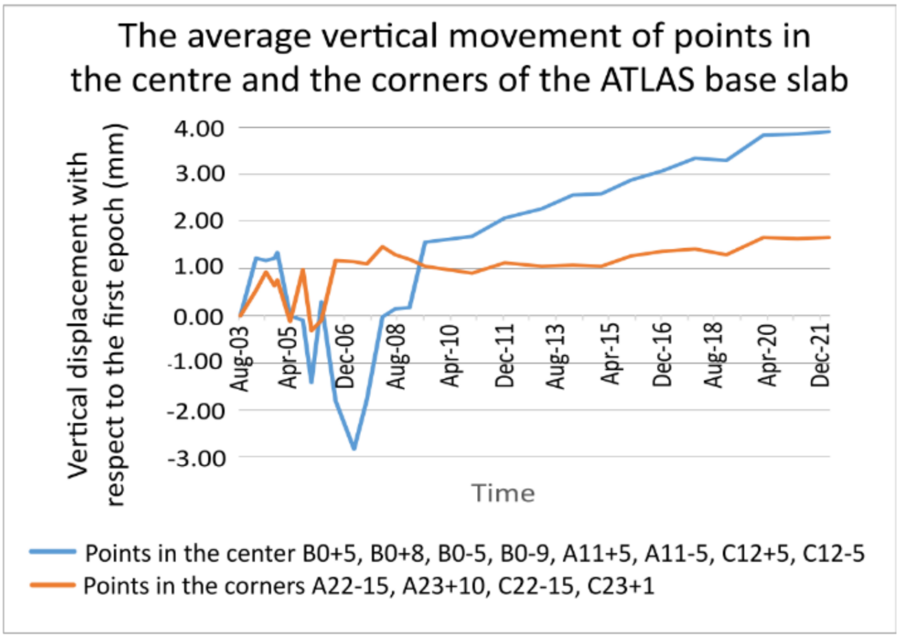

Figure 10. The average vertical movement of points in the central area and in the corners of the ATLAS base slab.

Two opposite phenomena have an impact on the deformation in the central area of the base slab: the upward pressure of the earth and the load of the detector. The interplay between the two different regions of the base slab has resulted in the current position of the ATLAS experimental setup. The corner areas are the most stable zones on the floor, confirmed by long-term observation; see figures 6, 7, 8 and 9, while the forces of the earth pressure and the detector load have the largest effect in the centre area.

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The rapid heave observed during the first year of monitoring may be explained by the newly excavated cavern and the recently poured concrete. The movement is reversed once a major part of the detector load has been added on the base slab, with the floor pushed down exactly in the area of the ATLAS feet.

Once the construction of the ATLAS experiment was complete the earth pressure started deforming the floor once more, inducing a heave in the centre. The magnitude of the movement is not as large as right after the construction of the cavern but is noticeable with a constant level of yearly change since 2009.

3.3 Horizontal floor stability

Figures 11, 12, 13 and 14 show the horizontal displacement of points on the floor. The arrows indicate the direction and magnitude of the displacement vectors. The accuracy of the points is presented as scaled error ellipses. Considering 14 measurement epochs and excluding the measurement of August 2003, the horizontal displacement does not exceed 1.3 mm for any point. The average horizontal movement of 8 points near the ATLAS feet is limited to 0.5 mm in the period from 2004 to 2022. This is a confirmation that the centre of the floor remains horizontally stable throughout the entire monitoring period, while points on the A-side and C-side tend to move towards the USA wall and the centre for most of the analysed epochs.

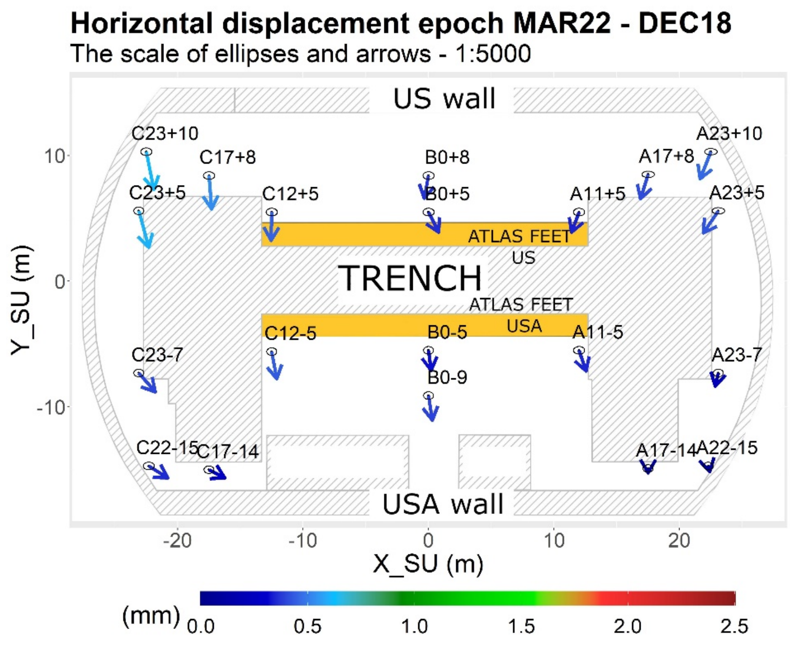

Figure 11. The horizontal deformation of the ATLAS cavern floor comparing measurements from December 2018 with those from March 2022.

In the case of 2D floor deformation in the X_{SU}-Y_{SU} plane, the most important parameter is the deformation in the Y_{SU} direction perpendicular to the beamline, as any displacement creates an eccentric position of the detector with respect to the beamline. This can lead to a reduction in the performance of the ATLAS detector and could contribute to the asymmetric ageing of certain

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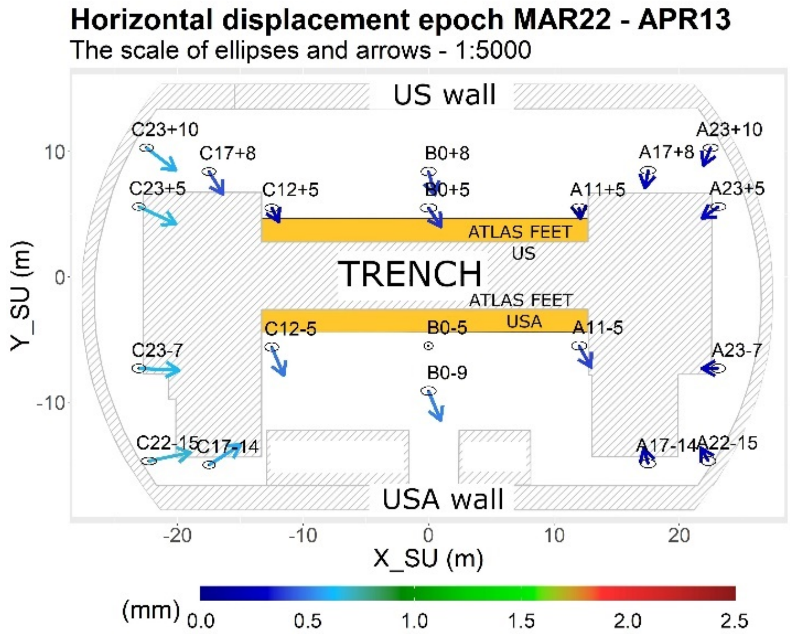

Figure 12. The horizontal deformation of the ATLAS cavern floor comparing measurements from April 2013 with those from March 2022.

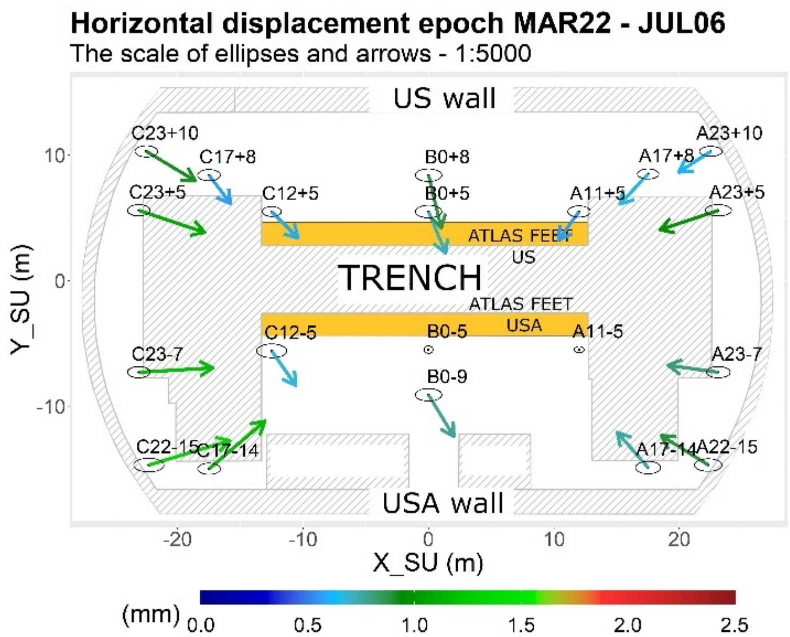

Figure 13. The horizontal deformation of the ATLAS cavern floor comparing measurements from July 2006 with those from March 2022.

detector parts [34]. The alignment along the X_{SU} axis, in the nominal beamline direction, is less critical as any misalignments still maintain a symmetric distance of the detector components to the beamline.

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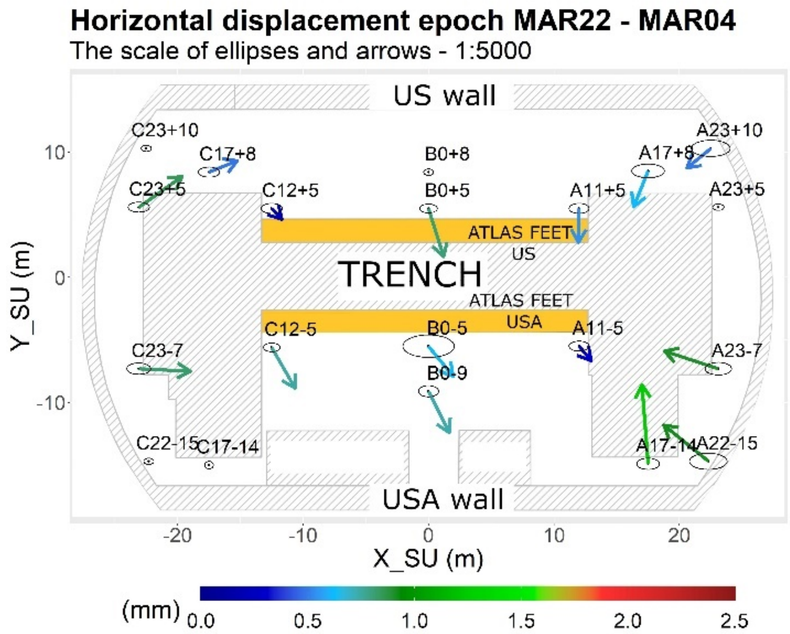

Figure 14. The horizontal deformation of the ATLAS cavern floor comparing measurements from March 2004 with those from March 2022.

Similar to the 1D stability along Z_{SU}, the most sensitive part of the floor to horizontal movement is the central part, due to its proximity to the ATLAS feet. The average horizontal movement since 2004 confirms a relatively small shift of the central part of the base slab in the Y_{SU}-direction. This behaviour has allowed the experiment to maintain the correct position with respect to the nominal interaction point. On the other hand, a movement of points on both the A and C sides towards the centre of the cavern can be seen, which could be an effect of the thermal expansion of the cavern base slab resulting in a scaling factor.

The first epoch acquired in August 2003 is not as precise as the following epochs. This can be explained by a different measurement technique and the environmental conditions associated with parallel civil engineering works such as temperature differences, significant airflow and construction co-activities. In addition, the process of concrete setting influences the result. The second measurement epoch in March 2004, as presented in figure 14, took place as the newly constructed cavern was gradually stabilizing after the end of the civil engineering works. The 2D movement decreases significantly after the ATLAS detector construction phase is completed in 2009.

Figure 11 shows a recent, systematic movement of all points, with a displacement towards the USA wall that is difficult to interpret. This might be connected to the ongoing civil engineering works for the LHC upgrade that are taking place since 2019. Due to this, the analysis for the remaining epochs shows horizontal movement along the Y_{SU}-axis. The influence of this displacement on the centre of the detector is limited due to the vertical movement of the base slab. As there is a stronger heave on the USA side, this induces a displacement of the detector centre towards the US wall which is enhanced due to the lever arm effect. The horizontal and vertical movements, therefore, mitigate each other when considering their influence on the centre of the detector.

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3.4 Walls stability

Both the USA and US walls have been subject to a similar analysis as the floor since 2003. Y_{SU}-coordinate differences have been calculated with respect to the most recent epoch in March 2021, showing that the magnitude of the movement in the perpendicular direction to these walls is much higher than for the floor, reaching up to 11.2 mm for the US wall and up to 14.7 mm for the USA wall. The measured vectors indicate a movement of both walls towards the centre of the cavern. The accuracy of point coordinates can be estimated to be better than 0.15 mm. It is visible that points near the centre of the wall are more affected by this movement than points close to the wall corners, similar to what was observed on the floor. The displacement has been increasing over the years and is in the direction expected from the earth's pressure.

The distribution of points on the walls is less adapted for monitoring purposes as the reference points are less numerous and not equally distributed. A detailed analysis of the wall deformation is not considered reasonable.

4 Conclusion

The precise observation of the geometrical network of the ATLAS cavern for nearly 20 years gives some important information on the stability and behaviour of the underground cavern. To meet the constraints applied to the detector positioning, it is necessary to take into account the deformation of the cavern, since it has an influence on the detector position. The values of the deformation reach 5.0 mm for the floor which are significant. In addition, the non-linear character of the deformation makes precise forecasting extremely difficult, added to the fact that recent civil engineering works for the LHC upgrade could be further influencing the deformation.

It is possible to distinguish three main periods of floor movements. The first is the phase at the end of cavern construction, which is characterised by a sharp rise of the floor. The second concerns the installation of the ATLAS detector from 2005 to 2008, where the floor experiences a noticeable sag in the centre. Finally, from 2009 onwards, as the LHC enters operation, the movement stabilises with the heave of the floor centre around 0.15 mm/year with respect to the cavern corners.

The measured vertical deformation is significantly lower than the civil engineering predictions for the cavern with the installed detector that can therefore be considered very conservative. The predicted vertical heave of 1 mm/year has never been reached since the handover of the ATLAS cavern, with the highest heave since the start of LHC operation being 0.30 mm/year for a single point and 0.15 mm/year on average for the entire floor. Even after 20 years, this heave continues on the base slab.

The conclusion from this characterisation of base slab movement is that the range and sensitivity of the chosen measurement system were well adapted and that the detected continued deformation should be taken into consideration during the design of the mechanical adjustment system for any future upgrades.

The horizontal stability of the floor has been monitored using polar techniques, where the maximal horizontal movements are almost 5 times smaller than in the vertical plane, at an average of only 0.5 mm. The largest deformation is visible on the end sides towards the USA wall, however, the movement is irregular and difficult to interpret, but might be explained by the excavation works taking place for the LHC upgrade in the close vicinity that started in 2018.

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Wall monitoring shows significant deformation of both lateral walls despite the limited measurement accuracy. The deformation is three times larger than for the base slab, influenced by the weight of the detector. This is especially visible on the USA wall with the deformation reaching almost 15 mm, which is 4 mm larger than for the US.

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