DEVELOPMENT OF A NEW LEVELLING PROCESS INTEGRATED INTO A 3D GLOBAL CALCULATION

G. Kautzmann on behalf of: J.-F. Fuchs, J.-F. Segers, C. Vendeuvre, Geneva, Switzerland

11 October 2024

AGENDA

HL-LHC and FRAS

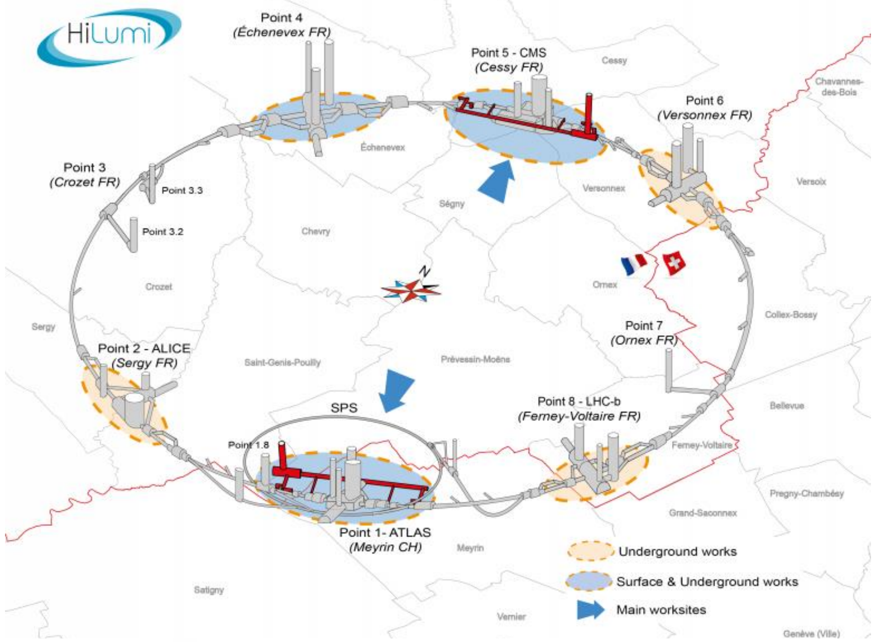
2D + 1 and LEVELLING AT CERN

DLEV STUDIES

LEVELLING PROCESS UPDATE

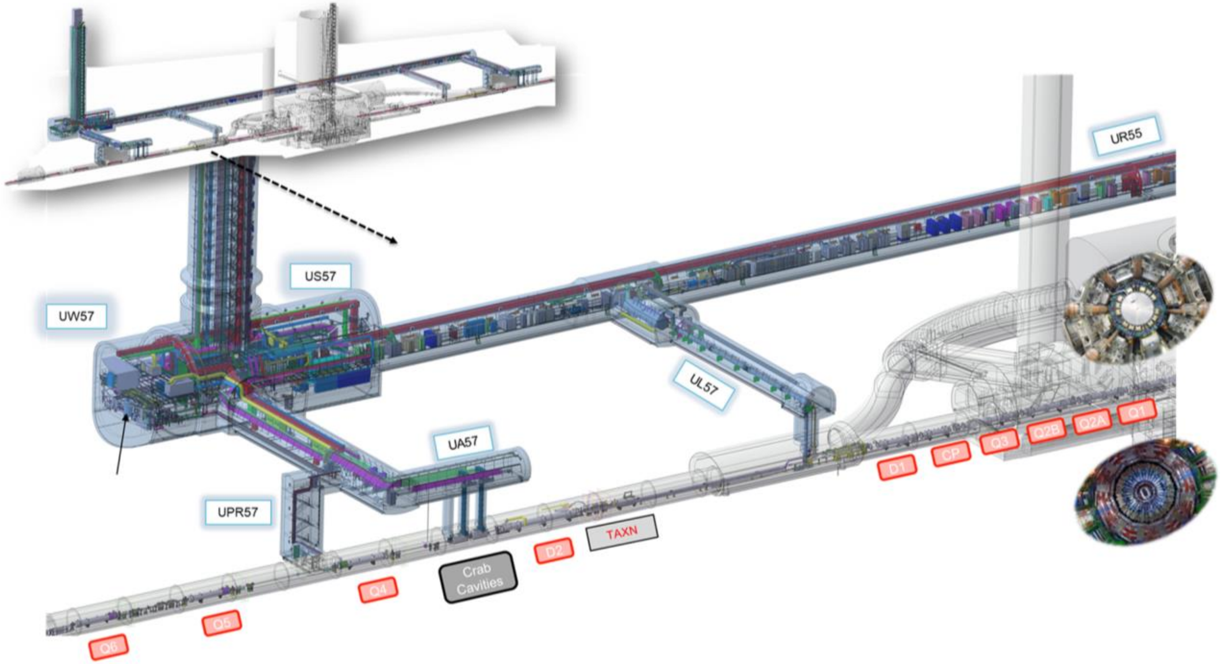
PERSPECTIVES ….

HL-LHC & FRAS



HL-LHC Project will be installed during the LS3 in PT1 and PT5 (LHC)

- High radiation level

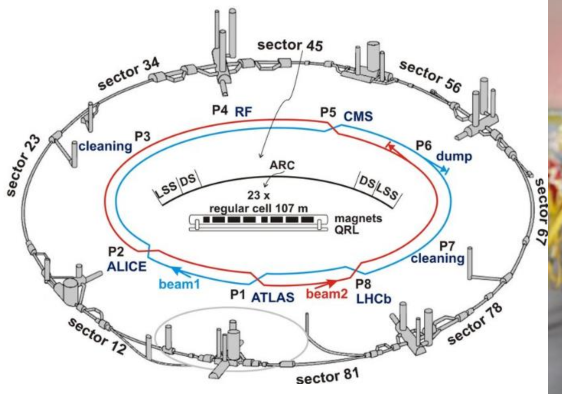


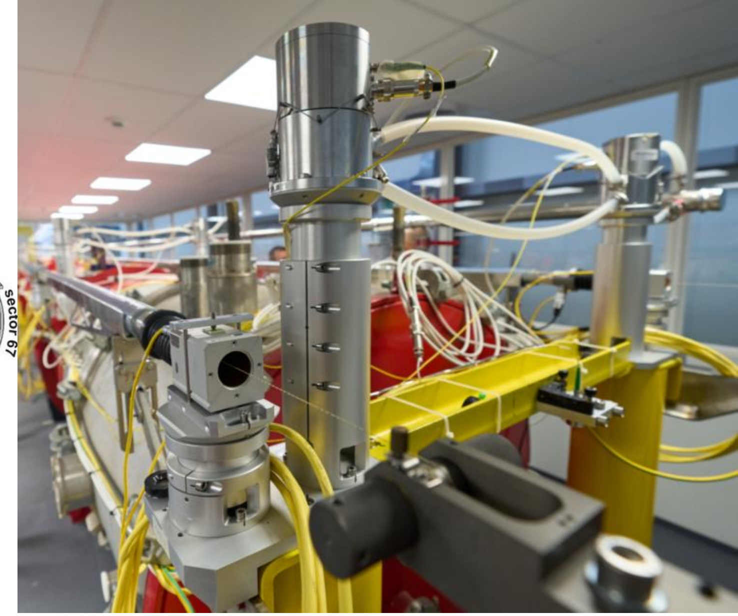
FRAS (Full Remote Alignment System)

- The remote determination of the position will be performed by **alignment sensors**
- The remote adjustment will be carried out by motorized jacks or platforms

[**Helene's Presentation**]

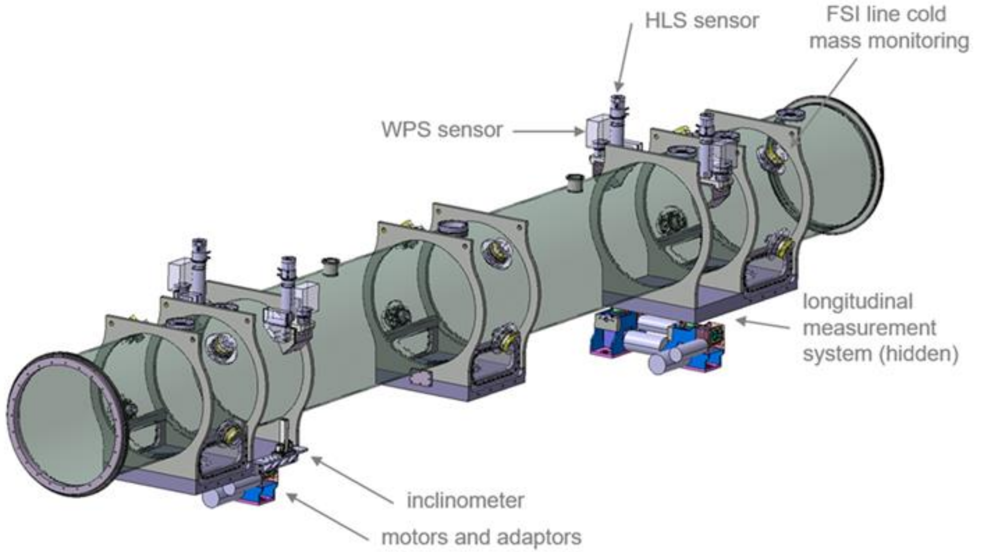
HL-LHC & FRAS

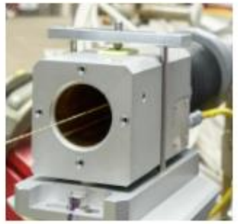




About 26.5km of LHC will still need to be regularly smoothed using a standard solution

- A new workflow is studied with automation measurement by photogrammetry **to link standard components to FRAS Area**
  [**Florian's Presentation**]
- The LHC smoothing process should be adapted near PT1 and PT5 as the sensor input will be delivered **only in 3D format** (compared to "2D + 1" today)





WPS

HLS

With FRAS, a new smoothing strategy should be developed for LSS1 and LSS5 moving from a 2D+1 to a 3D process

Components are equipped with a combination of capacitive WPS, FSI based HLS

AGENDA

HL-LHC and FRAS

2D + 1 and LEVELLING AT CERN

DLEV STUDIES

LEVELLING PROCESS UPDATE

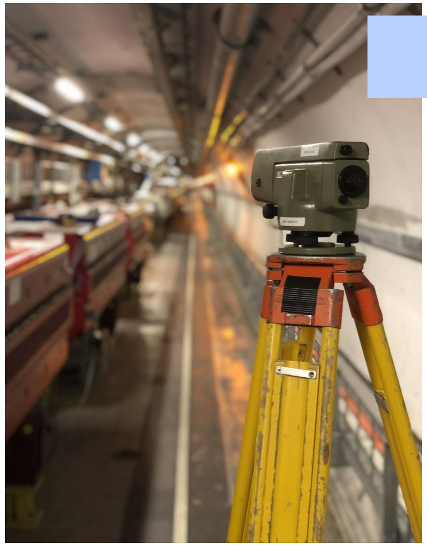
PERSPECTIVES ….

2D + 1 Process

Direct levelling remains the most efficient for accurate vertical measurements over long distances (> 200 m)
For decades CERN surveyors have been smoothing beamlines using the 2D + 1 measurement and calculation process

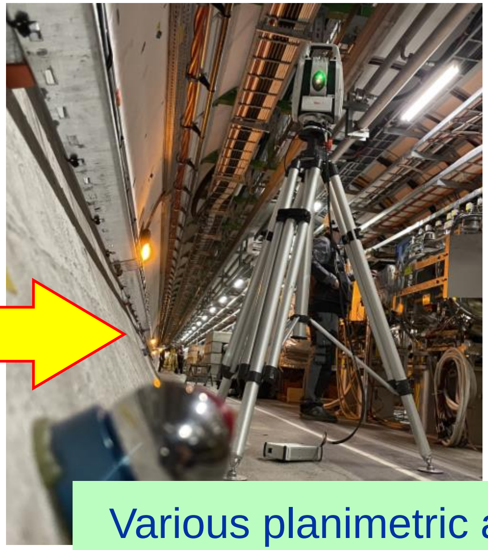
Various levelling input

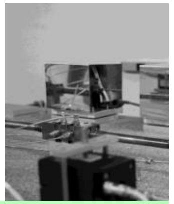
LS15 (digital level)



NA2 (Optical level)

HLS Sensors





Various planimetric and 3D measurements

AT403 (Laser tracker), Ecartometry (wire offset measurements), sensors, …..

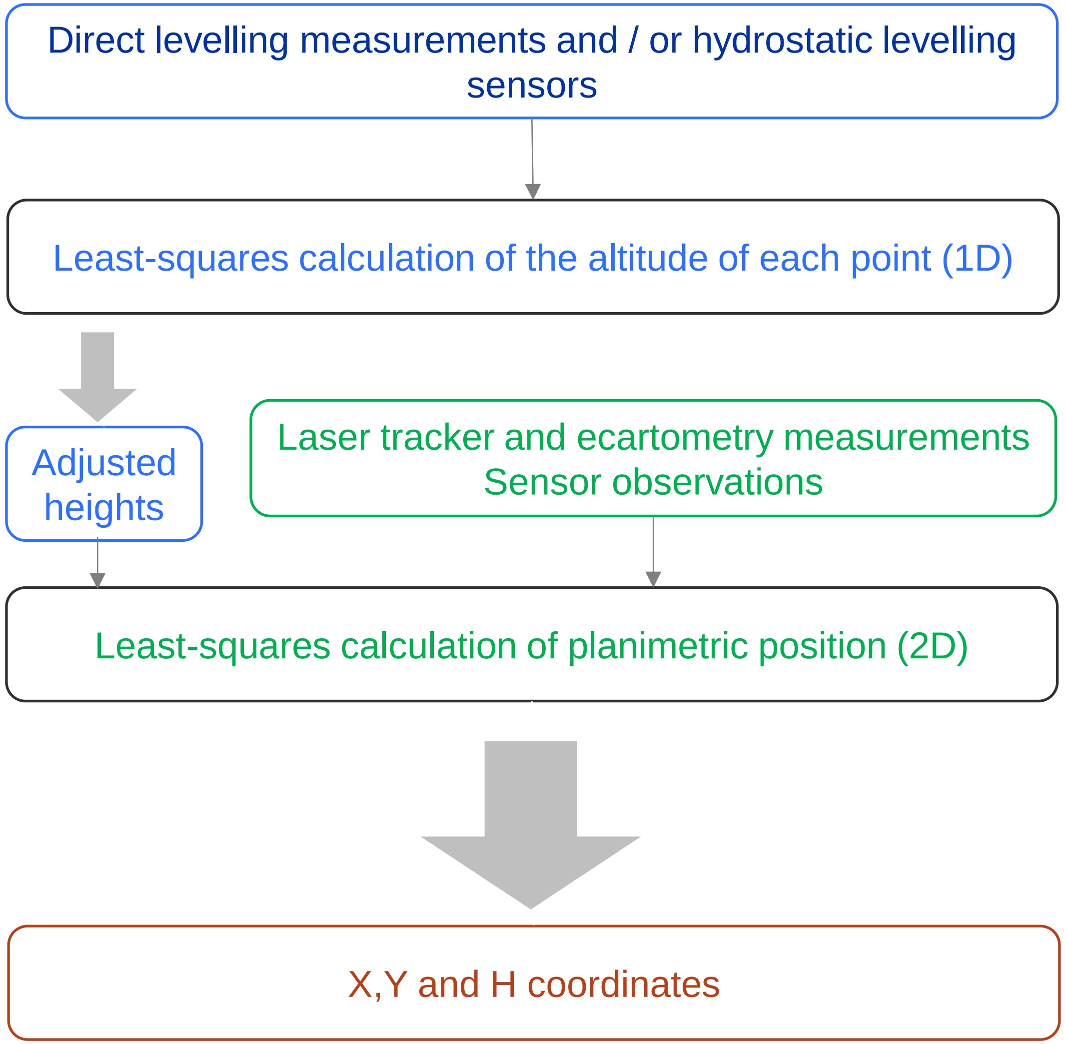
2D + 1 Process

2 steps computation using LGC (in-house Least Square Adjustment)

1. Levelling: DVER / OLOC (Cartesian)
2. Other observations : RS2K Datum (Geodetic)

Today direct levelling and 3D measurement cannot be combined within a single geodetic computation (RS2K)

Use of another LGC observation model (DLEV) for full 3D computation



AGENDA

HL-LHC and FRAS

2D + 1 and LEVELLING AT CERN

DLEV STUDIES

LEVELLING PROCESS UPDATE

PERSPECTIVES ….

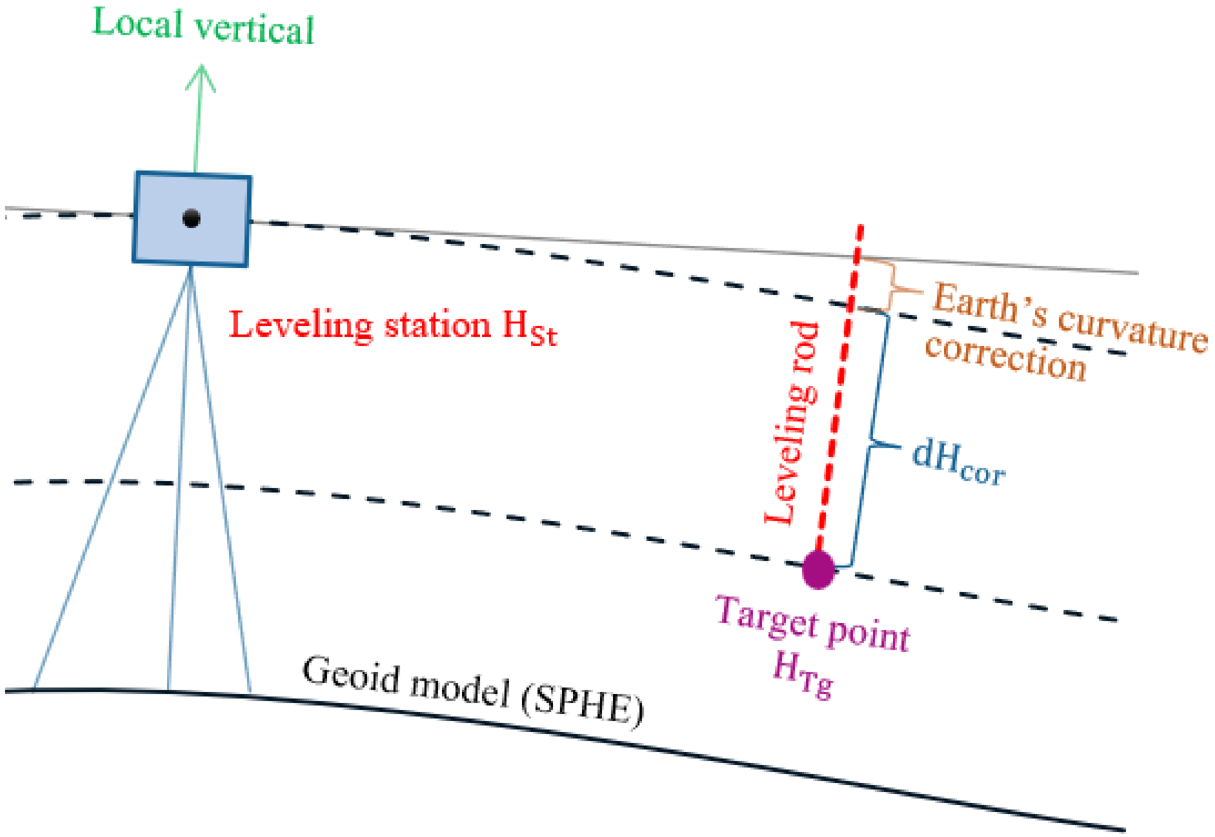
DVER?

A simple difference in height between 2 points

Used in the normal process as a 1D vertical computation in a Cartesian System

Limitations:

- Earth Curvature and collimation
  - Nullified by acq. procedure (equidistant shots)
  - To be corrected with distance observation (digital level)
- Not using the direct observation
- Not adapted for 3D computations



DLEV?

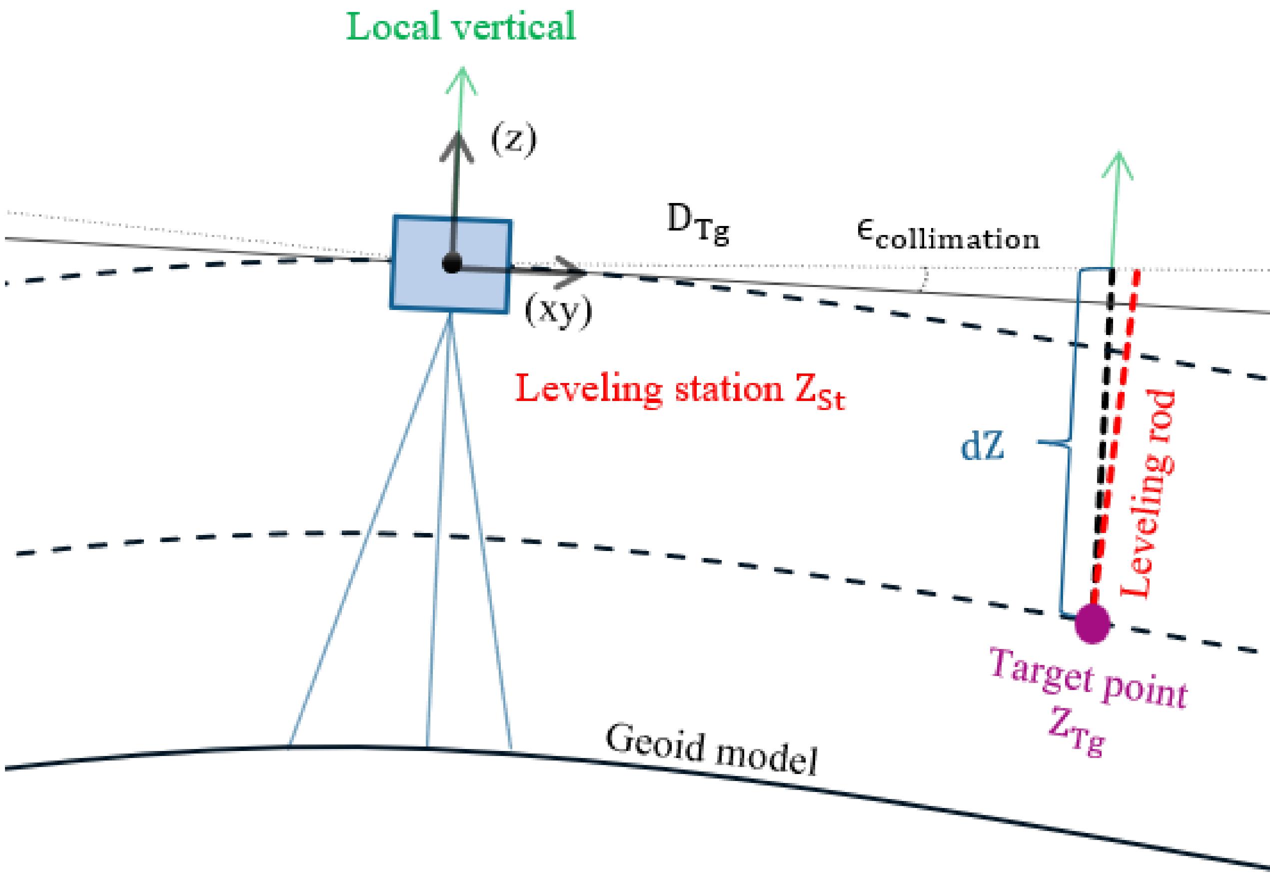
Offset to a horizontal plane

Considering the geoid model

Use of the raw observation

Can estimate the collimation error during the Least Square process

Adapted to 3D calculation



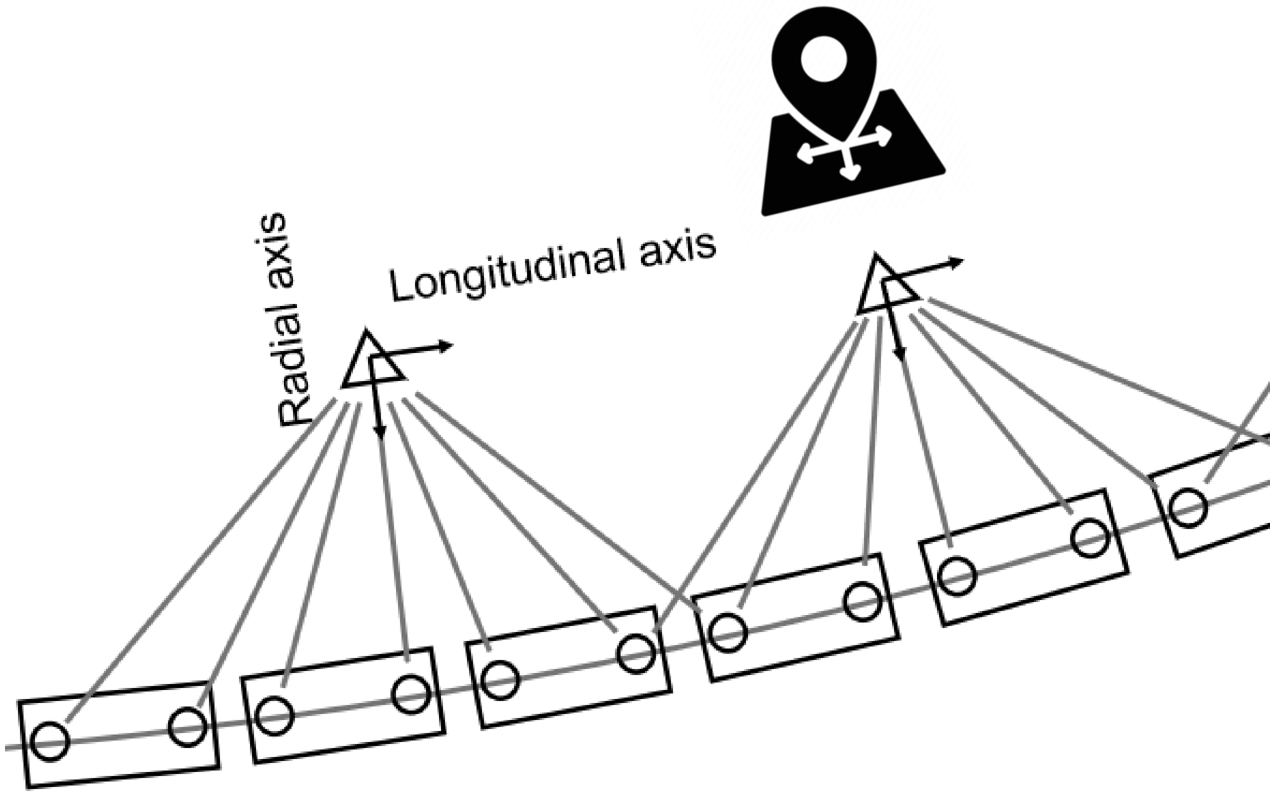
Limitations:

- Need to know the position of the station
- Acquisition and workflow to adapt

DLEV: Station position error

The DLEV model requires an input that includes the coordinates of levelling stations and target points

How well should the station position be known longitudinally and radially?

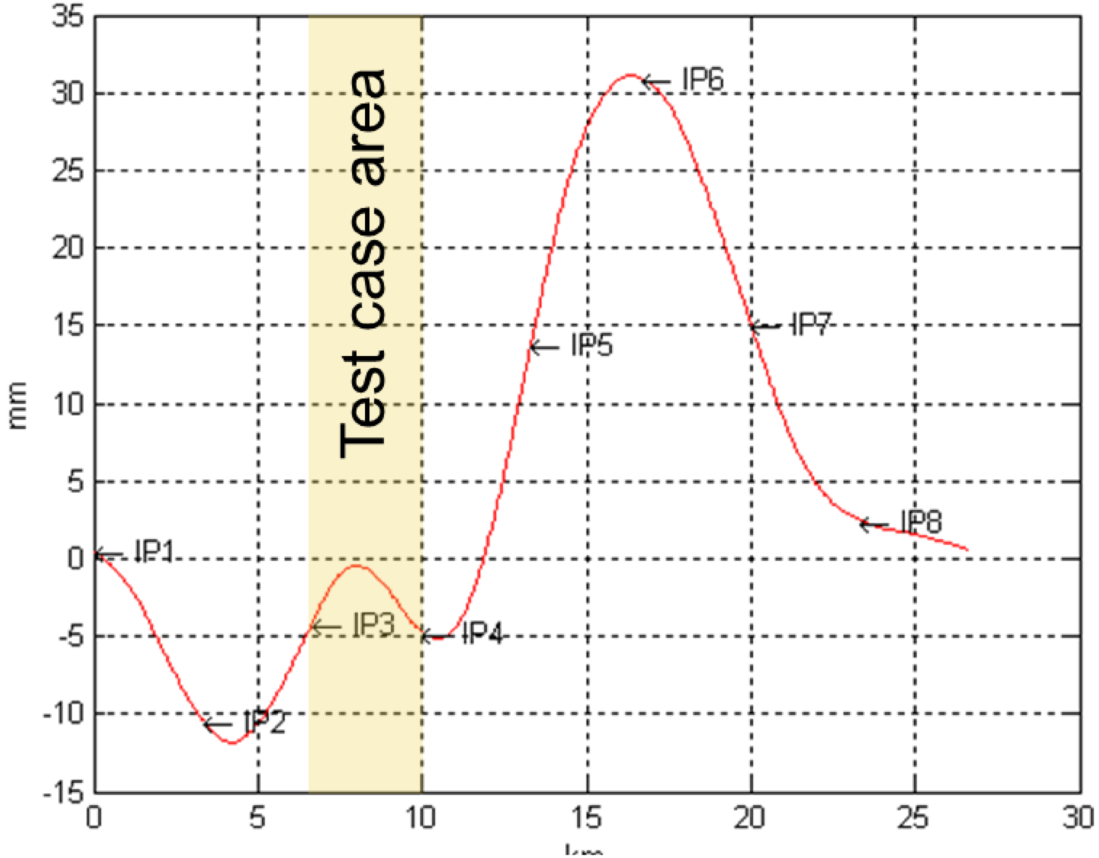


DLEV: Station position error

Studies on LHC arc 3-4 area, ~3km

Methodology

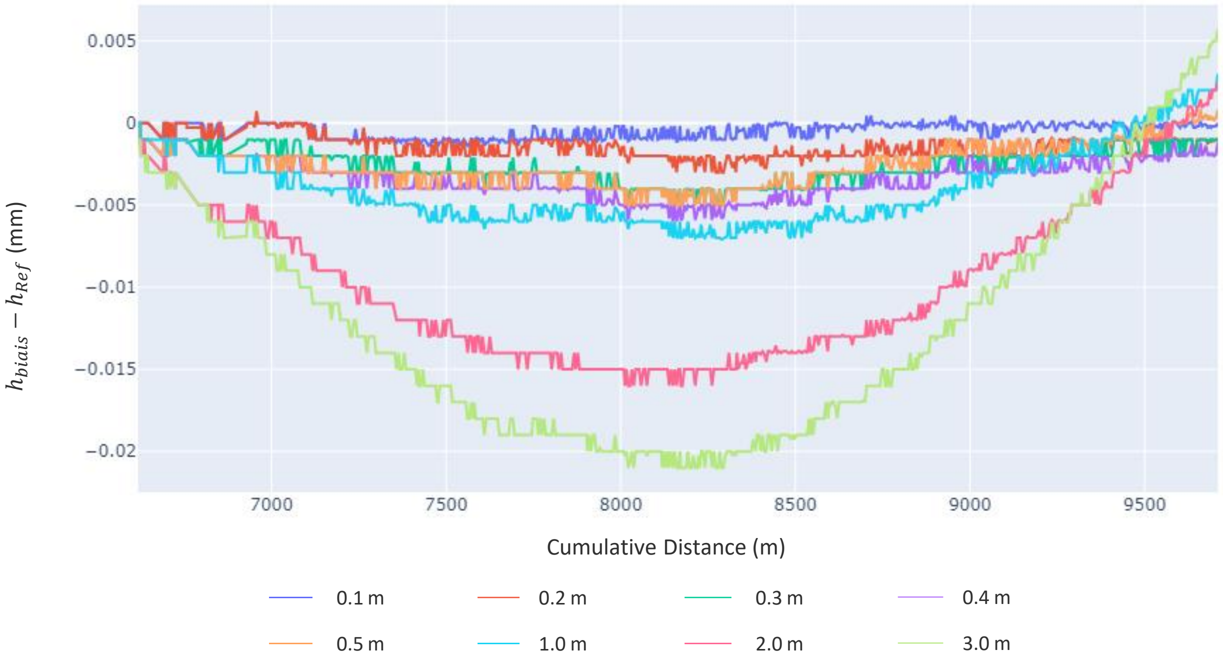
- Starting with an initial file containing the true coordinates of the stations and target points, the levelling observations were generated through **simulation in LGC**
- The observations follow a Gaussian distribution centered at 0 with a standard deviation of 0.015 mm
- Gaussian and systematic errors are added to the coordinates of the levelling station
- Altitudes are then calculated and compared to the altitudes determined using the true station positions



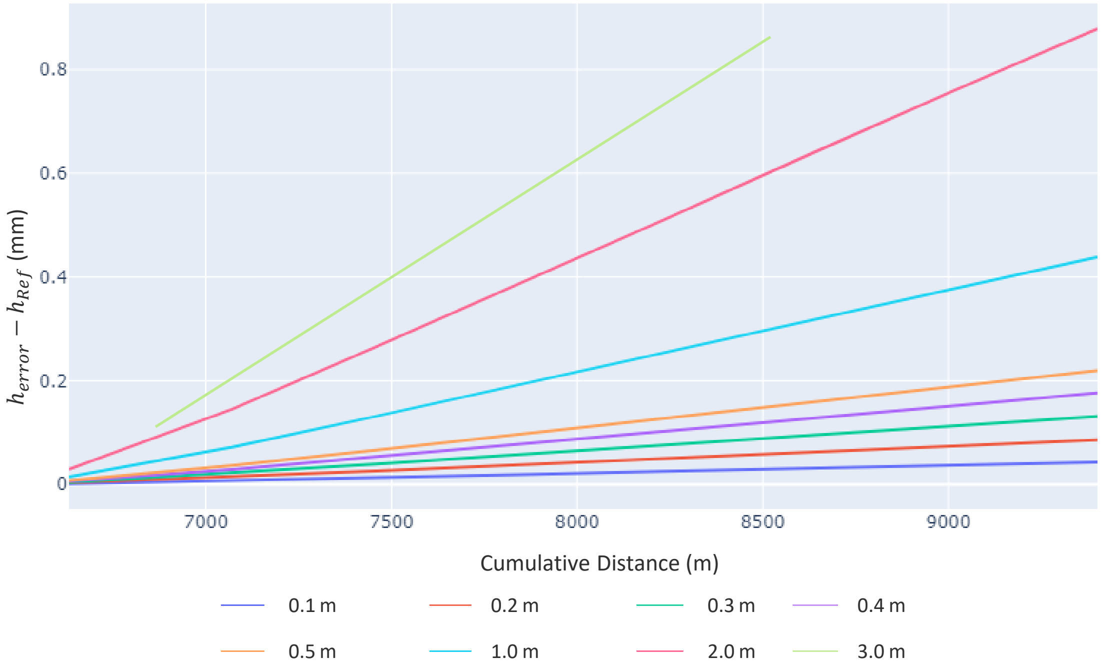
RS2K geoid deviations along the LHC

DLEV: Station position error

Radial bias on station coordinates (10,000 simulations)



Longitudinal bias on station coordinates (10,000 simulations)



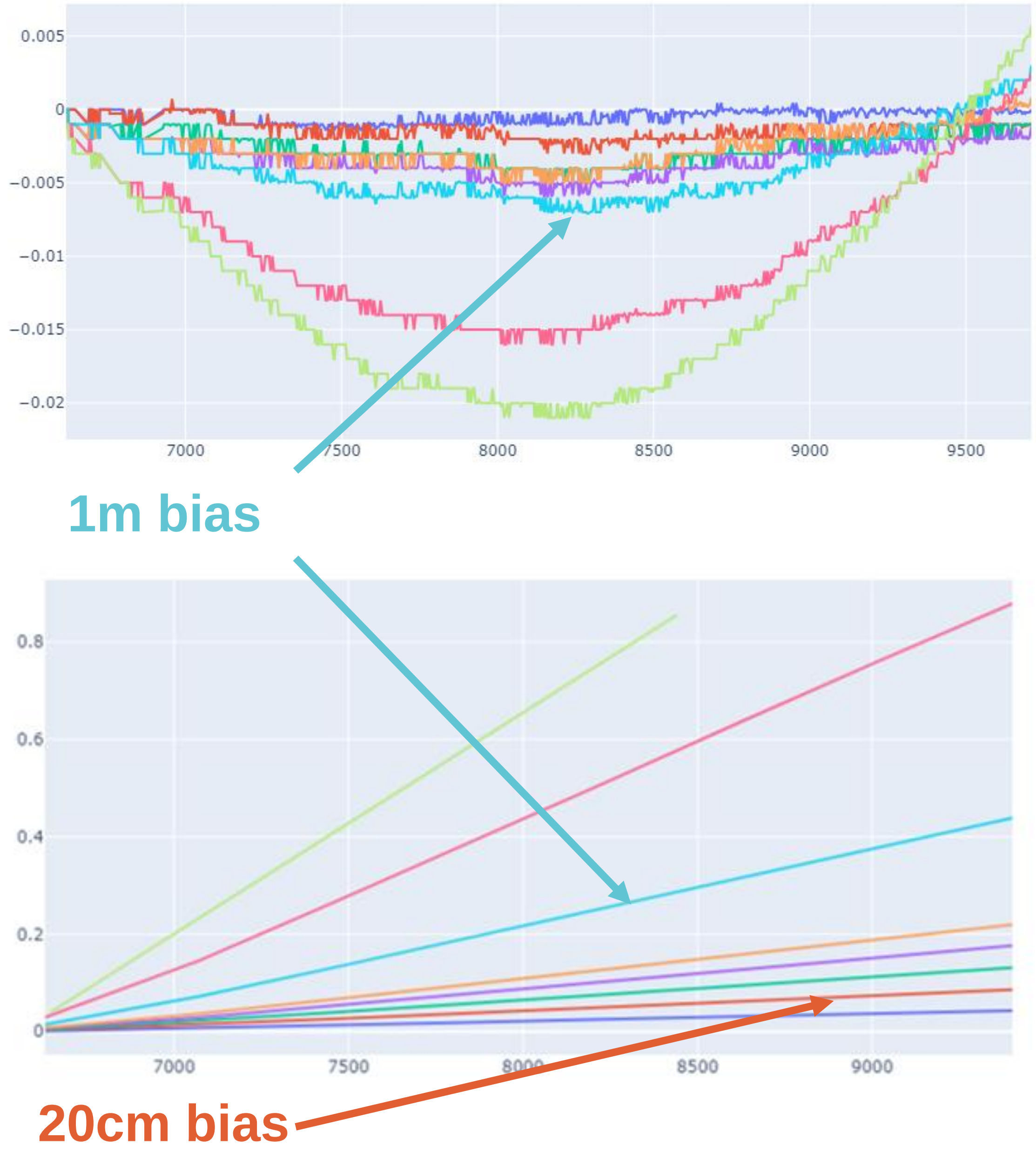
DLEV: Station position error

Only systematic errors in the longitudinal direction significantly affect the altitudes of fiducial points

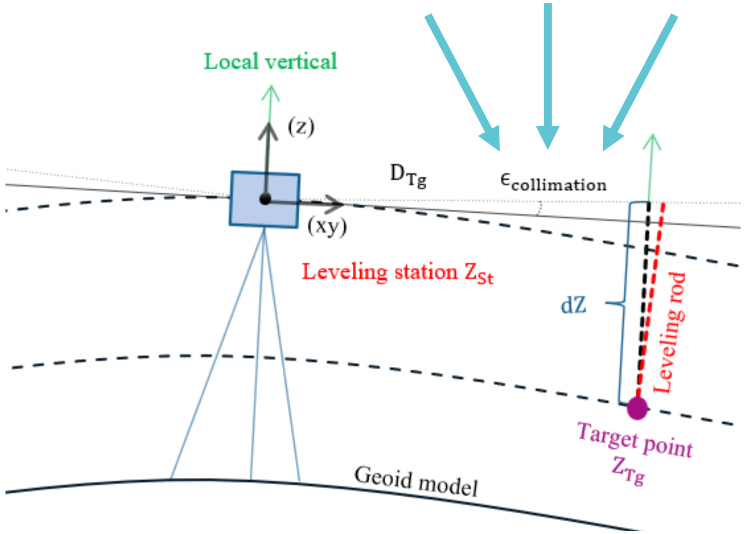
A 1 m bias results in a 0.4 mm difference at the arc's end, which exceeds acceptable tolerance levels

Radial errors are negligible, with only a few micrometers of difference for a 1 m radial systematic difference

Station positions must be calculated within a 20cm uncertainty longitudinally



DLEV: Collimation effect

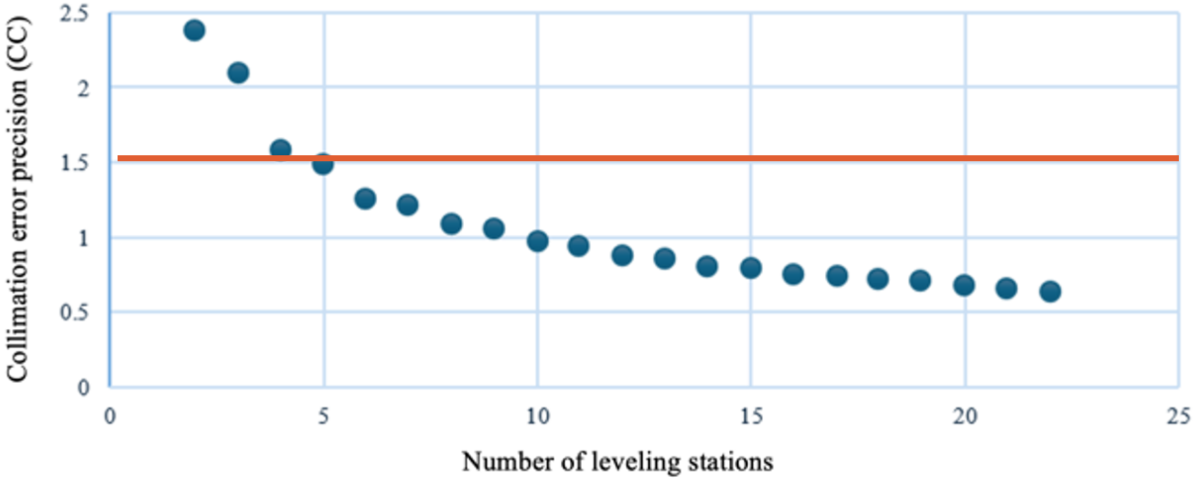


LGC can estimate the collimation error

Study on real measurements in LHC Arc 78

Collimation was evaluated

- Näbauer procedure (2/3, 1/3) every morning
- Estimated in the DLEV computation



By estimating the collimation error with the DLEV calculation for each measurement day (40 to 50 stations), the collimation error will be better determined leading to improved measurement accuracy

After more than **five** levelling stations, the DLEV model provides a **better collimation estimation** than the Näbauer method.

AGENDA

HL-LHC and FRAS

2D + 1 and LEVELLING AT CERN

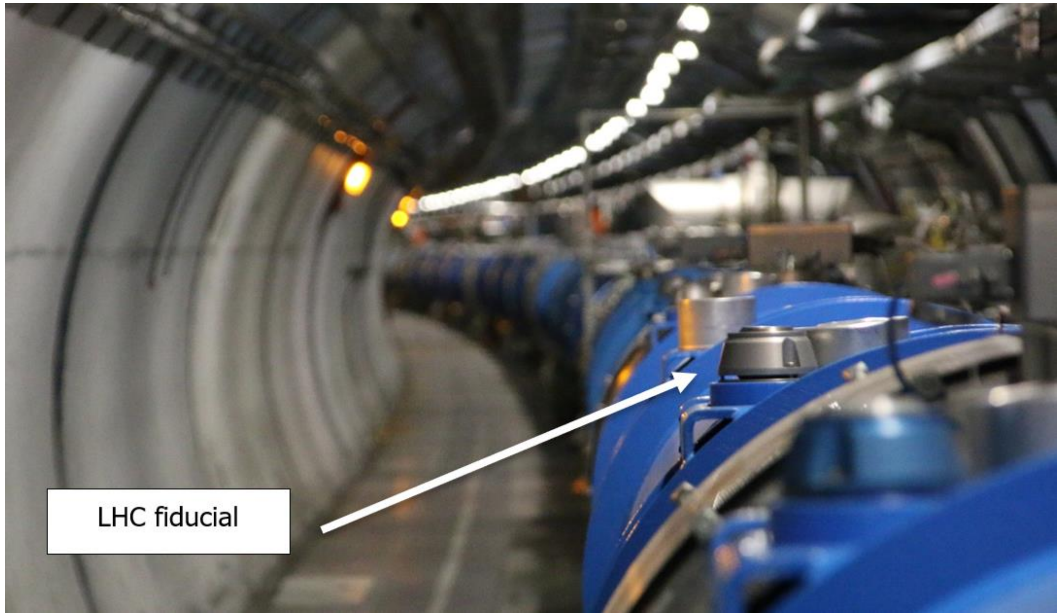
DLEV STUDIES

LEVELLING PROCESS UPDATE

PERSPECTIVES ….

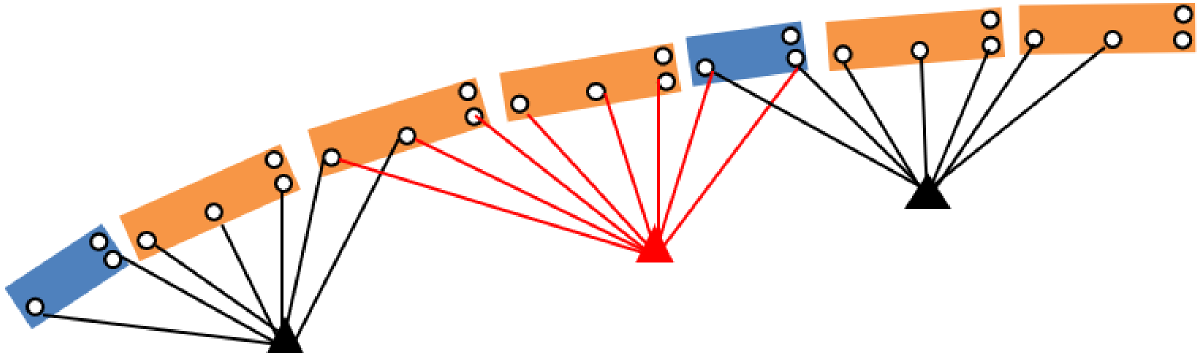
How to determine the station position?

Multilateration (digital level only) based on known point coordinates and horizontal distances.



Challenging Tunnel Geometry

- The tunnel's quasi-linear network geometry makes it difficult to measure the station's radial position accurately
- Radial positioning is less demanding than the longitudinal one

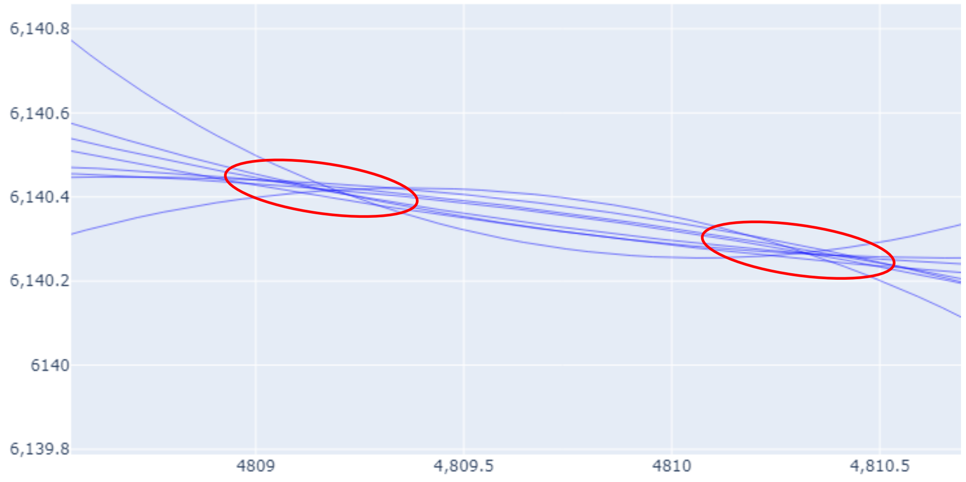


Levelling configuration in the ARC LHC tunnel

How to determine the station position?

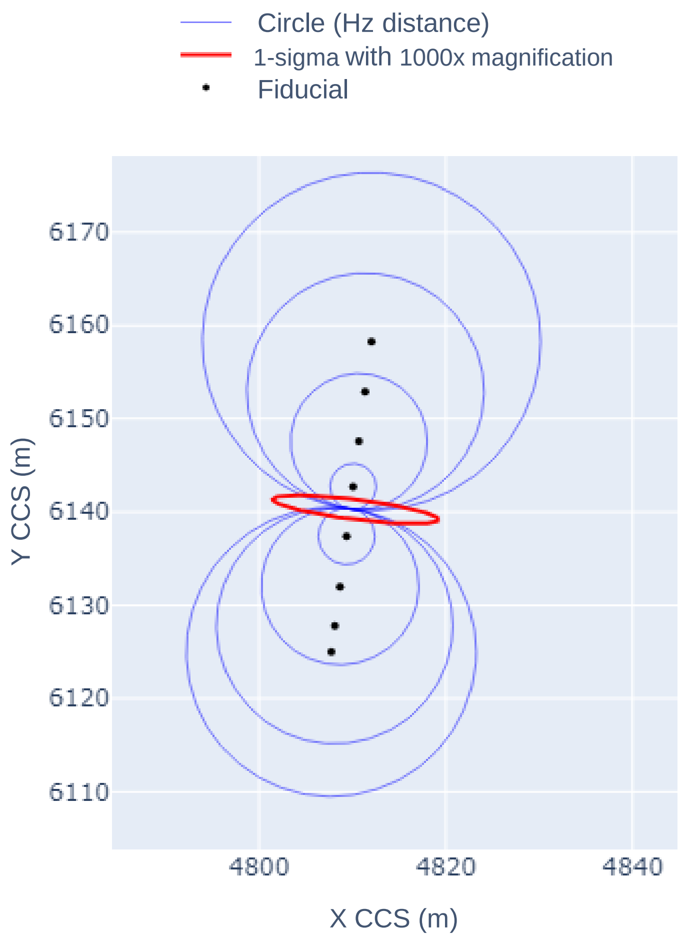
Distance Circles Intersection with fiducials

- Two potential intersection points appear, symmetrical to the beam axis
- Final convergence depends on the initial approximate coordinates
- Radial Error: Misleading coordinates can cause an error of up to 2 m in radial positioning but do not affect longitudinal or altitude accuracy



2 convergence points, a-priori coordinates crucial

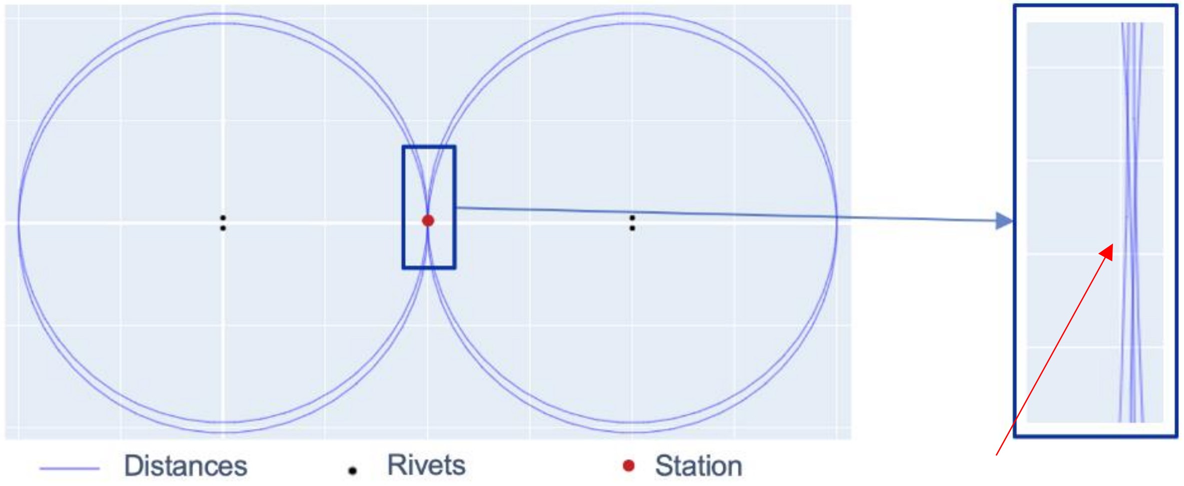
Radial precision < 5 cm and longitudinal precision < 5 mm



How to determine the station position?

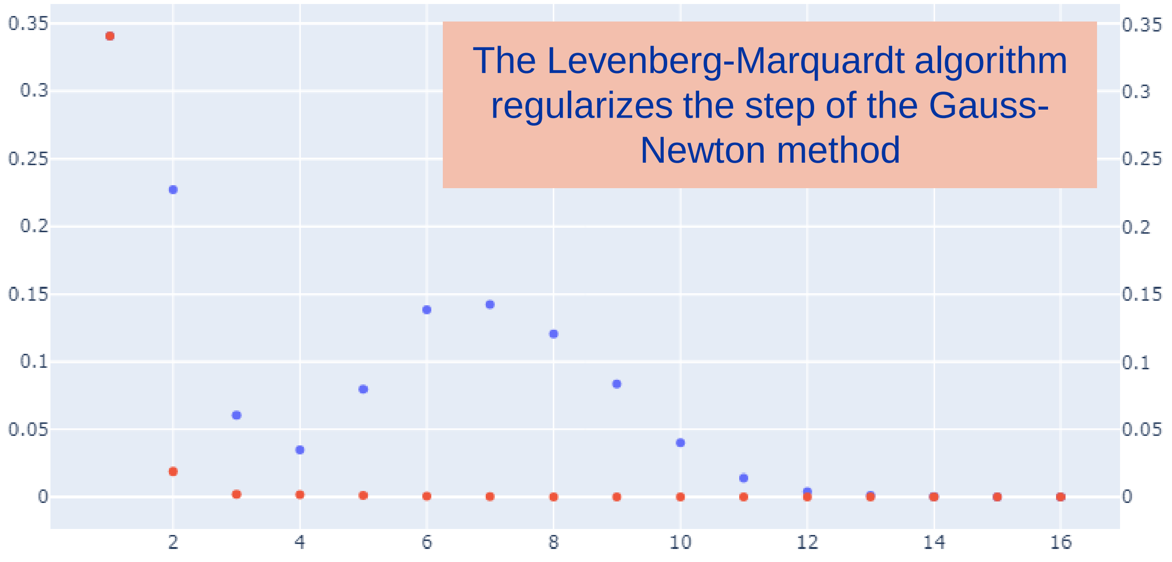
Gauss-Newton Method:

- Failed to converge in 80% of cases studied due to poorly defined intersections and too short distances



Levenberg-Marquardt Method:

- Introduces a damping factor to prevent divergence
- Adjusts iteratively to ensure the residuals decrease
- Successfully converged for all cases that failed with Gauss-Newton



Evolution of the sum of squared residuals and corrections obtained at each iteration with the Levenberg-Marquardt algorithm

Implemented in an LGC input file pre-processing Python Script

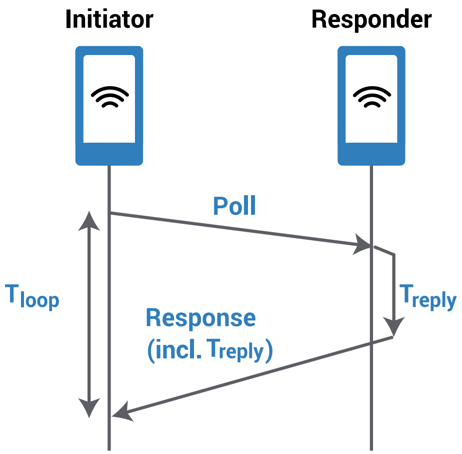
Optical levelling

Optical levels remain necessary when environmental constraints prevent the use of digital levels

Various solutions have been explored to define position, improve precision and minimize setup time

GIS positioning, stationing equidistant between known points, Ultra-Wide-Band (UWB) sensors, stationing over known points, stadia distance…

Optical levelling & UWB sensors

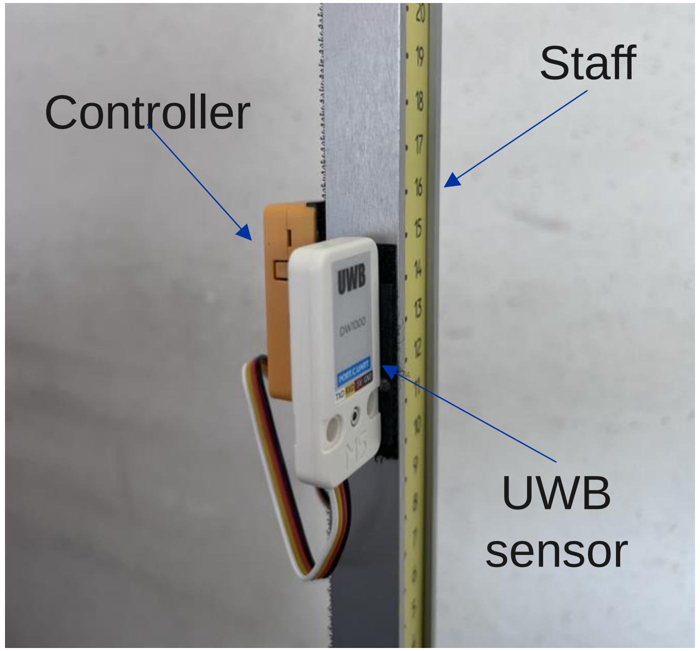


$$ToF = \frac{T_{loop} - T_{reply}}{2}$$

UWB technology offers high temporal resolution for precise distance measurements

- Ai-Thinker BU01 transceiver module with Single-Sided Two-Way Ranging.
- After correcting for systematic errors, the standard deviation is 10 cm, matching the manufacturer's specifications. Calibration is recommended.

Tested on real levelling observations with reliable results



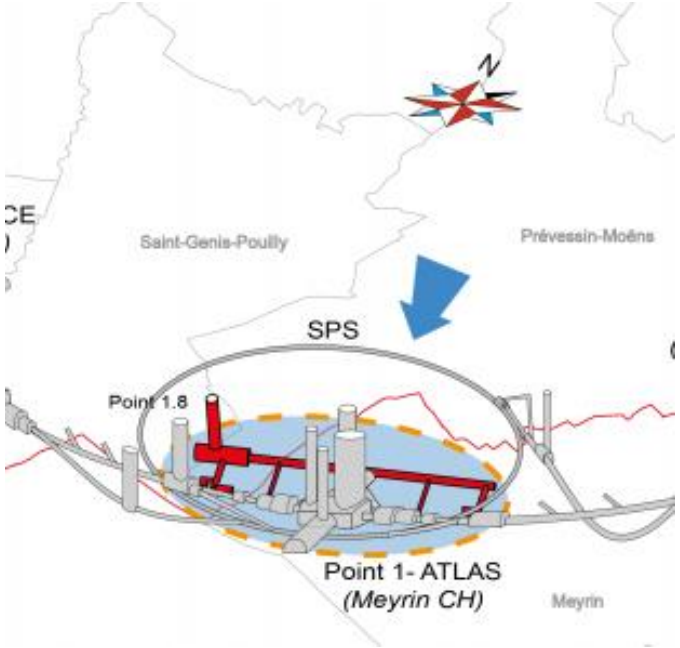
Prototype installed on the levelling staff

Comparison 3D vs 2D+1

Calculation with initial measurements for LSS1 (LHC)

Methodologies:

- 2D+1 Approach: 1D with Levelling and HLS sensors. 2D with laser tracker and WPS
- 3D Approach: Combines all observations in a single step. Incorporates geoid model and geo-referenced levelling stations (DLEV)



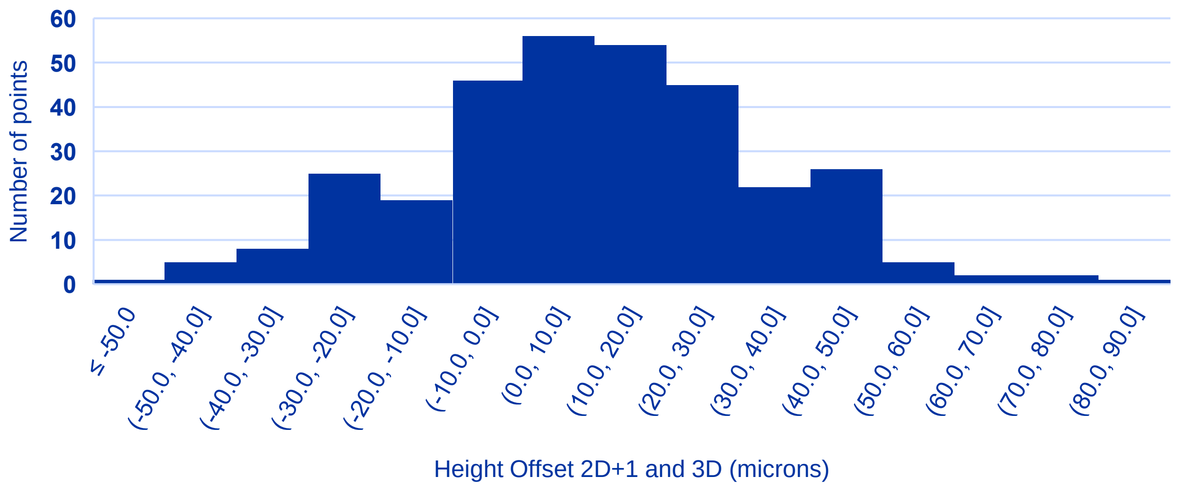
Levenberg-Marquardt algorithm converged in <1 minute (3,402 obs., 1,411 unk.)

Standard deviations matched a-priori values

Comparison 3D vs 2D+1

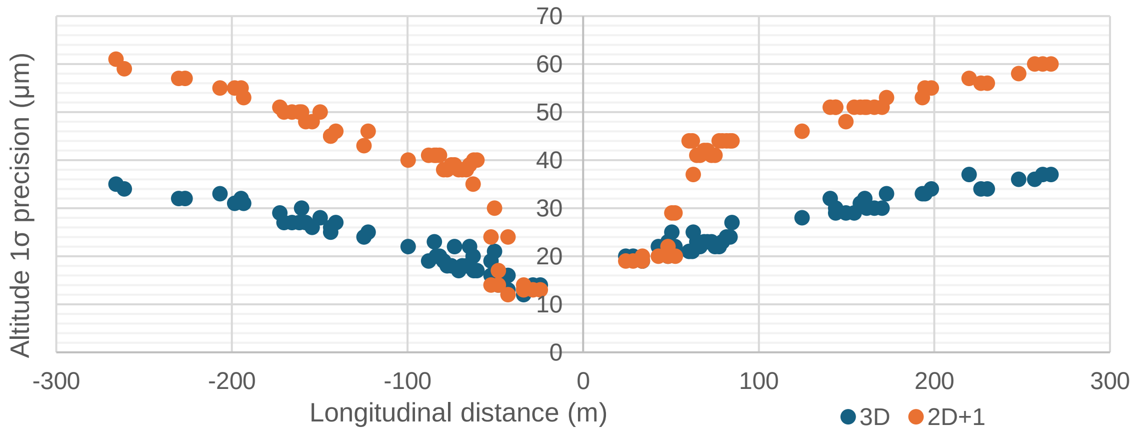
Height differences 3D vs 2D+1

- M = 23 µm, SD = 10 µm
- from -50 to 90 µm



Altitude precision (1σ):

- **2D+1: 60 µm**
- **3D: 35 µm**



Combining levelling measurements with laser tracker data significantly improves point position quality.

AGENDA

HL-LHC and FRAS

2D + 1 and LEVELLING AT CERN

DLEV STUDIES

LEVELLING PROCESS UPDATE

PERSPECTIVES ….

Perspectives

Validation of a new process using DLEV

- **Calculation Method**: Multilateration meets precision requirements; Levenberg-Marquardt method for robust coordinate determination
- **Distance Solution**: Optical level measurements need georeferencing; testing of UWB sensors shows feasibility for adding distance observations
- **Collimation errors**: estimated during Least Square adjustment to improve the levelling calculation
- **LHC LSS1:** integrating all measurements into a single 3D LGC calculation enhances the result

Upcoming challenges: implement the process in production from tunnel acquisition to data computation (tooling, software development and workflow adaptations)

Goal to be ready before LS3 for the HL-LHC project (mid-2026)

THANK YOU !

home.cern