# Validation of micro-triangulation with direct wire measurements in the LHC tunnel


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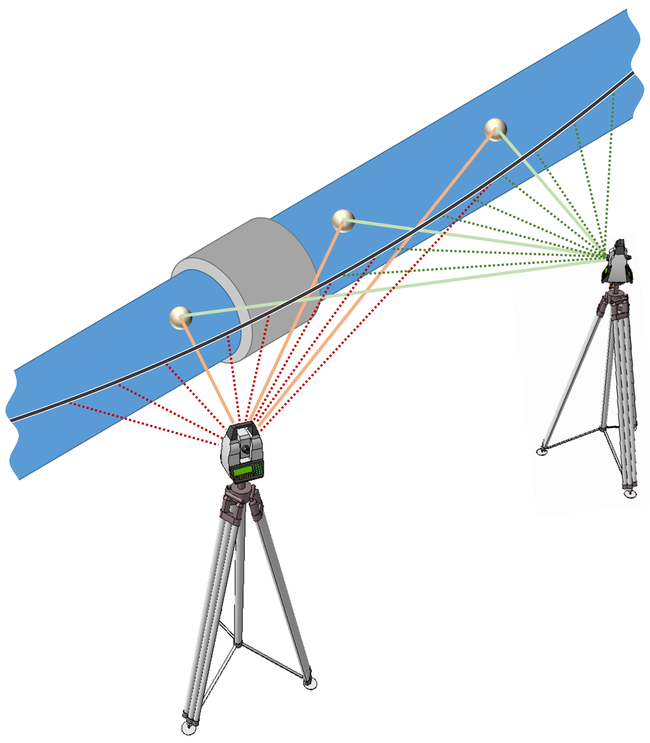
## Introduction



**Objective**
Measure offsets between fiducial points and wire(s).

**Method**
Automatic micro-triangulation with direct wire observations.

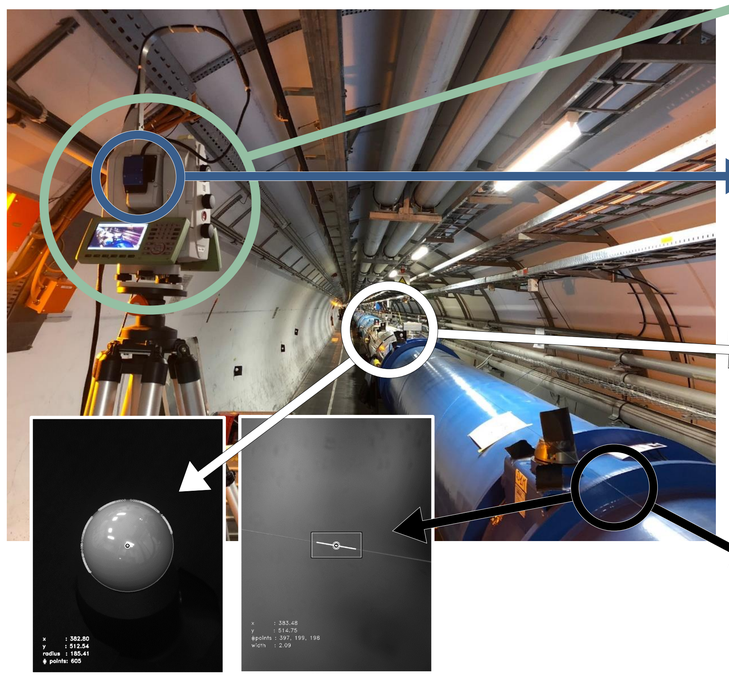
**Principle**
Measure horizontal and vertical angles to targets and wire(s).

**Problem**
Observations to non-corresponding points on the wire.

**Solution**
Wire modeled as straight line, parabola, catenary.

## Equipment

**Micro-triangulation measurement in the LHC tunnel**




*Circle matching* *Line matching*

**Leica Nova TS60:**
- Robotic theodolite.
- High accuracy:
  $0.5\ \text{arcsec} \,/\, 2.4\ \frac{\mu\text{m}}{\text{m}}$

**QDaedalus:**
- Developed at ETH Zurich.
- Reversible replacement:
  eye-piece ↔ CCD

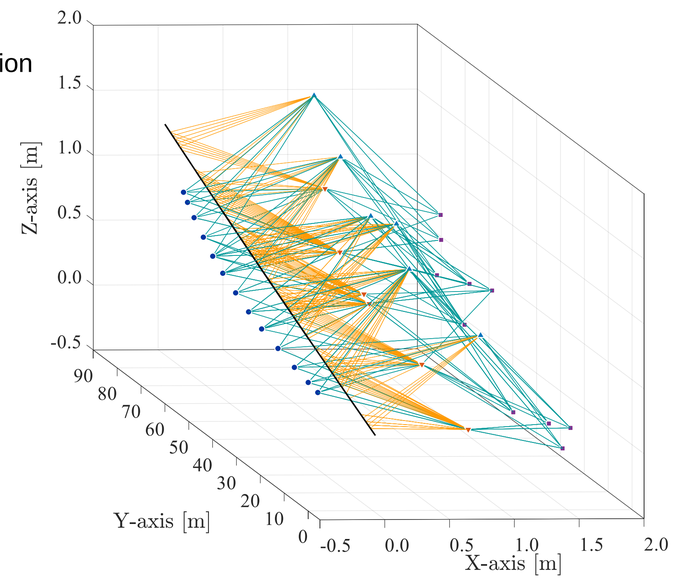
**Ceramic spheres:**
- Ø 38 mm (1.5 inch).
- Grade 40 (sphericity 1 μm).

**Vectran wire:**
- Multi thread.
- Ø 0.4 mm.

## Surveying network

**Configuration**

- 12 theodolite positions
- 2 series of measurement per position
- 13 magnet fiducial points
- 10 points on the tunnel wall
- 1 stretched wire



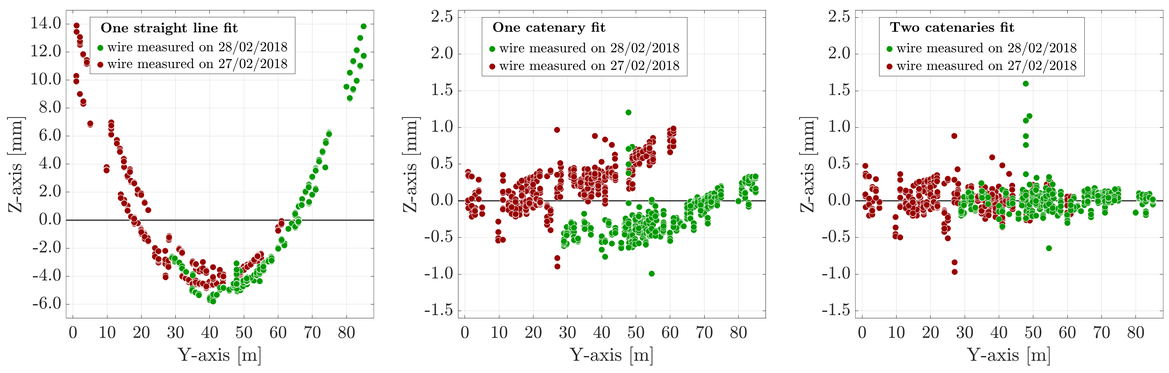

**Least-squares adjustment**

- 3312 observations
- 1233 unknown parameters
- Minimum constraints solution
- Robust fit with Iteratively reweighted observations
- Scale adopted by Laser Tracker measurements

## Wire model

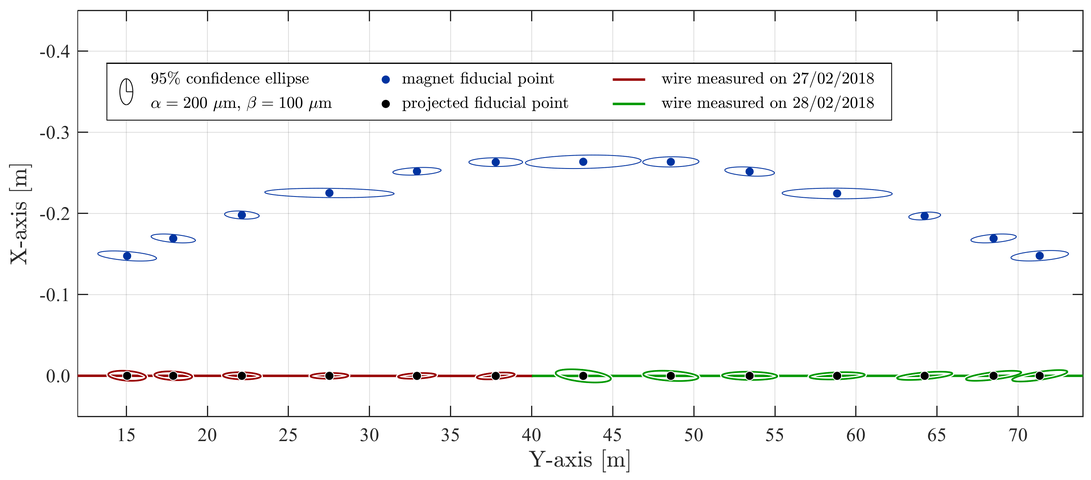
**Vertical component of the deviation between the observation and the estimated wire**

- 1st case: **One straight line fit**. We observe the catenary shape (≈2 cm for 80 m wire).
- 2nd case: **One catenary fit**. We observe two group of deviations (consistent with the day of measurement).
- 3rd case: **Two catenaries fit**. Standard deviation of the vertical deviations equals 0.16 mm (wire diameter equals 0.4 mm).



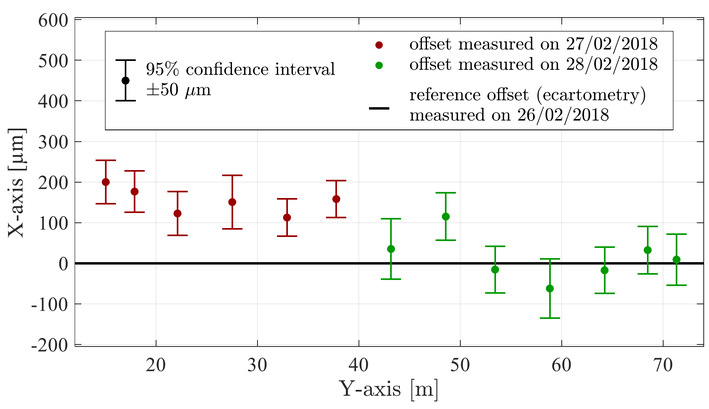

## Results

**95% confidence ellipses for the fiducials point and their projections on the wire**




**95% confidence intervals for the offsets between fiducials and wire**

Comparison with ecartometry measurements on 26/02/2018.




**1st day (27/02/2018)**
- precision (1σ): 25 μm
- accuracy (rms): 170 μm

**2nd day (28/02/2018)**
- precision (1σ): 30 μm
- accuracy (rms): 60 μm

## Conclusion

- Successful validation of the method in the LHC tunnel.
- Micro-triangulation can be used for to measure stretched-wire offsets.
- Precision at the level of a few tens of micrometres, depending on the conditions.
- The method is more time efficient in static configurations, but works well otherwise.
- Suitable for complex configurations with many wires.

➢ Advantages: accurate, automatic, contactless, remote-controlled, portable

➢ Limitation: Lack of scale 

- Future work:
  - ➢ Hardware upgrade (e.g., new CCD camera, coaxial light).
  - ➢ Software tools development (towards automation).
  - ➢ Include more systematic effect in the model (e.g., curvature, refraction).
  - ➢ Evaluation in more cases (e.g., multiple wires, vertical offset estimation).