VALIDATION OF MICRO-TRIANGULATION WITH DIRECT WIRE MEASUREMENTS IN THE LHC TUNNEL

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Abstract

In the past few years, we developed the micro-triangulation method with direct wire measurements for magnets fiducialization applications. The method was previously validated in metrology laboratory conditions, on close range measurements of a few meters. Accuracy of a few tens of micrometers was achieved, in comparison with a coordinate measuring machine. Here, we attempt to validate the method for alignment applications in the LHC tunnel, in an elongated network of about 80 m, with angle observations up to 20 m. A robotic, image-assisted theodolite was used to measure the surveying network that was later adjusted with the least-squares method. The results demonstrated precision of 30 µm (1σ), and accuracy of 60 µm (rms) for the estimation of the horizontal offsets between the magnet fiducials and the stretched wire, in comparison with the ecartometry method.

INTRODUCTION

Stretched wires are used at CERN as reference for the alignment of the accelerator components. The *ecartometry* method is based on the measurement of the horizontal distances (offsets) between a stretched wire and the reference points (fiducials), located on the components. The method, which has been developped and used at CERN for over 50 years [1], is in general fast and easy to apply. Significant limitations can be consider the facts that: a) it can measure only the horizontal offset between a fiducial and a wire, b) the wire should be stretched on approximately the same height as the fiducials, following the components' slope, and c) it cannot be used for complex configurations with additional wires.

In recent years, much research at CERN has focused on alternative solutions that can overcome the aforementioned limitations. These solutions should be portable, accurate in the level of a few tens of micrometers, and able to establish a geometrical link between the fiducials and the wire(s), by conducting non-contact wire measurements. Three new methods are currently under study at CERN, one is based on photogrammetry [2], another on the optical Wire Positioning Sensor (oWPS) technology [3], and a third one is based on micro-triangulation. Recently, a comparison of these three methods took place in the LHC tunnel; the results are discussed in [4].

The micro-triangulation method with targets and stretched wires goes beyond the standard method, by also including into the network angle observations to one or more wires (Fig. 1). The particularity is that there are no distinguishable points on a wire, especially when it has a uniform surface. Therefore, it is impossible to observe the same point from two or more stations, or even worse, in the two faces of the theodolite. Consequently, arbitrarily selected points on the wire are observed only once. To solve such networks, the angle observations to the wire are fitted to a model that corresponds to the shape of the wire, e.g. straight line, parabola, catenary (hyberbolic cosine), e.t.c.

We developed this novel method as part of a PhD study, in the frame of the Particle Accelerator Component Metrology and Alignment to the Nanometre scale (PACMAN) project [5]. A first evaluation of the method took place in the metrology lab of CERN, in a quadrupole fiducialization application. The method demonstrated accuracy of 20 µm and 40 µm/m, for the wire position and orientation, when compared with coordinate measuring machine (CMM) measurements [6].

The main objective of this study is to examine the feasibility and the efficiency of the micro-triangulation method with direct wire observations in the special environmental conditions and space limitations of the LHC tunnel. Moreover, we aim to estimate the accuracy of the method for alignment applications, in comparison with the standard ecartometry method.

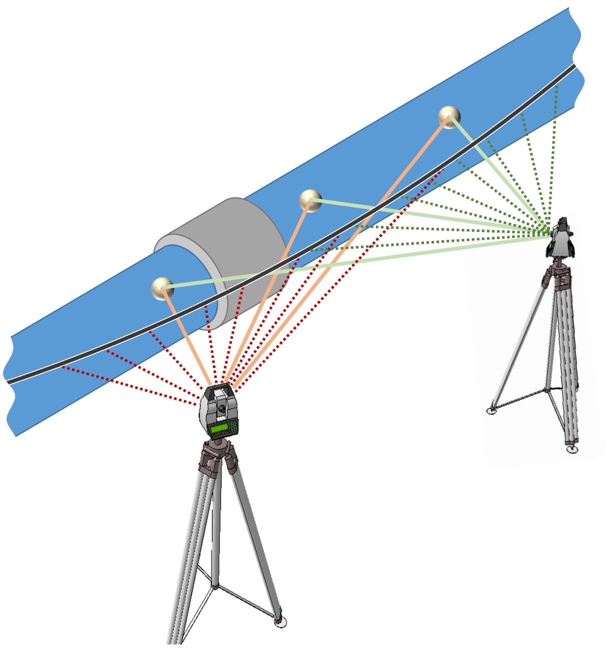

Figure 1: Concept of micro-triangulation with targets and wires in the LHC tunnel. Two theodolites observe the fiducial points (white spheres) and the stretched wire (black line), composing a surveying network.

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MATERIALS AND METHODS

Equipment

The micro-triangulation method with direct wire observations is based on automatic, contactless observations, acquired by image-assisted theodolites.

Theodolite The new Leica Nova TS60 total station was used for this measurement. According to the manufacturer specifications, the angular accuracy is 0.15 mgon ≈ 2.4 µrad or 2.4 µm/m (1σ, ISO17123-3), and the reference to the vertical is < 0.1 mgon.

QDaedalus The technique of automated micro-triangulation is applied by the QDaedalus measuring system [7], which is mounted on the theodolite's telescope. The system is designed and developed by the Geodesy and Geodynamics Lab, Institute of Geodesy and Photogrammetry, ETH Zurich. The fundamental idea is to replace the eye-piece with a CCD camera in a non-destructive way. The QDaedalus software provides automatic detection algorithms for different type of targets. In our study, we use the *Circle matching* algorithm, to observe the spherical fiducial points [8], and the *Line matching* algorithm (also developed in the PACMAN project) to observe the wire (Fig. 1).

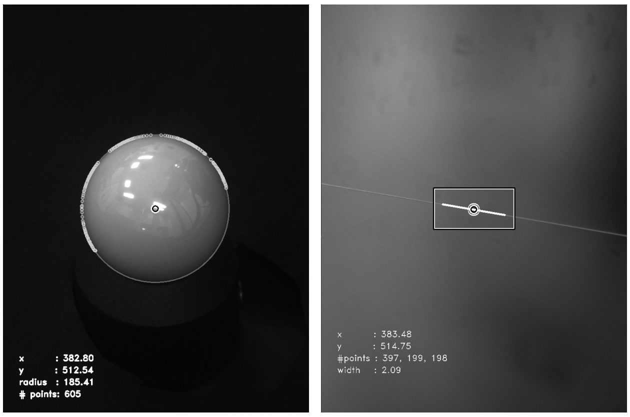

Figure 2: Sample images of the QDaedalus target detection algorithms. Left: *Circle matching* algorithm (provided with the QDaedalus software) used to measure the spherical fiducials. Right: *Line matching* algorithm (developed in the PACMAN project) used to measure the stretched wire.

Tripod The TS60 was mounded on a Leica AT21 aluminium tripod. For half of the stations, the instrument height was the minimum (1.4 m), while for the other half it was the maximum (2.1 m). Both the theodolite and the tripod was left in the tunnel for a few days in advance to acclimatize.

Targets White ceramic spheres made by Zirconium dioxide (ZrO_2) were used as fiducial points. The spheres have 1 µm sphericity (Grade 40, ISO3290) and 38 mm (1.5 inch) diameter.

Wire A black, multi-thread, vectran wire of 0.4 mm diameter was stretched for ≈80 m. The height difference of its extremities was approximately 1 m, forming ≈2 cm sag.

Network configuration

For the reliability of the comparison, it was decided to measure 13 fiducial points, which correspond to an arc of about 60 m in the LHC tunnel, containing two quadrupoles and three dipoles.

To estimate the horizontal offsets between the fiducials and the wire, we designed a surveying network that includes, the fiducials, the wire and additional targets mounted on the available tunnel wall (Fig. 4). The additional targets were introduced to strengthen the bad geometry due to the elongated network, and to allow a much better constraint of the network scale in the lateral to the wire direction.

Before the actual measurement, a numerical simulation was carried out to ensure that the network can be solved in terms of least-squares adjustment and that the network has the required redundancy.

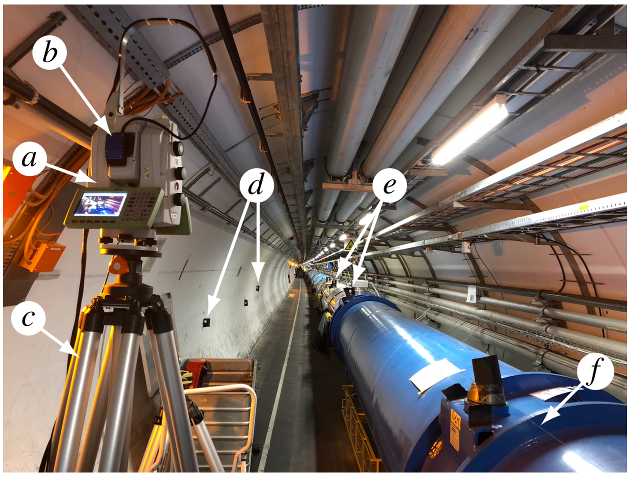

Figure 3: Micro-triangulation measurements in the LHC tunnel. The Leica Nova TS60 theodolite (a), equipped with the QDaedalus system (b), mounted on the Leica AT21 aluminum tripod (c). The spherical targets mounted on the wall (d) and on the magnets (e), as well as the stretched wire (f).

Measurement procedure

The network was measured with sequential stations of the theodolite. In each station, the measurement procedure follows the three following steps.

Theodolite installation The theodolite is installed and leveled properly. Its approximate position and orientation is obtained by resection, using a corner-cube prism. This information is important for the next step, the target parameters configuration.

Parameters configuration A few automation tools provided by the QDaedalus software facilitate and expedite the target parameters configuration. The known approximate coordinates of the station, the targets, and points on the wire are used: a) to compute the direction of the targets with respect to the station, b) to focus on the targets, using a pre-calibrated distance to focus function, and c) to choose the targets to be observed, given a range of distances.

The operator continues with the configuration of parameters, such as the camera gain and shutter speed, the number of CCD shots to average per angle measurement, and parameters relevant to the target detection algorithms. At the end, the operator defines the measurement scenario, by setting the number of repeated angle measurement per point, the number of faces and the sequence of the measurements.

In our case, the processes of installation and target parameters configuration lasted for about 1 h for each station.

Observations acquisition After the parameters configuration, the system is ready to perform the observations. This part used to take about 20 min, given the number of shots per angle measurement and the number of angle measurements per target. In our case, we chose to acquire ten CCD shots for each angle measurement to a point-target and five CCD shots for the wire points, respectively. Two series of angle measurements were registered for the selected group of targets.

A series of measurement is completed when all the selected targets are observed in both left and right faces. From each position, the theodolite was set to perform two sequential series of measurements. Each series was later considered as a different station with different coordinated, orientation and systematic errors. Following this technique, we practically reduce the observation time for each station, as an attempt to reduce errors caused by dynamic effects, such as the tripod instability due to the temperature variation.

Least-squares adjustment

For the least-squares adjustment of the observations, we use the parametric model, where each observation is expressed as a function of the unknown parameters. The horizontal directions and the zenith angles to the point-targets and to the wire are considered as the observations. The unknown parameters include:

- station coordinates and horizontal orientation, as well as three systematic errors per station (collimation error, tilting-axis error and vertical index),
- targets coordinates, and
- the wire position and orientation vector, as well as a form factor when required, depending on the model in use.

The approach of the proposed method is similar to the approach of a standard surveying network. The observations to the point-targets are expressed as functions of the corresponding station and target unknown parameters, while the observations to the wire are expressed as functions of the corresponding station and wire parameters, according to the model in use.

Minimum constraints are introduced as Helmert conditions to cover the default of datum, which is five for a three dimensional triangulation network. Another two constraints are added for each wire, one for the longitudinal position and one for the orientation. The coordinates used to constraint the solution were obtained by the prior measurement and adjustment of the network using a Laser Tracker. In this case the scale of the triangulation network adopts the accuracy of the scale provided by a Laser Tracker.

Offsets computation

For the horizontal distance between a fiducial point and a wire, we firstly calculate the projection of each fiducial to the wire, by using the estimated wire parameters and the estimated coordinates of the fiducial. In addition, we calculate the 3×3 covariance matrix for each new point. Consequently, we calculate the horizontal distance between each pair of fiducial and projected point, and the distance uncertainty. This offset is finally compared with the result of the ecartometry measurement.

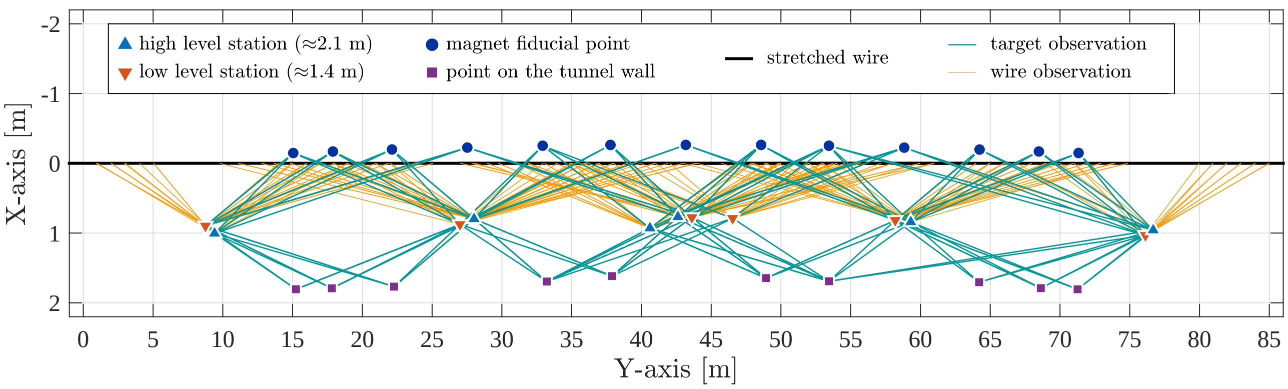

Figure 4: Top view of the surveying network configuration. The 80 m long network consists of a row of 13 fiducial points on the magnets, the stretched wire in the side of the magnets, the theodolite positions in the LHC tunnel corridor and a row of targets mounted on the tunnel wall. Angle observations to the targets and to the wire are depicted in different color.

RESULTS

Station closures

As we have already mentioned, from each theodolite position two series of measurements were acquired. Each series was considered as a different station. Thus, from the 12 theodolite positions we count 24 stations. The analysis of the observations starts with the computation of the station closures for the horizontal and vertical angles (Fig. 6). The closure is computed as the difference of the observations for one point at the beginning and at the end of a series of measurements. Six stations were rejected from the adjustment as they exceed the threshold, which was set to be four times the manufacturer precision for the used theodolite, i.e. 10 μrad. Unfortunately, we cannot further reduce the threshold due to the fact that by rejecting more stations the network will significantly loose redundancy. In Fig. 6 we see that the horizontal angles are more problematic than the vertical, and that the high stations tend to demonstrate larger closure values.

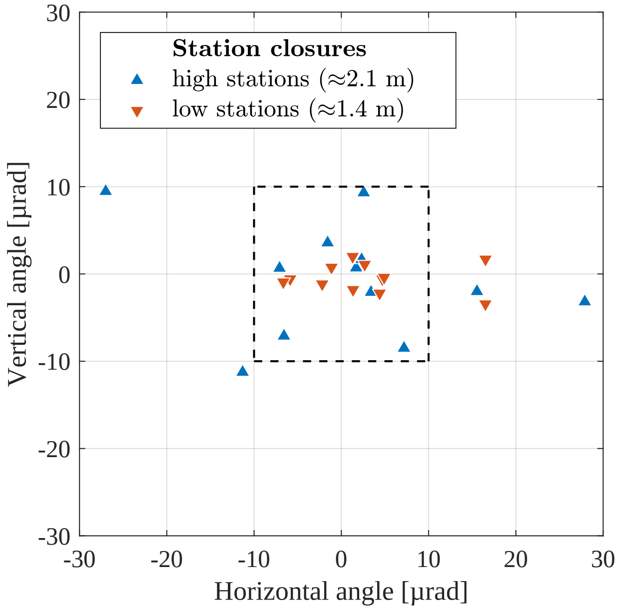

Figure 6: Closures of the horizontal and vertical angles for the 24 stations. Six station with closures above the threshold of 10 μrad were rejected.

Wire models

For experimental purposes, we adjusted the network three times with different assumption for the wire modeling. In Fig. 5, we present the vertical deviations of the observation rays with respect to the estimated wire, for each experiment. These deviations could be considered as the residuals of the vertical angle, expressed as vertical distances in the exact location of the wire.

For the wire observations we initially used the straight line model to show that it is unsuitable for wires with such lengths. In the left graph of Fig. 5, the deviations form a parabolic-like shape with approximately 2 cm sag for 80 m wire.

In the central graph of Fig. 5, we present the deviations when we model the wire as a catenary. Two groups of points are formed, one for each day of measurement. This indicates that the wire was moved significantly between the measurements of the first and the second day.

Finally, we proceed to a network adjustment with two catenary wires, one for each day. In the right graph of Fig. 5, we see that the systematic effect disappeared and the deviations seem to have a random distribution.

This finding indicates two issues concerning the comparison with the ecartometry measurement. Given the fact that the ecartometry measurement took place on 26/02/2018, a day before the first micro-triangulation measurement, it can raise reasonable doubts about the comparability of the two measurements. Moreover, by splitting the wire observations in two parts we estimate two wires that each one has better precision in the area of the measurements than in the other side. For that reason, we decided to also split the offsets

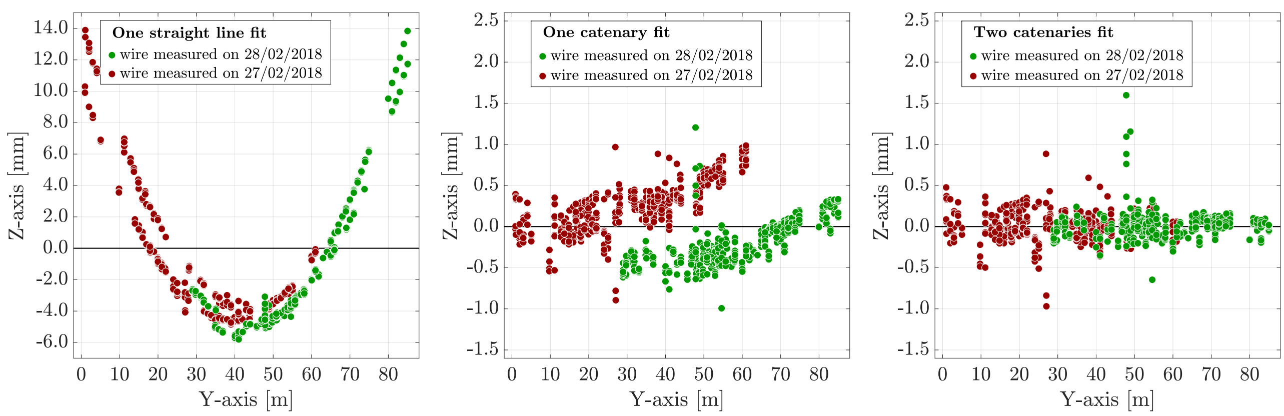

Figure 5: Vertical deviations of the observation rays with respect to the estimated wire for different solutions. Left: Wire observations are fitted to a straight line. Center: Wire observations are fitted to a catenary. Right: Wire observations are fitted to two catenaries, one for each day of measurement.

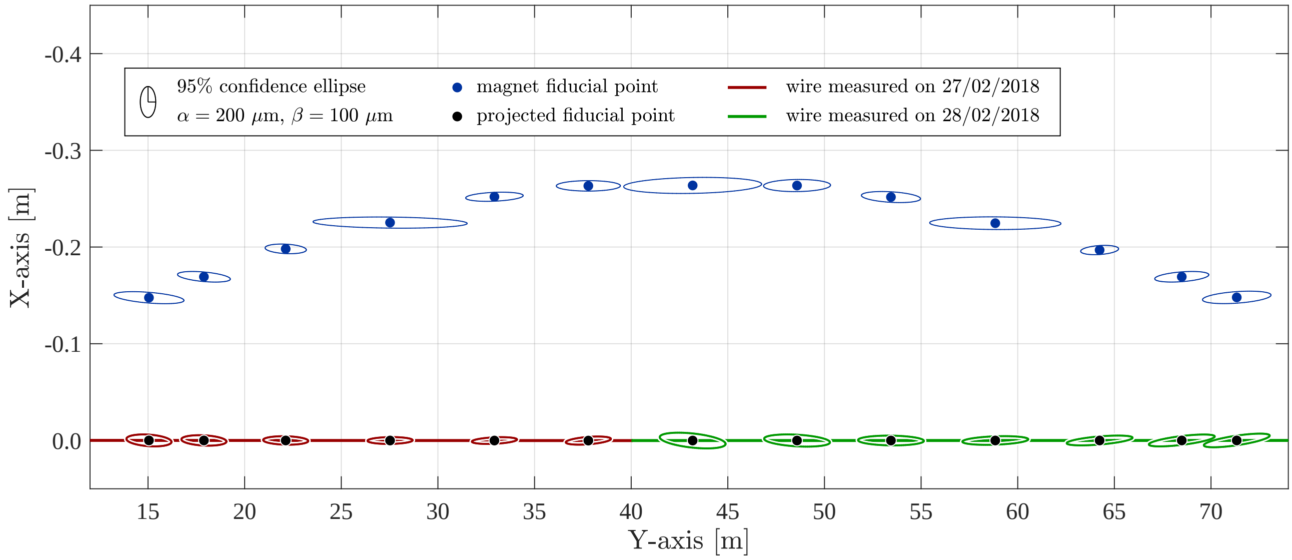

Figure 7: Top view of the fiducial points, the projected points to the wires and their 95% confidence ellipses. For visualization purposes, the axes ratio X:Y equals to 1:50, while for the ellipses the ratio remains 1:1.

calculation into two groups, according to the longitudinal position of the fiducials.

Confidence ellipses

In Fig. 7, the fiducial points and the corresponding projected points on each wire are depicted. The wire estimated by the observations of the first day is depicted in red and the one of the second day, in green. The 95% confidence ellipses are also depicted. The small semi-axis of the ellipses are always directed to the lateral direction, which is imposed by the geometry of the network and it is very advantageous given the fact that in the domain of the accelerator alignment we are in general interested more in the lateral and the vertical direction than in the longitudinal. For visualization purposes, the axis ratio X:Y equals to 1:50, while for the ellipses the ratio remains 1:1.

Concerning the 95% confidence intervals in the X-axis (lateral) direction, which are not depicted in Fig. 7, the average values are: 60 µm for the fiducials, 45 µm for the projected points on the first wire (red), and 60 µm for the projected points on the second wire (green).

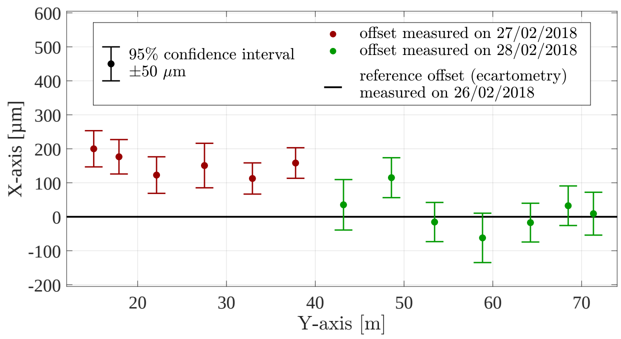

Figure 8: Offsets comparison with respect to the ecartometry measurement. For visualization purposes, the axes ratio X:Y equals to 1:25.

Offsets comparison with ecartometry

We considered the ecartometry offsets as reference values for the offsets comparison, so they are depicted as a straight line in Fig. 8. For each fiducial point, the ecartometry offset is subtracted from the offset calculated by the micro-triangulation network. The difference is depicted as a point in the exact longitudinal position. We can notice two point groups in different colors, depending on the day of the measurement. The 95% confidence intervals of the calculated distances are also depicted as error bars.

Evaluation of precision The average value of the 95% confidence intervals for the first day is at the level of 50 µm, which means 25 µm precision in 1σ. The same value for the second day in at 60 µm, or precision of 30 µm in in 1σ. The measurement shows consistent performance in terms of precision for the two days.

Evaluation of accuracy As we see in Fig. 8 there is a systematic difference in the comparison for the first and the second day, although the precision of the estimation remains almost the same. This result agrees with the findings of Fig. 5 and indicates that the wire had changed its horizontal position as well as the vertical.

From the comparison, we can estimate the accuracy of the novel micro-triangulation method with respect to the standard ecartometry method. For the first day the accuracy is calculated at the level of 170 µm (rms), while for the second day the accuracy is calculated at the level of 60 µm (rms).

DISCUSSION AND CONCLUSIONS

General remarks

The micro-triangulation method with direct wire observations was successfully tested in the LHC tunnel. The method is proven to be feasible in measuring and estimating the offsets between fiducial points and a wire. The efficiency of the method depends on factors, such as the available time for preparation and execution of the measurement, and the nature of the application (e.g. number of employed theodolites, static or moving configuration, e.t.c.).

The method benefits form the least-squares analysis for the full control of the systematic errors and the gross errors. Moreover, the wire can be modeled accordingly (e.g. straight line for vertical or short wires, catenary for the rest of the cases). Important fact is that the estimated parameters are accompanied with a full covariance matrix, which allows the rigorous estimation of the uncertainty of any derived quantity.

The method is advantageous especially in cases when the vertical offsets are required, except from the horizontal ones. This is feasible due to the fact that all the measurands (points, wires) are measured and computed in the three dimensions, in a coordinate system that is precisely linked to the gravity field, thanks to the use of theodolites. Moreover, this method could be considered as a solution in configurations with two or more wires.

In fact, more time was spent on the installation and target configuration than on the actual measurement. This is due to the current harware and software implementation, and it cannot be considered as limitation of the method. A few developments, such as software automation tools, wide range cameras, coaxial lights, e.t.c., can dramatically increase the efficiency in terms of time and effort.

LHC tunnel environment

With regard to the LHC tunnel environment – except from the limited space, which affects the network's geometry – three conditions can be considered as main contributors in the deterioration of the micro-triangulation measurements quality; the temperature variation, the airflow and the light conditions.

The temperature variation causes expansions-contractions to the aluminum legs of the theodolite's tripod that can be up to 50 µm, for 1 °C, when the tripod is fully extended at 2 m height.

The airflow contributes in two different ways. a) it causes the hanging wire to move/swing, and b) it changes unpredictably the vertical temperature gradient of the air, therefore the refraction index and consequently the optical paths.

The ambient light conditions in the tunnel affect the quality of the measurement, especially in our case, where there is no illumination coaxial to the theodolite's optical axis. Rapid changes of the light intensity, in space, and reflections on the targets due to non-defusing light bodies, make the observations difficult, imprecise or even impossible.

Precision

The analysis of the measurements indicated a significant horizontal and vertical displacement of the wire between the two days of measurements. A probable cause could be the fact that many measurements were conducted close to the wire, by a number of colleagues, and at the same time. This results to a reasonable doubt about the comparability of results obtained in different days.

In terms of precision, the estimation of the offsets for both days is consistent at the level of 25 µm to 30 µm (1σ). The accuracy with respect to the ecartometry is estimated to be at about 170 µm (rms) for the first day and at about 60 µm (rms) for the second day of measurements.

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REFERENCES

[1] J.-P. Quesnel, *et al.*, "Stretched wire offset measurements: 40 years of practice of this technique at CERN", in *Proc. IWAA'08*, KEK, Tsukuba, Japan, February 2008.

[2] A. Behrens, *et al.*, "Evaluation of stretched wire measurements based on photogrammetry in the context of CERN", in *Proc. IWAA'16*, ESRF, Grenoble, France, October 2016.

[3] P. Bestmann, *et al.*, "Validation of an optical WPS system", in *Proc. IWAA'10*, DESY, Hamburg, Germany, September 2010.

[4] J.-F. Fuchs, *et al.*, "Inter-comparison of wire measurements in the LHC tunnel", presented at IWAA'18, Fermilab, Batavia, Illinois, October 2018, this conference.

[5] H. Mainaud Durand, *et al.*, "Main Achievements of the PACMAN Project for the Alignment at Micrometric Scale of Accelerator Components", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, paper TUPIK077.

[6] V. Vlachakis, *et al.*, "Recent developments of micro-triangulation for magnet fiducialisation", in *Proc. IWAA'16*, ESRF, Grenoble, France, October 2016.

[7] B. Bürki, *et al.*, "DAEDALUS: A versatile usable digital clip-on measuring system for Total Stations", in *Proc. IPIN'10*, Zurich, Switzerland, September 2010.

[8] S. Guillaume, *et al.*, "QDaedalus: Augmentation of Total Stations by CCD Sensor for Automated Contactless High-Precision Metrology", in *Proc. FIG'12*, Rome, Italy, May 2012.