VALIDATION OF WIRE MEASUREMENTS IN THE LHC TUNNEL

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Abstract

The High Luminosity LHC (HL-LHC) is an upgrade of the LHC accelerator, this challenging project requires the installation of new high-technology components along more than 200 m of the current machine on each side of IP1 and IP5. As the radiation level will increase during beam operation after Long Shutdown 3 all these new sections will be online monitored by sensors and equipped with motorized jacks.

The survey sections of the EN-SMM group (Engineering Department - Survey, Mechatronics and Measurements) are studying various wire measurement solutions in order to be able to geometrically link the HL-LHC components, monitored by sensors and the LHC components measured by standard methods. This area is called the “matching section”. While the design study and R&D are still in progress, a global comparison with different solutions inside the LHC tunnel environment, including all the constraints and working conditions, has been organized during the last Year End technical Stop (YETS) in February and March 2018.

INTRODUCTION

A common “wire measurement” campaign along 65m of LHC magnets has been applied in order to evaluate the following processes inside a tunnel environment : standard offset measurement, oWPS associated with laser tracker (AT40x), photogrammetry (D3X, Aicon software) and micro-triangulation with a Leica TS60 total station.

Until now, all the studies and validation tests have been done in laboratory but never inside a tunnel including all the constraints such as ventilation, co-activity, planning, limited space, light, ...

The main objective of this study is to evaluate the feasibility and the accuracy of various method with indirect and direct wire observations in working conditions and constraints of the LHC tunnel.

LHC TUNNEL

The LHC, a large circular collider of 27km circumference, is composed of more than 2000 “cold” magnets : the measurements took place between two quadrupoles from MQ.12.R2 to MQ.13R2 including the 3 dipoles located in between.

Layout

Two or three sockets (see Figure 1 and Figure 2) have been measured on each magnet and the following conventional naming has been used :

- Q for quadrupole and D for dipole,
- E = entry point on the magnets following the conventional beam direction,
- M = middle point on the dipole magnets,
- S = exit point on the magnets following the conventional beam direction.

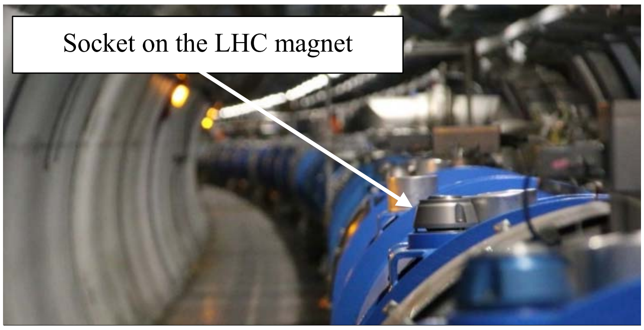

Figure 1 : LHC tunnel with sockets on magnets

The stretch wire has been installed to cover the 5 magnets with a radial distance from 120 mm to 275 mm and at 1.6 m height from the floor.

This setup is convenient for all the measurement processes.

LHC Constraints

The main objective of the campaign was to evaluate all the LHC constraints compared to the ideal conditions in laboratory with close range measurements (less than 5 meters).

The LHC environmental conditions (temperature variation, airflow and light conditions) are the most critical disruptors. As for the microtriangulation measurements, the wire need to be visible from different stations it was not possible to protect the wire with the duct as it is done during regular radial smoothing activities in the LHC [1]. Therefore the airflow speed has been reduced but wire oscillations have been observed. The workload and the time needed for the measurements did not allow the execution of all the acquisitions during one day, so the stretched wire stayed in place during few days. The long term stability was not as good as expected.

Another issue was the coordination and co-activities from other CERN groups that need to pass in the LHC tunnel for correction or maintenance works. This was part of external perturbations, as we have to stop the measurements

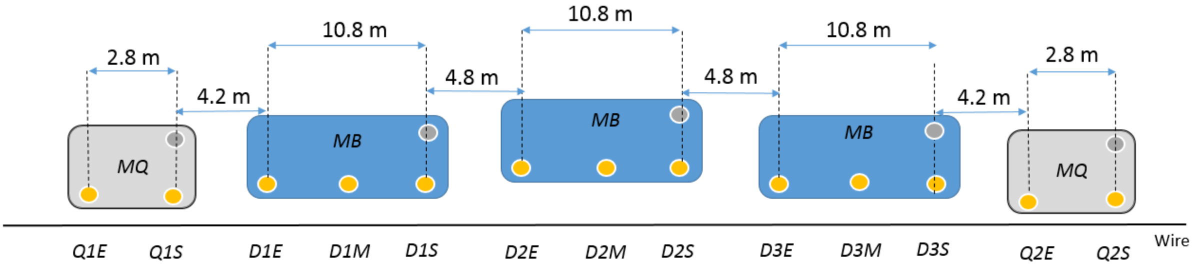

Figure 2 : Wire configuration and socket naming on the MQ and MB magnets **measured** in the LHC tunnel

MEASUREMENT SETUP

A vectran wire has been measured with different solutions and a common network has been defined, installed and measurement as a common input data.

Sequences

The common "wire measurement" campaign has been done along LHC magnets with the following processes :

- Standard offset measurement with a wire offset measurement device,
- oWPS sensor associated with laser tracker AT401 and Spatial Analyser software,
- Photogrammetry with a D3X camera and Aicon software,
- Micro-triangulation with a Leica TS60 total station and QDaedalus software,

Targets

In order to minimize the mechanical issues, a universal support for laser tracker and microtriangulation was developed for 1.5" diameter sphere. The centre of the sphere is identical as the one obtained by using a Taylor-Hobson ball, 3.5" diameter, standard support used at CERN.

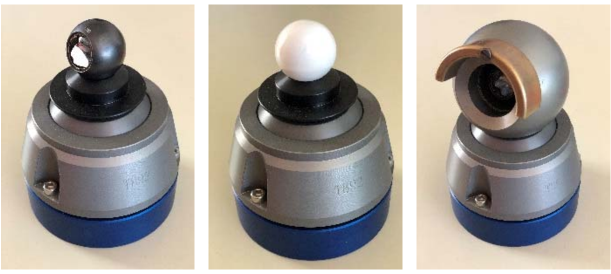

Figure 3 : Universal support with CCR1.5" (tracker), 1.5" white sphere (microtriangulation) and a CCR1.5" inside a Taylor-Hobson ball

Common Network

A network measuring about 80 m has been defined along the LHC tunnel using the magnet sockets and additional support fixed on the vault where 1.5" targets/spheres can be installed. All the points have been measured 3 times or more by 7 laser tracker stations. The network calculation has been compute with Spatial Analyzer using a Unified Spatial Metrology Network (USMN).

Figure 4 : LHC tunnel with additional network support equipped with a 1.5" white sphere for microtriangulation measurements

STANDART OFFSET MEASUREMENT

Since the construction of the Intersecting Storage Rings (ISR) and the Proton Synchrotron (PS) at CERN in the 1960s, the Survey Group is using alignment with stretched wire techniques. This process appeared as the best solution for solving the problems of atmospheric refraction, the limits of calculations possibilities, and for speeding up the work [2].

Campaigns with a standard optic offset measurement device was done at the beginning and at the end of the test period. This manual process should not be used for the HL-LHC matching section in the future.

The offset measurement is made manually with the eye of the operator using a CERN developed instrument called "ecartometer" which measures the distance to the straight line materialised by the wire with a resolution of the pointing that is estimated to +/- 0.025 mm.[3]

Feedback - Advantages and disadvantages

The same wire has been measured three times by this instrument during the test period. The standard deviation is less than 0.03 mm (see Table 1). As the wire protection was not used, the airflow was the biggest constraint during the manual measurement as the vibrations of the wire were visible by the operator.

Figure 5 : Manual ecartometer installed in a socket of a LHC magnet

The offset measurement is the fastest process used during the tunnel test and as the computing process is light : the offset results are available directly in the LHC tunnel without any post processing.

Socket Name	E1	Q1E	Q1S	D1E	D1M	D1S	D2E	D2M
STDEV [mm]	0.02	0.01	0.02	0.02	0.01	0.00	0.01	0.00

Socket Name	D2S	D3E	D3M	D3S	Q2E	Q2S	E2
STDEV [mm]	0.03	0.02	0.01	0.03	0.02	0.00	0.01

Table 1 : Standard deviation of the ecartometry measurements

OWPS ASSOCIATED WITH LASER TRACKER (AT401)

An optical Wire Positioning Sensor (oWPS) associated with laser tracker measurements were used in order to determine the horizontal distance between the stretched wire and the sockets

Instrumentation - Requirements

This optical sensor, developed and manufactured by Open Source Instruments, was equipped with two CCD cameras which take pictures of the stretched wire from two different angles under red light. The position of the wire is deduced from each CCD by image analysis. As the position and orientation of each camera have been determined previously in a calibration process, the position of the stretched wire can be deduced in the coordinate system of the sensor. The coordinate system of the sensor is determined in relation of the 3-balls kinematic mount allowing a micrometric installation of the sensor.

For this application, the oWPS sensor has been installed in a plate equipped with 7 fiducials. The fiducials and the 3-balls kinematic mount of the sensor plate were previously measured with Romer arm within an accuracy of 15 µm. Therefore, a Helmert transformation between the coordinate of the sensor and the coordinate system of the plate can be defined.

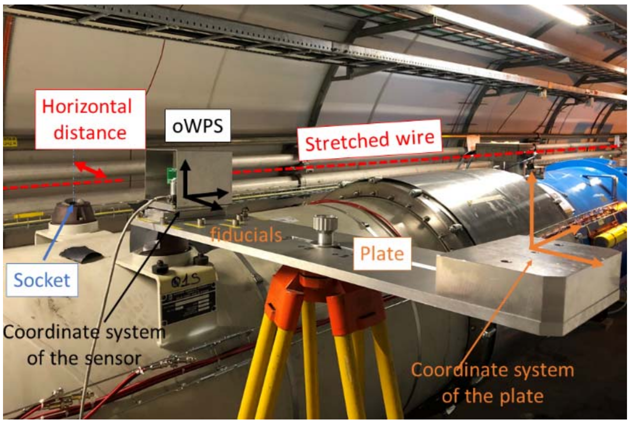

Figure 6 : oWPS plate

The fiducials were measured with a Leica laser tracker AT401 in order to define the Helmert transformation between the coordinate system of the tracker station (linked to the gravity) and the coordinate system of the plate. At the end, the position of the wire can be determined in the coordinate system of the station.

The plate was moved and measured at four different positions along the stretched wire. Thus, the equation of the stretched wire can be determined in the coordinate system of network. The horizontal and vertical distance between stretched wire and each socket can be determined.

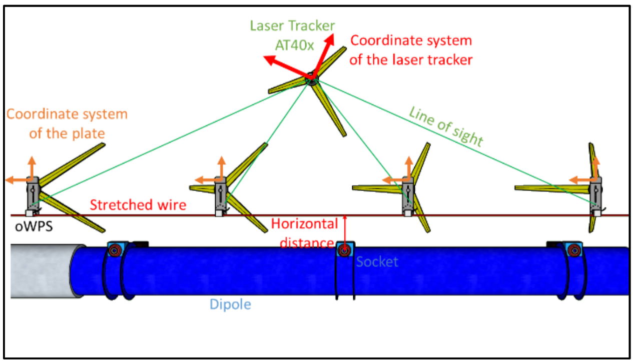

Figure 7 : Setup of the oWPS measurements

Computation of the measurements

Four stations have been done along the tunnel in order to cover the entire experimental area. For each station, the adjusted parameters of the wire modelling (straight line in the horizontal plane and a catenary curve in the vertical plane) were assessed from the oWPS observations and estimated using the least square method with the 4 points.

The following table explains the maximum residual of the wire modelling in radial and vertical on the oWPS observations for each station.

Station	Position	Maximum residual Radial (µm)	Maximum residual Vertical (µm)
ST1	**From Q1E to D1M**	16	9
ST2	**From D1M to D2M**	9	10
ST3	**From D2M to D3M**	66	2
ST4	**From D3M to Q2S**	60	13

Table 2 : Maximum residuals of the wire modelling

Feedback - Advantages and disadvantages

The oWPS can observe the vibration of the wire and compute a mean value even if the global wire shapes is affected by the airflow.

On the other hand, this process requires two sensors : (oWPS and a laser tracker) with accessories and laptops and need a post processing time to compute the coordinates of the points on the wires before the calculation of the mean line

Conclusion

The wire was not stable during the measurements due to the ventilation. Some noise up to +/-50 µm has been observed. An average on 5 points has been applied for each observations. This instability on the wire can explain the residuals for the wire modelling.

The horizontal distance between stretched wire and each socket can be determined from the equation of the wire modelling and the measurements of the sockets. The uncertainty of these distances was estimated at 50 µm (mainly due to the instability on the wire).

PHOTOGRAMMETRY

Introduction

Digital photogrammetry is used at CERN since nearly 20 years and has demonstrated efficiency in the case of close range photogrammetry. Recent improvement in wire photogrammetry led CERN to start a study concerning this type of measurement.

The precision has been evaluated around 20 µm for a 3D distance between a wire and a point [4]. The automation of this measurement is still under study by CERN [5]. The semi-automatic measurement is tested simultaneously in this project of wire measurement comparison.

Instrumentation – Requirements

The camera is a Nikon D3X with 6048x4032 pixels sensor equipped with a shifted flash, the lens is a 28mm AICON “metric” and images are black and white JPEG. 25 pictures are taken in 5 columns of 5 images, in front of the setup, which is inclined by around 45 degrees.

The scale is introduced with three 60 cm carbon fibre scale bars that have been calibrated on a CMM.

In order to measure horizontal offsets, verticality has been introduced with an 86 cm bar equipped with 2 targets that are measured in parallel by other methods in order to determine the vertical offset.

The exterior and interior orientation is calculated based on dot targets placed on a wooden panel that is moved by the operator from one position to another.

The software part is ensured by AICON 3D studio for photogrammetry and line measurement combined with Spatial Analyser for the mean line computation and offset calculation.

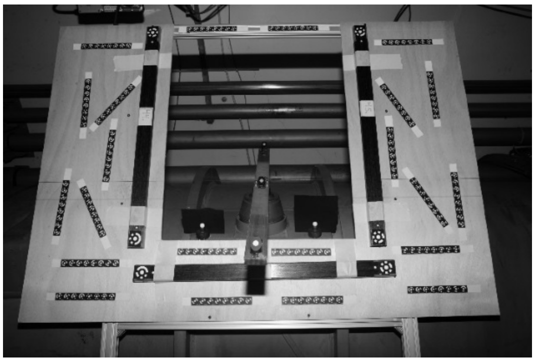

Figure 8 : Typical configuration for photogrammetry

Computation of the measurements

The target detection, interior/exterior orientation and the measurement of the wire by measuring individual points on the wire every 0.25 mm are done by Aicon 3D Studio. Then, all the points are imported in Spatial Analyzer for a mean line computation. Many outputs of the bloc computation can be used to evaluate the precision of the measurement.

	SX (µm)	SY (µm)	SZ (µm)
Points	2	2	4

Table 3 : Precision of the measured targets on the 13 photogrammetry projects

In order to evaluate the precision of the line, the computation of the line and the residuals provides a good view of the precision since there is around 4000 points for the computation.

	RMS (µm)	min (µm)	max (µm)
Line best fit	31	23	38

Table 4 : precision of the orthogonal distance best fit for 13 parts of single wire

Residuals are distributed randomly along the wire. There are some spikes of errors, which are due to the difference of background colour behind the wire. All errors are in the shooting direction, which means that the precision for measurement is higher than the sag of the wire and may be an indication on some vibration of the wire.

Then the definition of the coordinate system is made by defining the origin on the socket. Y-axis is set parallel to the wire and the rotation is fixed by using same Z for points on the bar, this involves that the 2 points on the bar has the same Z. With the axis, the radial offset is the X position of the line. This step marks the introduction of the vertical direction. The bar has been measured with the AT 401 and the offset of vertical position between the 2 points used to introduce verticality is 0.3 mm (on 860mm). A second error is added because of the bar. The way the reflector is made induce a centering error of 50 µm for every measurement since the bar was always used on the same side. This error was measured after in lab by turning the bar and measuring the offset between measurements.

After computation, we can estimate the precision of the measurement around 30 µm.

Feedback - Advantages and disadvantages

The main advantage for this method is that it saves time during the measurement. It takes 10 minutes to install the panel, the points on fiducials and take the images. The computation is relatively fast, about 10 minutes to compute the bloc photogrammetry, the wire measurement, the wire computation and to compute the distance.

The method is also highly automatable since there is no heavy material to handle.

The precision of the measurement, estimated around 20-30 µm, is sufficient for this application and can be improved.

There is one disadvantage related to the fact that photogrammetry is not related to gravity. The link to gravity has to be introduced and this leads to a loss of precision depending on the way the link is done.

The other disadvantage is the lack of link between two sockets. Each measurement is independent, as they are not compute all at once.

Conclusion

The photogrammetric measurement is already quite fast and the margin of progress is still important in terms of speed, efficiency and automation.

However, a few differences on the results push us to analyse further the accuracy of our measurement and to make some laboratory test. This will allow us to understand in controlled condition what are the sources of errors between measurements.

MICRO-TRIANGULATION

Micro-triangulation is a special type of the triangulation method that has two main characteristics:

- it is applied in small volumes of a few metres, where we consider a topocentric coordinate system,
- it employs high-accuracy robotic theodolites with a few µm/m angular accuracy.

The combination of these characteristic leads to high-precision surveying networks with estimated coordinated in the level of a few tens of micrometres depending on the conditions.

The micro-triangulation method with direct wire observations goes beyond the standard triangulation method. Here, a network includes angle observations to objects like stretched wires. The particularity is that there are no discrete points on wires with uniform surface, thus from one station we are able to observe each point on the wire only once.

In this study, we apply the micro-triangulation method with direct wire observations. This method was developed within the Particle Accelerator Component Metrology and Alignment to the Nanometre scale (PACMAN) project [6], and it was evaluated in a quadrupole fiducialisation application. First results demonstrate accuracy in the wire position of about 20 µm over a volume of about 5 m, compared with a coordinate measuring machine (CMM) [7].

Instrumentation - Requirements

The micro-triangulation with direct wire observations is based on automatic contactless observations, obtained by image-assisted theodolites. For this measurement, we use the new Leica Nova TS60 total station [8].

The theodolite is equipped with the QDaedalus measuring system [9] which is designed and developed by the Geodesy and Geodynamics Lab, Institute of Geodesy and Photogrammetry, ETH Zurich. QDaedalus consists of the software and hardware add-ons to a robotic total station. The fundamental idea is to replace the eye-piece with a CCD camera in a non-destructive way. The software offers a variety of image processing algorithms that are used to detect different types of targets.

The LHC tunnel environmental conditions may affect the quality of the measurement. The variation of the ambient temperature results to expansion-contraction of any object, the airflow in the tunnel causes the swing of the stretched wire, and the light conditions can significantly affect passive optical measurements.

Constraints in the geometry of the networks are also imposed by the narrow shape of the tunnel, by the length of the experimental area (80 m), and by the nature of the measurements that need stations in different heights in order to be able to determine the position of the approximately horizontal wire.

Computation of the measurements

Least-squares adjustment is used to estimate the parameters of the network. In principle, the standard algorithm is followed with some variations, mainly concerning the constraints. In our implementation, we use the parametric functional model, where each observation is given as a function of the unknown parameters. The observations we use are the horizontal and vertical angles, while the unknown parameters consist of the 3D coordinates of the point-targets and stations, the horizontal orientation plus three systematic error coefficients for each station, and parameters to define the form, the position and the orientation of the wire in space.

The network solution provides the estimation of the unknown parameters and the relevant covariance matrix. In this validation test, we are interested in the horizontal distances between each fiducial and the wire. Starting from the estimated parameters we can calculate the required for the comparison distances moreover, we rigorously calculate the uncertainty of the horizontal distances, by propagating the uncertainties of the covariance matrix.

More information about the methodology, concerning the measurement and the data analysis, can be found in [10].

Feedback - Advantages and disadvantages

Main advantage of the micro-triangulation with direct wire observations method is the fact that it works with the same type of observations as in the standard triangulation. Moreover, the logic to build a network remains the same as in the standard triangulation. The measurements can be acquired automatically, in order to increase the precision and decrease the acquisition time, however an experienced operator is needed, especially during the instruments installation and the target parameters configuration.

Another advantage is the portability of the system and the ability to perform the measurements remotely, while disadvantage can be considered the fact that in the current implementation there are a lot of cables that makes the hardware difficult to manage and non-robust.

In term of surveying networks, the disadvantage is the well-known fact that triangulation cannot provide information about the scale of the network. The scale should be introduced either in the form of constraint, or in the form of observations. Advantage of the method is the fact that the observations are uniformly adjusted, with good control of outliers and with the ability to compute the uncertainties of the parameters in a consistent and well understood procedure.

The fact that a network may include observations to many wires is extremely advantageous. As for example, we can include in a network two or more stretched wires that follow the catenary shape, plus a few vertical wires that can be considered as straight lines. Moreover, the ability to compute both horizontal and vertical offsets a wire with respect to fiducial points or another wire, makes the method suitable for fiducialisation and alignment applications.

Conclusion

Despite the non-desirable ambient conditions in the tunnel environment, the tightness of the schedule and the parallel activities in a confined space, we managed with success to measure the 80 m network in two days, using one image-assisted theodolite.

The results show that the horizontal distance between a fiducial and the wire can be measured with about 40 μm precision at 95% confidence level. The comparison with the other methods tested in the frame of this campaign demonstrates differences in the horizontal distances in the range of 10 – 100 μm.

Finally, the positive result can justify the effort for more development in the hardware and software that is relevant to the micro-triangulation method with direct wire measurements.

INTERCOMPARAISON

Introduction

The aim of the collaboration was the demonstration of the feasibility of the wire measurement in the LHC using four different methods and not dedicated to an inter-comparison as the environmental conditions are not suitable.

However, the horizontal distance between the stretched wire and each socket obtained with all the methods can be compared. The uncertainty of these values was estimated at +/-50 μm due to the instability on the wire.

A fifth artificial method has been added with the measurements of the wire fixing points during the network campaign : the 3D coordinates of the sockets have been projected on the line defined by the 2 fixed points. Theses horizontal distances are added in the comparison process and named “AT40x”. This solution is correlated with the oWPS results as the same AT40x stations are used in the calculation.

Results

As no method can be considered as the reference value, two different comparisons have been done :

- Comparison with the mean value obtained by the 5 methods (Figure 9).
- Comparison with the ecartometry measurements considered as the historical and standard measurement process (Figure 10).

Considering the Figure 9 :

- All the offset are in +/- 0.15 mm but the photogrammetry seems to measure systematically a higher value in the second part on the wire (bad light ? shadow ?) and the ecartometry methods is systematically lower even if the repeatability is good.
- The AT40x process obtains with only 3D measurements of the sockets (offsets points and fixations points of the wire) stays inside the +/- 0.05 mm.
- The maximum offsets between methods are 0.26mm on the first socket (Q1E) between ecartometry and photogrammetry acquisitions and on the penultimate socket (Q2E) with 0.22mm between photogrammetry and oWPS.

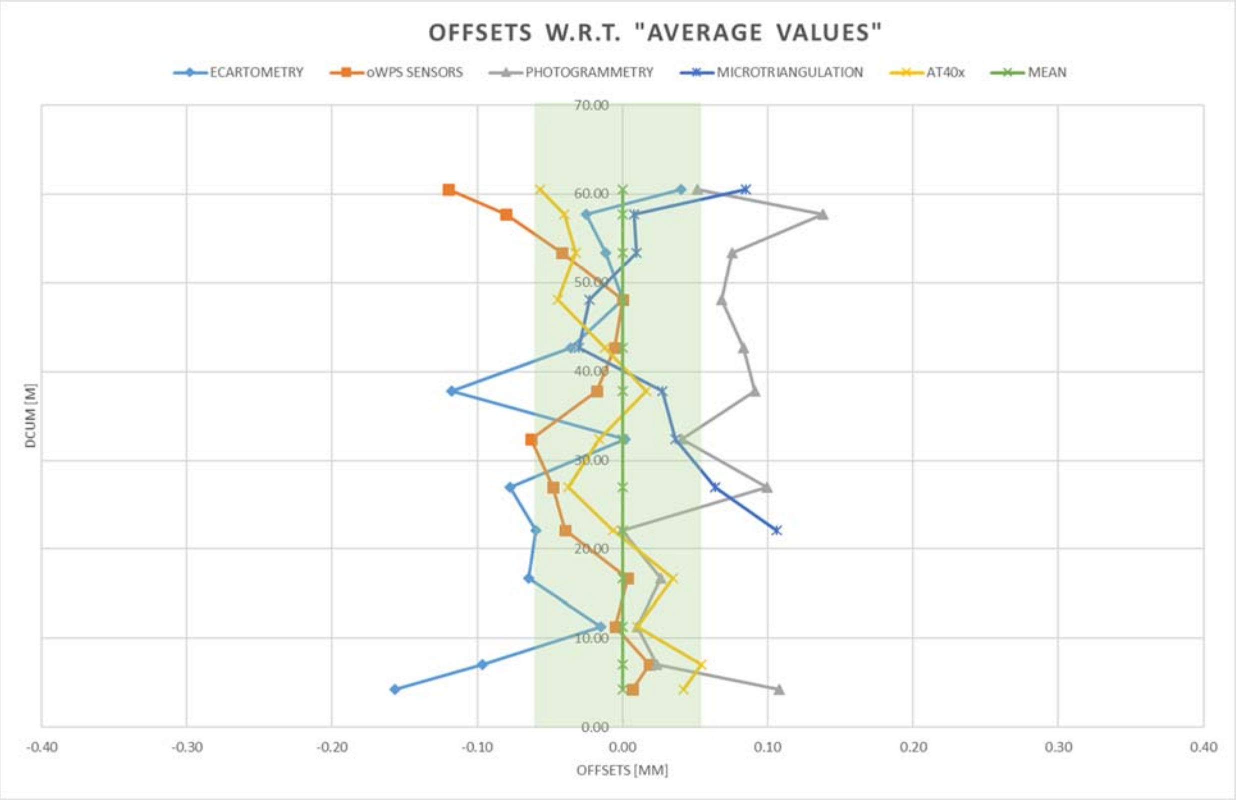

Figure 9 : Offsets of the horizontal distances with respect to the “average values”

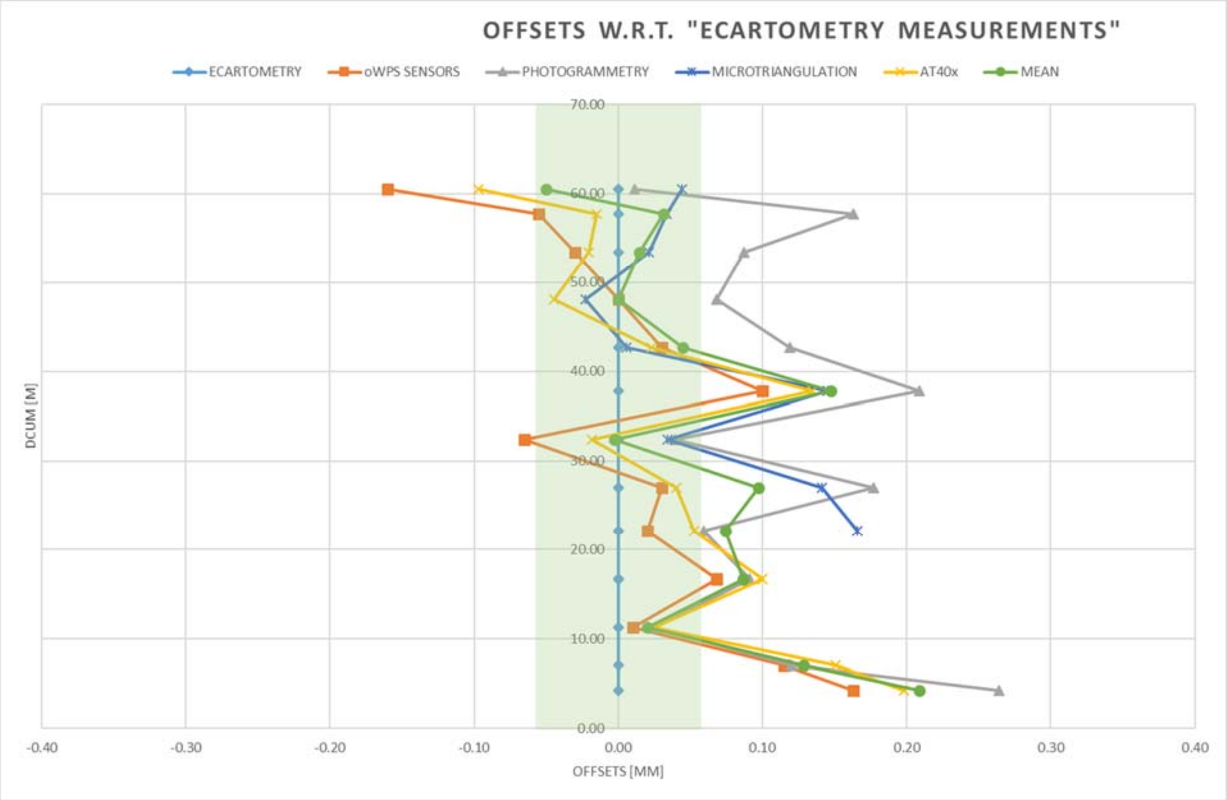

Figure 10 : Offsets of the horizontal distances with respect to the “ecartometry values”

As there is no way to say which method gives the best values neither used an absolute reference : the comparison cannot established more conclusions.

Figure 10, shows the offsets of the different acquisitions with respect to the ecartometry values, it is again difficult to conclude but this graphic provides an intersecting global view with all the curves homogeneous between them.

A better way to compare … in the future

A dedicated laboratory test environment with stable parameters on a smaller stretched wire should be organized in order to compare with accuracy the offsets between the various methods.

The LHC tunnel was not a good place for a precise comparison and all the efforts were focus on the validation tests.

IMPROVEMENTS AND NEXT STEPS

The validation tests will continue with new cautions (lights, network optimization, computing process, …) and mainly the stability of the wire need to be improved :

- As the airflow was the most disturbing constraint : a total stop of the ventilation should be asked in the LHC,
- The coordination of the measurements need to be optimized in order to reduce the time measurement and so any issue with the reference wire.

As photogrammetry need a good vertical definition, the introducing of vertical wires also measured by microtriangulation can be a good option for a new common session.

Morever, the vertical distance between the stretched wire and each socket can be computed from oWPS sensor, photogrammetry and microtriangulation data. A common strategy will be defined in order to take in account the earth curve and evaluate the different methods and results.

Whatever the solution chosen, the final acquisition process should be more automatized due to the future radiation level. All the instrumentations that were used can be enforced with less human intervention even if software and hardware developments will be needed.

CONCLUSION AND OUTLOOK

It is the first time that a so long stretched wire was measured by various methods inside the LHC tunnel with real working conditions. This validation measurements was a success and demonstrate the feasibility of the different methods for the measurement of the horizontal offsets between fiducials on magnets and the wire.

The ability to compute both horizontal and vertical offsets from a wire with respect to fiducial points will be a real asset for the challenging measurements of the HL-LHC components with the rest of the LHC.

ACKNOWLEDGEMENT

Five surveyors colleagues from two sections of the SMM group were involved in these validations tests. The wire measurement was a great collaboration success with a warm and hearty team spirit during the preparation, coordination of the activities and also inside the LHC tunnel.

My sincere thanks go to all of them.

Figure 11 : CERN staff who were involved in the wire measurements

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