# STRETCHED WIRE OFFSET MEASUREMENTS: 40 YEARS OF PRACTICE OF THIS TECHNIQUE AT CERN

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*Abstract*

Since the construction of the Proton Synchrotron (PS) at CERN in 1965, the Survey Group has developed various specific tools for aligning the elements of the machines more efficiently and more accurately than with the existing tools which existed at this time. The distinvar is an example of these specific tools. Among others, the alignment with stretched wire techniques has been intensively used on all the CERN accelerators. The quality of the wires, their length, and the sensors themselves have improved a lot during 40 years. This paper describes this very simple technique and its evolution, the results obtained, gives some recommendations when using this technique, as well as future possibilities in using stretched wires for alignments.

## INTRODUCTION

To fit with the precision requested for the alignment of the components of the accelerators, the surveyors had to adapt their classical tools and techniques to their needs. They also improved them according to the size of the accelerators to speed up the measurement processes. As an example, for aligning the 28 GeV Proton Synchrotron (PS) in 1965, the team in charge of the alignment used the polar method, using the theodolite WILD T3 for the angles, and the invar wire (or tape) for the distances, with all the problems due to the refraction.

At this time also, the first computers had just made an appearance, and the adjustment computations of the geodetic networks where still made with calculating machines. So it was a great importance to imagine techniques as simple and as accurate as possible, in order to simplify the calculations, at least during the alignment work.

This technique appeared as the best solution for solving the problems of atmospheric refraction, the limits of calculations possibilities, and for speeding up the work.

After a description of the cases where this method is used, attention will be paid to the possible future of this method.

## PRINCIPLE OF MEASUREMENT

The principle of the measurements consists in measuring the shortest distance of a point B to a straight line AC. Usually, such a distance can be obtained by measuring the angle ABC and two distances AB and BC for example.

The line AC can be materialized with a laser beam. In our case, we consider that a stretched wire materializes the straight line, which is the case at the first order.

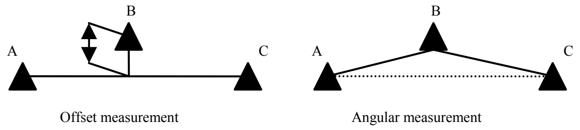


Figure 1: Principle of the offset measurement

## THE ALIGNMENT WITH STRETCHED WIRES AT CERN

### *The ISR*

The stretched wire has been used for the first time for the alignment of the accelerator components in the Intersecting Storage Rings (ISR) machine, from 1964 to 1971. The geodetic reference network of the ISR was a 930 m long ring materialized by pillars located at each corner of a series of 32 quadrilaterals (see fig. 2).

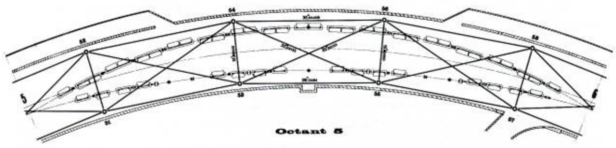


Figure 2: The ISR reference network

This network was only determined by invar distances measurements with the distinvar. Each magnet was equipped with 2 reference sockets. One socket of each magnet was aligned by measuring simultaneously the distance from two pillars. [1]

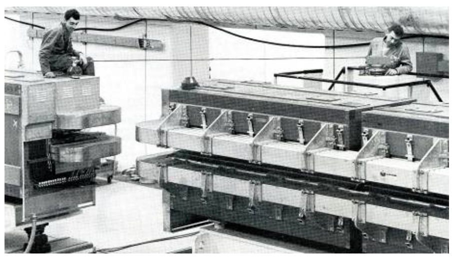

Figure 3: Distance measurements

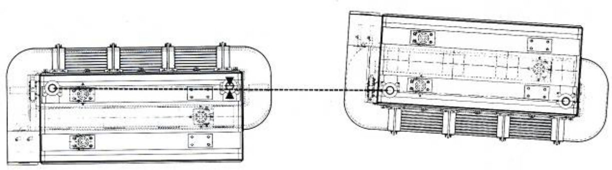

Figure 4: The alignment of the ISR magnets

Then the second socket was aligned with a nylon wire in relation to the straight line between the first socket and that of the next magnet, so that the curve could be smoothed between magnets. The detection of the wire was made simply with the eye, by comparing the position of the wire with respect to a point graved on a plate centred on the socket. The resolution of the pointing was estimated to +/- 0.05 mm. [2]

The nylon wire has been intensively used also in the two transfer lines from the PS machine and the ISR. The wires were stretched over a distance of 83 m, covered series of 4 pillars, and the measurements were carried on the intermediate pillars 2 and 3.

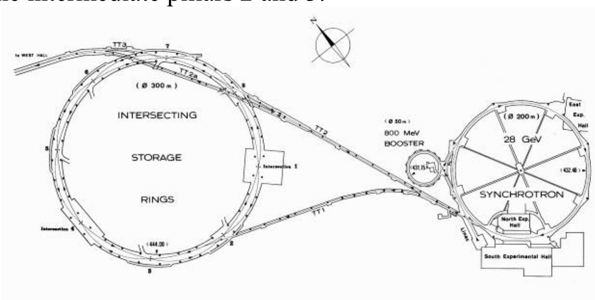


Figure 5: The ISR complex layout

Then the wire was translated to the next pillar for another series, with overlapping, and so on. The ventilations were stopped during the measurements, and the configuration of the tunnels made it not too difficult to prevent from the natural wind. At this time, the measurements were performed with a prototype with no microscope for the readings. The principle of the system was based on the observation of the projection of the shadow of the wire on a screen. The instrument was composed of a support with precise holes each 10 mm. The sensor was plugged in the holes corresponding to the offset to be measured, and used for the interpolation. The resolution of the instrument was 0.02 mm. Similar sensors are still in use for manual measurements.
The Nylon was chosen simply because it is cheap, easy to handle, and for its low density and a high tensile strength. The diameter was 0.2 mm, with a tension of about 15 N. The measurements where very fast to be performed, and avoided all the problems of the refraction in the tunnels.

## *The SPS*

From 1974 to 1976, CERN built the 300 GeV Super Proton Synchrotron (SPS). This machine has a radius of 1100 m. The geodetic reference network has been transferred from the surface trough 6 pits 1100 m apart. In the tunnel, the primary reference network was based on a series of brackets fixed each 32 m on the vault.

At the inverse of the ISR where the ratio between the width and the length of the quadrilaterals was favourable, the same ratio in the SPS was 1:10. This made the reference network too flexible if it was determined only by invar distance measurements. It is why for the first time in a machine the rigidity of the figure was controlled by additional wire offset measurements. The following figures show the network and the propagation effect of random errors of the measurements on the absolute determination of the network. [3]

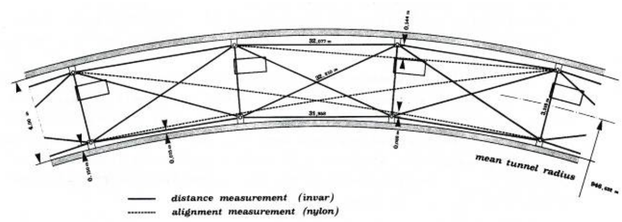


Figure 6: The SPS reference network

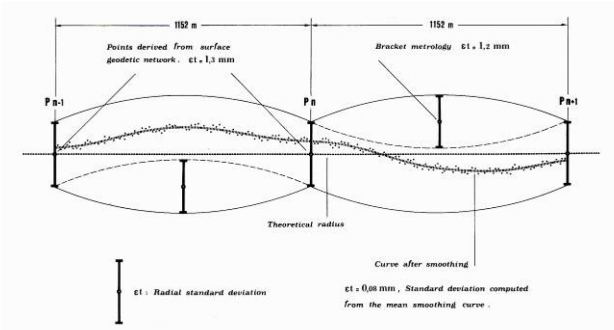


Figure 7: The alignment accuracy of the SPS quadrupoles

In order to minimize systematic deformations of the wire due to the unavoidable wind in such long tunnels connected to wide and deep pits, the speed of the wind was measured, and the measurements where carried out from the two sides of the tunnel. Also, the ecartometers where calibrated over their full range on the calibration base.

At this time CERN developed an automatic ecartometer.

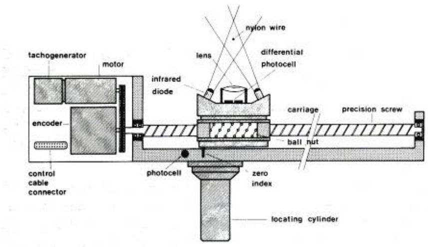


Figure 9: The automatic ecartometer principle

Two diodes are mounted on blocked moved on a long screw. The sensor moves on a screw until the reflection of the lights of the two diodes on the wire are detected on the optical receiver. At this moment the sensor is centred on the wire. The accuracy of the system is better than 0.1 mm.

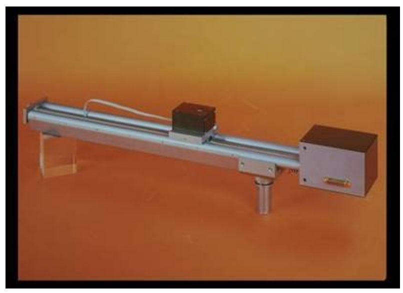

Figure 10: The automatic ecartometer

It appeared very quickly that the walls of the tunnel were not stable enough to be considered as the support of our geodetic reference network, and it was decided to abandon it after the first alignment of the machine. The alignment of the quadrupoles is now done directly on the magnets themselves.

The figure 8 shows the wire offset measurements performed for the smoothing of the quadrupoles.

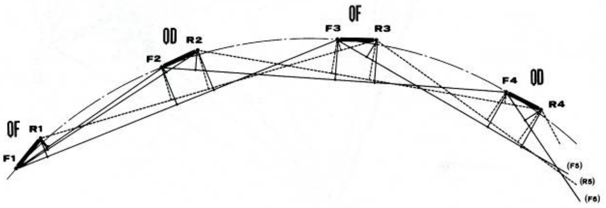


Figure 8: The SPS smoothing measurements

The wires were stretched over one period (3 quadrupoles) over 64 m, and the offset measurements devices have been extended to be able to measure an offset of 650 mm.

In this process, no absolute calculation of the measurements is considered. The rigidity of the figure is too weak for that. The measurements are least square adjusted, and the elements are only smoothed, the figure obtained being considered globally at its theoretical place. This method allows a very accurate relative alignment of the SPS quadrupoles. It is very efficient, very fast and cheap.

Actually the method is still in use. The length of the wires has been extended to 92 m, in order to cover one and a half cell, and the ecartometers can measure up to 1.40 m offsets. The longer the wire is, the more accurate is the smoothing.

It takes 1 day with 3 technicians for measuring one 1.1 km long arc. The following figure shows the repartition of the residuals after adjustment of the 1286 offset measurements carried out around the SPS, with an r.m.s. value of 0.08 mm.

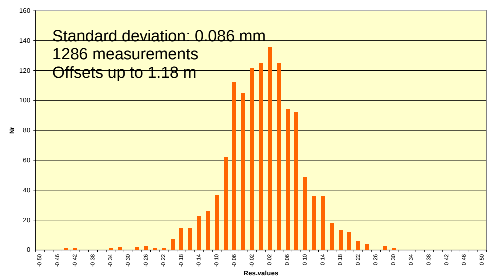


Figure 11: Offset measurements accuracy in the SPS

## *The LEP*

From 1982 to 1989, CERN built the LEP. This 27 km long ring had 8 sectors 3.3 km each. The initial reference network was transferred from the surface trough 8 pits, and was based on a series of tripods fixed each 42 m (the length of a half cell of the machine) directly on the floor. The experience gained from the SPS induced this choice for having no points on the walls. The radial position of the tripods was measured with the stretched wire technique.

After their first alignment from the network, the LEP quadrupoles have been smoothed using the SPS smoothing technique [4].

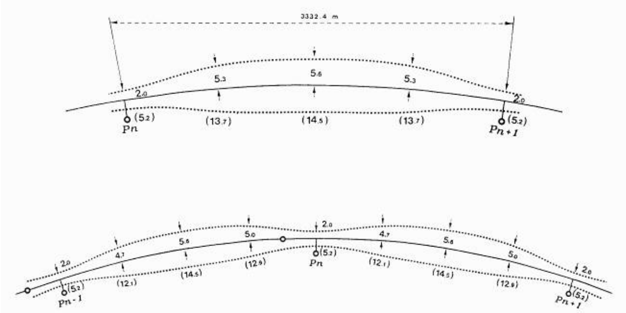

Figure 12: Accuracy of the LEP reference network

The stretched wire technique was used for the monitoring of the motion of the LEP machine elements during the excavation of the caverns for the two LHC detectors ATLAS and CMS. Two carbon wires have been stretched over 120 m along the elements just centred under the zone affected by the civil engineering works, and 11 bidirectional capacitive sensors have been installed on each wire. The wires were a local reference for monitoring the deformations in the vertical and horizontal planes. The accuracy of the detection of the ground motion was about 0.01 mm [5].

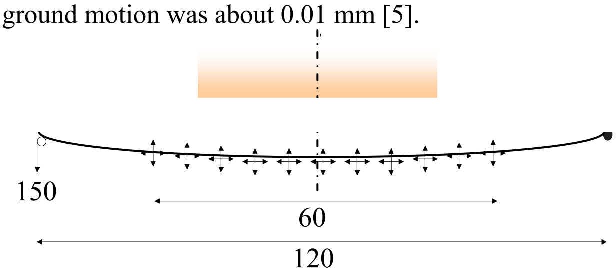


Figure 13: Layout for monitoring of the LEP tunnel

The precise monitoring of the energy spectrometer elements used for measuring the energy of the LEP with a relative accuracy of $10^{-4}$ was also performed using the wire technique [6]. Capacitive wire positioning sensors installed around a ~30 m long carbon wire have been used to determine the relative mounting stability of each BPM and to calibrate the beam position monitors. This experiment shown in particular the sub-micrometric resolution of the sensors and their sensitivity to the radiation environment, and proved the possibility to shield them with lead against the synchrotron radiation.

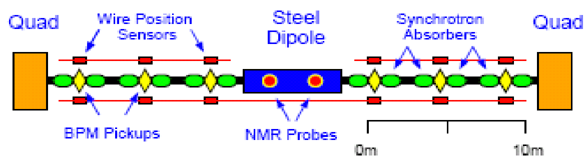


Figure 14: Layout of the spectrometer monitoring

## *The LHC*

The reference network of the LHC is materialized by a set of points sealed in the floor of the tunnel each 52 m (the half cell length of the machine). This network has been determined by distances, azimuths, and angular measurements from the LEP quadrupoles before their removal and after a complete radial smoothing with wires [7]. The points have been also measured with stretched wires, but the measurements appeared as not accurate enough due to a lack of care when they were carried out. These measurements have been repeated just before the first alignment of the magnets took place for improving the relative accuracy between the points. This was done successfully thanks to the attention paid to the wind and the centring of the tools.

The cryomagnets have all been aligned radially with wire stretched over about 120 m, and the final alignment, so called smoothing, is now also performed with long wires [7].

After their alignment and when cold, all the cryomagnets are smoothed, (not only the quadrupoles as in the previous machines). The speed of the measurements is about 450 m and 9 wires per day, with a team of two persons, and 18 offset measurements are carried out per wire. The wires are stretched over a period of the machine (~110 m), and shifted by a half period, which makes at least 2 measurements per point. Figure 15 shows the repartition of the residuals after adjustment, with an r.m.s. value of 0.04 mm thanks to a mobile protection of the wire against the wind.

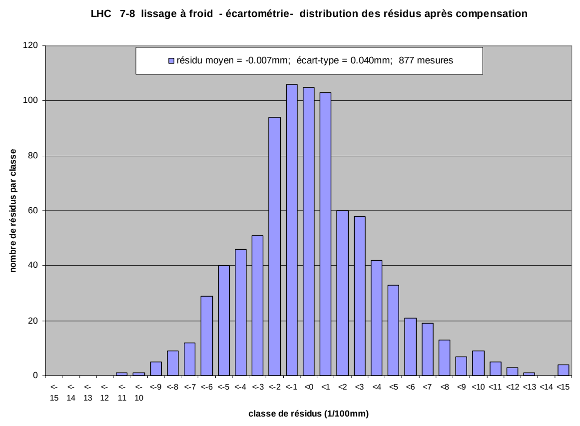


Figure 15: Offset measurements accuracy in the LHC

## *The Alignment of the LHC inner triplets*

The radial alignment of the low beta sections around the 4 LHC experiments is done with wire technique. A 140 m long carbon wire is stretched all along and parallel to the section, across the experimental cavern, and through two dedicated galleries. Another wire is stretched on the elements themselves and the distance between the two wires is measured in three sections, on each side of the experiment. Capacitive sensors with sub-micrometric resolution are used for detecting the wires. Calibrated invar bars and contact-free capacitive sensors are used for measuring the transversal distances. The relative accuracy of the measurements is some microns on all the system. The signals are stored in a database and the magnets can be re-aligned remotely from the control room thanks to motorized jacks.

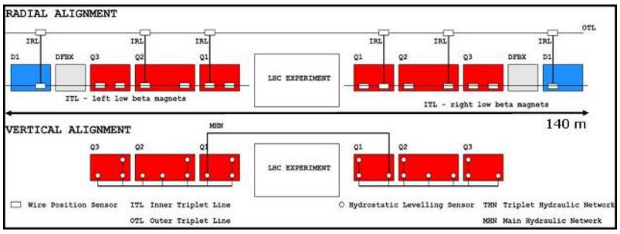


Figure 16: Layout of the inner triplets measurements

# IMPROVEMENT OF THE TECHNIQUE

For the “classical” alignments (~ 0.1 mm), the sensor has not changed a lot in 40 years. The microscope is the same. The only improvement is to have mounted it on a digital reading calliper.

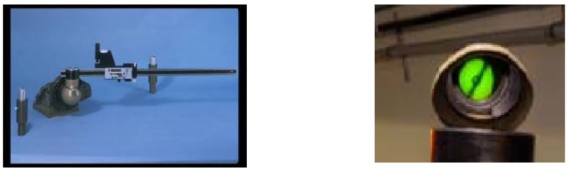

Figure 17: Wire offset device

The SPS automated ecartometer brought only comfort and reliability, but neither accuracy nor faster measurements.

Attention has been paid to trying to minimise the effects of the wind and to eliminate the systematic errors.

The straightness of the wire depends of the speed of the wind and the orientation with respect to the wire. A wind parallel to the wire is not a problem. It makes the wire vibrate but the oscillations can be observed by integrating the measurements during few seconds. The effect of a lateral wind can be controlled by changing the tension, as it changes also the lateral sag of the wire. It was a major improvement to build a 100 m long train carrying a light venting duct for protecting the wire in the LHC.

A fundamental characteristic of this technique is that the accuracy does not depend of the length of the wire. All the measurements carried out on a same wire can have the same accuracy. Nevertheless, residual systematic errors can have a disastrous effect on the absolute precision of a traverse. The following formulae gives the propagation effect of a systematic error of 0.1 mm over a traverse of n points when measuring the wires 1-2-3, 2-3-4, 3-4-5,…, (n-2)-(n-1)-n.

$$E = (n-1).(n-2).s$$

Where *n* is the number of points and *s* is the systematic error.

Three main sources of errors can be identified. The scale factor of the sensor, first, can be easily done with the interferometer. Then, the centring of the wire on the points at its two ends is also to be considered, as well as the constant error of the sensor. These two last points are solved in one go by measuring the offsets also at the two ends with the same instrument as for the intermediate points.

New fibres have appeared (e.g. used for fishing), allowing a higher tension, a smaller vertical sag, and less sensitivity to the wind. For "itinerant" measurements, fishing wires can be used. The new Dyneema™ fibre is very efficient, and its creep and elasticity is not a problem because the wire is stretched during a short time. For monitoring deformations or ground motion, a wire with no creep, no elasticity, a low sensitivity to the humidity is needed.

A stretched wire is affected by the rotation of the Earth. The influence on the vertical sag has been studied by F. Becker [8]. It is only very recently that T. Touzé (CERN) studied the influence of the rotation of the Earth on the lateral sag of the wire, and has shown that this sag depends on the latitude and the azimuth of the wire and is proportional to the vertical sag [9].

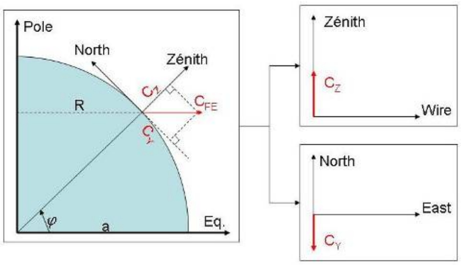


Figure 18: Inertial forces

$C_{Fe}$ is the inertial force field due to the rotation of the Earth.

$$C_{Fe} = \left\| \overrightarrow{C_{Fe}} \right\| = q.R.\Omega^2 = \frac{Cm.R.\Omega^2}{g}$$

It can be decomposed into $C_Y$ and $C_Z$ on the horizontal and the vertical plane respectively according to the latitude.

$$\begin{cases} C_Y = -C_{Fe}.\sin(\varphi) \\ C_Z = C_{Fe}.\cos(\varphi) \end{cases}$$

The sag in the horizontal plane is obtained by introducing these parameters in the catenary model $f_H = \frac{C_Y.l^2}{8T}$.

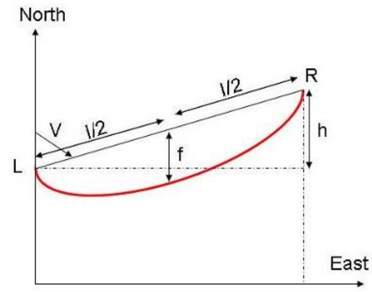


Figure 19: radial sag of the wire

As an example, our 125 m long wire stretched along the ATLAS experiment has a deviation of 0.04 mm in its central part from the straight line.

Intensive research is made on the stretched wire alignment technique in the frame of the CLIC project. Comparisons are done with optical systems (see Rasclic), [10] and [11]. Studies are under way to replace the fragile carbon wires by stronger wires with new fibres. Consequently, new sensors, wireless, based on CCD technology are also under study because the capacitive sensors cannot work with these new wires.

Tests have shown a good stability of a 140 m stretched wire. Typically, for a temperature and a humidity constant, the stability of the wire is everywhere along the wire about 1 µm per day. Such a result at such a distance encourages increasing the length of the wire.

After two failures due to the elasticity of the wires, in the end of December 2007, a 500 m long carbon-peek wire has been stretched at CERN. Its sag is 49 cm. The first measurements of its stability have been carried out with WPS capacitive sensors on a completely unprotected wire. The following histogram gives some results during the Christmas period (from the 22.12.07 to the 06.01.08). It shows the noise and the standard deviation per day of the transversal measurements recorded by a WPS placed in the middle of the wire (240 m/500 m).

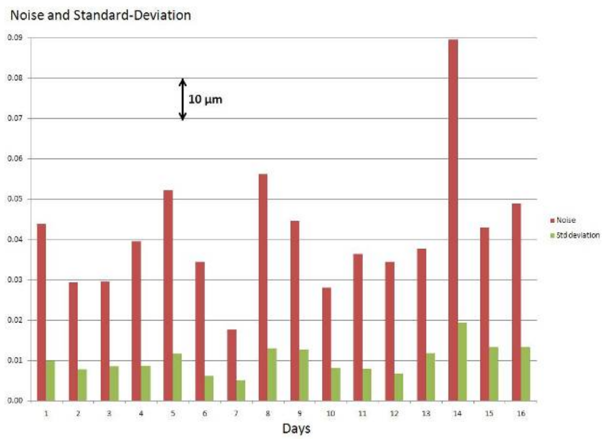


Figure 20: Stability of the 500 m long wire

Even if the wire is submitted to the air fluctuations, the stability of the wire is about 10 µm per day. In the following weeks, we will investigate further after having protected the wire.

## CONCLUSION

What is simpler and cheaper than a stretched wire, for the straight alignment of components? The Large Scale Metrology group at CERN has returned to this technique used since the mists of time, has improved it, in order to solve one after the other all the alignment problems set in the accelerators, even in circular ones. A dedicated instrumentation has been developed, measurements configurations have been implemented, and procedures have been set up in order to eliminate specific errors. Recently, the stretching of a 500 m wire and its first promising results opens new prospects concerning the alignment of the next linear colliders with wires.

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