MAINTENANCE OF THE GEOMETRY OF LEP IMPROVEMENT & OPTIMIZATION OF THE VERTICAL AND RADIAL SMOOTHING

M. Hublin, A. Mathieu, M. Mayoud, J.P. Quesnel, J. Schmitt, N. Woodhouse
European Laboratory for Particle Physics, CERN, 1211 - Geneva 23, Switzerland

1. INTRODUCTION

Since the start-up of LEP in 1989, the tunnel and the machine have undergone various deformations. The suspected ones were initially surveyed by partial measurements, but new technologies in instruments allowed for a vertical survey of the whole ring (27 km) in four weeks, and this complete levelling pointed out singular or regular moves in parts where stability was supposed. The results of several campaigns of comparative measurements will be commented. A new smoothing algorithm has been also developed and an optimisation of the bandwidth of correcting displacements have been derived from orbit simulations. A radial smoothing survey has been also undertaken, and the analysis of these data have shown possible improvements with the addition of precise azimuths - obtained from accurate gyro measurements.

2. RESTORING THE PLANE OF LEP

After the start-up of LEP, yearly measurements were made for controlling the vertical alignment of along the eight straight sections and along the part under the Jura mountain, since these areas were likely to be more unstable. But a rather large subsidence (- 10 mm) was incidentally observed in 1992 in a regular arc of the machine, a significant degradation of the alignment was also suspected, and it was therefore decided to measure the whole ring - taking advantage of a new automatic high precision level (LEICA NA3000) which allowed a much better efficiency in performing such a levelling loop of 27 km. Along the forward-backward traverses, about 1600 points were measured twice at each complete loop around the machine - and this operation took only four weeks, with two teams. Initial results are shown in fig. 1.

From this observed status, and in order to optimize the realignment effort, the search for corrective movements around an average trend curve fitted within the data (“smoothing” process) has been combined with orbit simulations made with MAD. A “realignment tolerance” has been defined as a given bandwidth along the smooth curve, within which quadrupoles can be considered as sufficiently well aligned - thus moving only those which are beyond. Using the real data relating to each scenario, vertical close orbit distortion and dispersion were expressed.

The results of these simulations could allow to appreciate the actual gain in quality of the orbits, according to the realignment effort, and a reasonable threshold of ± 0.3 mm was therefore fixed as starting tolerance for this initial realignment. This led to move 450 quadrupoles for rubbing out some of the biggest deformations and reducing the dispersion from 0.6 mm to 0.15 mm r.m.s. around a still ondulating smooth curve. All tilts were of course measured and corrected (if necessary) before this realignment, not only on the 750 quadrupoles but also on the 3300 dipoles. Among various refinements in the optics of the machine, this realignment effort contributed to the much better performances obtained during the following run period of LEP.

At the beginning of the following shut-down, in November 1993, a new levelling of the whole ring was undertaken. The results of these measurements showed that some of the major deformations were still ongoing (fig. 2), while smaller ones did degrade the global dispersion from the 0.15 mm r.m.s. left in April 1993 to 0.35 mm - observed after seven months. Again comparing with MAD simulations of the resulting orbits, a new realignment scheme led to move about 120 quadrupoles - reducing again the vertical dispersion to 0.15 mm r.m.s in April 1994.

Transversal tilt dispersion of the 3278 dipoles	$\sigma = \pm\, 0.34$ mrd
Vertical dispersion of the 784 quadrupoles (with respect to the smoothing polynomial)	$\sigma = \pm\, 0.65$ mm

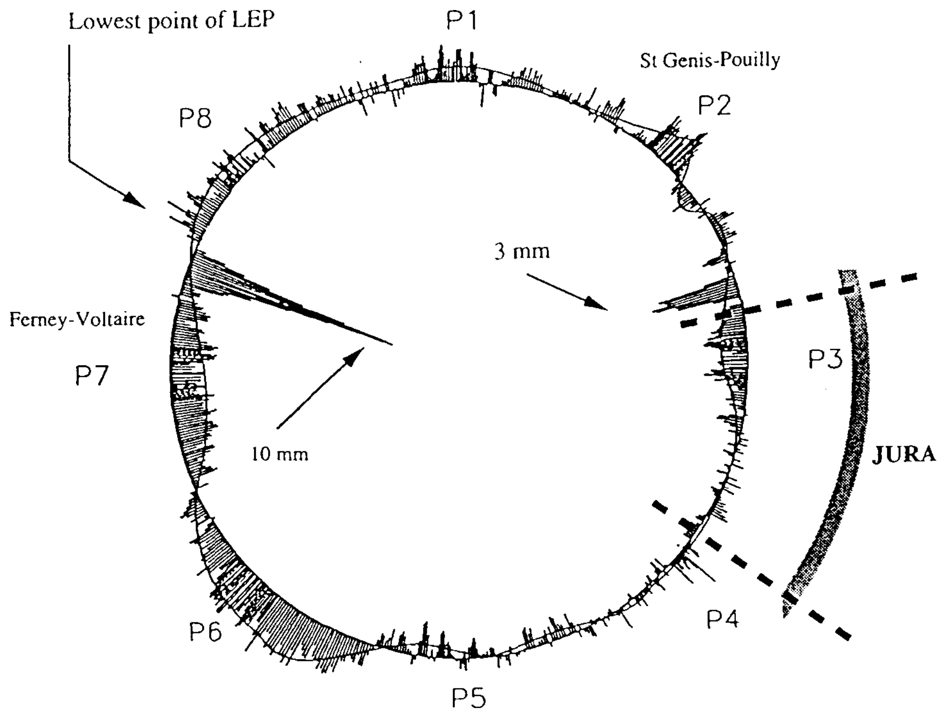


Figure 1 : observed status, end 1992

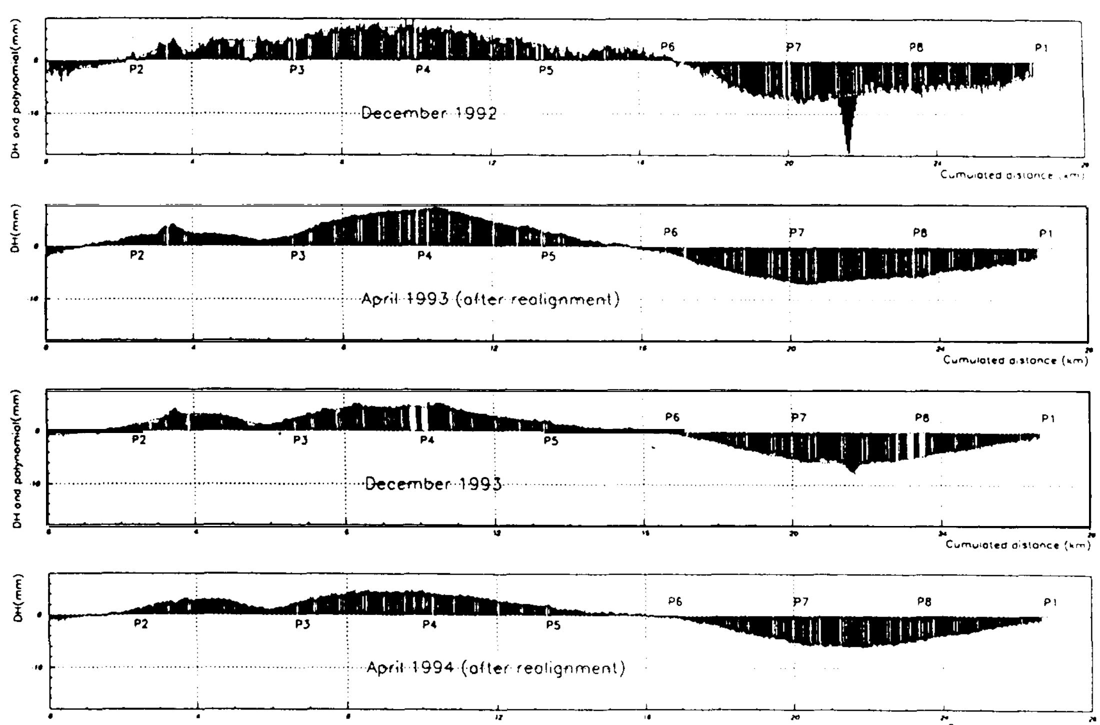


Figure 2 : progressive corrections in 1993 and 1994

Then a new levelling campaign was made end of 1994, showing that the two areas of major deformation were still active and that the global dipersion did not change significantly. As it appears to be a regular phenomenon, it was decided to anticipate the main subsidence by creating a smooth bump over the area. Altogether with some other refinements, about 70 quadrupoles were moved and the final dispersion was contained to 0.12 mm r.m.s.

It is now considered that the plane of LEP has been restored to the best, and the vertical positions will be regularly surveyed & maintained to this functional state.

3. IMPROVING AND OTIMIZING THE SMOOTHING PROCESS

For huge machines like LEP, the choice of a reliable and efficient smoothing algorithm is not so simple. When wanting to avoid parasitic constraints and erratic correlations along 27 km of data, parametric or harmonic solutions appear to be inadequate. A pragmatic way for a direct control of the smoothing of LEP has been to use concatenated polynomials (piecewise functions) kept at a low degree all along the pattern. Such a “craft” solution was rather laborious to handle, but it allowed to manage precisely the process within the data... In a similar approach - and referring again to craft industry - we developed what we have called the “carpenter’s plane” method, due to an evident analogy.

This method consists in making iteratively a succession of local fits in a sliding window, for expressing the best local trend curve (polynomial segment) within the selected data - after removal of “abnormal” offsets beyond a given dispersion bandwidth. Points out of the chosen tolerance are (virtually) moved to the fit, which is then readjusted in a new iteration. Such a process ensures a good continuity of the trend curve, geometrically and statistically as well. The desired degree of smoothness can be fixed on purpose, according to the chosen span of the tool (size of the window) and to the adjustment of the blade (given threshold of removal).

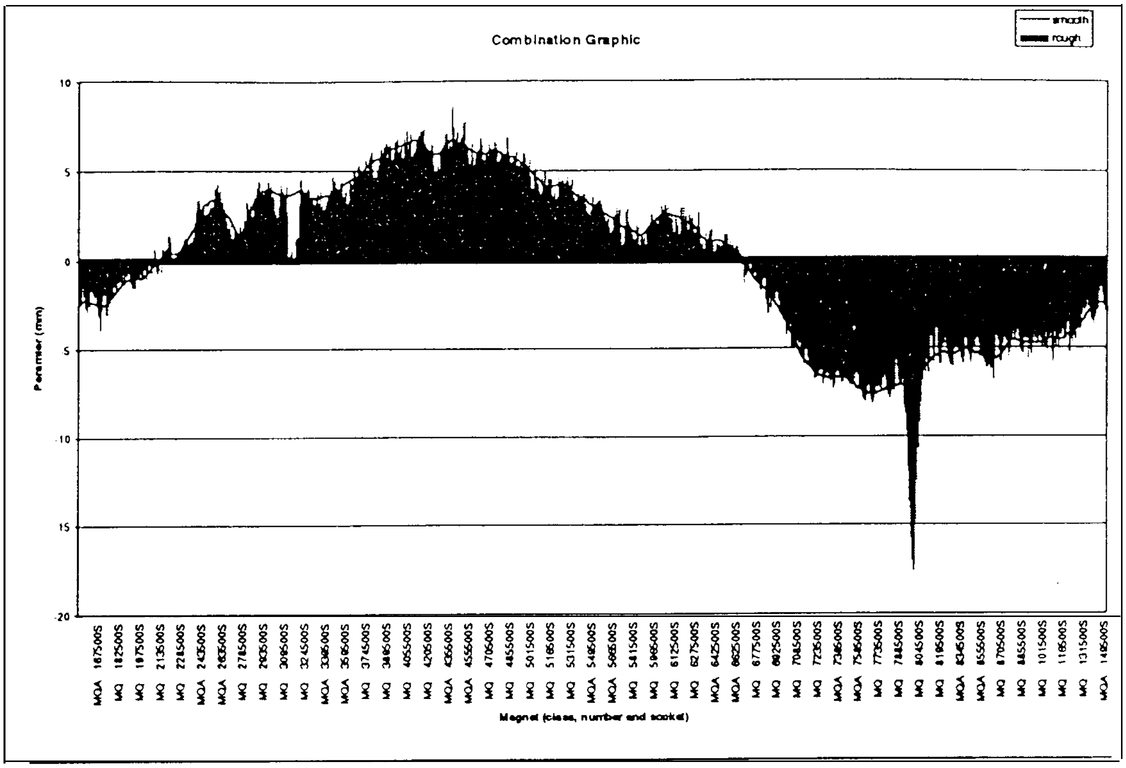
The program applies to either vertical or radial data. It proved to be very reliable and flexible : candidates for correcting movements are well identified, offsets are well quantified, and the whole work can be optimised according to the acceptable bandwidth of remaining dispersion (i.e. the “roughness”) left after processing. Test examples on vertical data of LEP (along 27 km) or radial data of the PS (along 660 m) are shown in fig. 3 & 4.

As mentioned above, simulations of related LEP orbits were carried out with MAD in conjunction with various hypothesis on smoothing tolerances - from which we deduced the optimal use of this new tool.

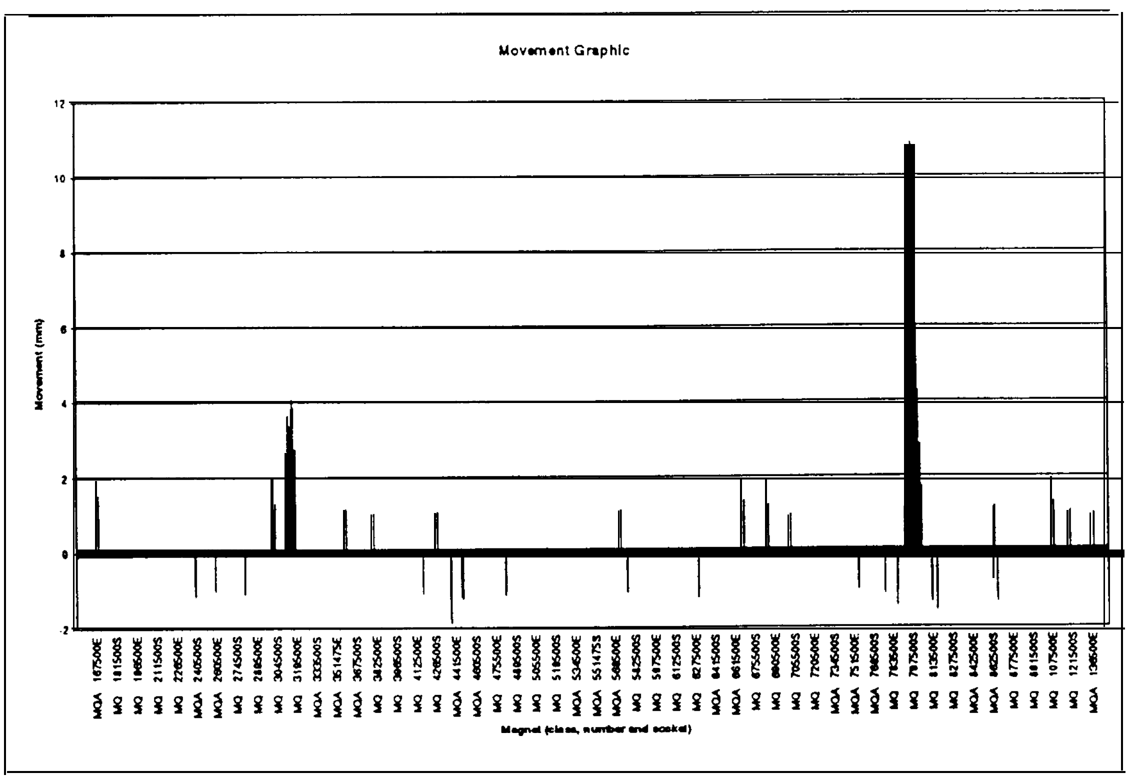
4. REDUCING DIGRESSIONS AND FLUCTUATIONS IN RADIAL SMOOTHING

The flexibility of long linear or curvilinear networks is well known : the effects of random errors combined with the cumulation of systematic ones may produce large and unpredictable distortions of the geometry. The amplitude and periodicity of these deformation depend on the accuracy, the redundancy, the span and the overlap of the successive measurements along the figure. The computation (least square adjustment) of such flexible figures leads to rather ill-conditioned systems, and such a stochastic behaviour can be assessed by Monte Carlo simulations including random and systematic errors.

It is well known that “horizontal” data are much more complicated to collect, process and analyse than vertical ones, and that they are subjected to errors which are more difficult to control. As horizontal movements were said less critical (because of the larger aperture), only a few radial measurements were made here and there since the start-up of LEP in 1989, in connection with the regular checking of low beta sections or with the realignment of modified sections of the machine.

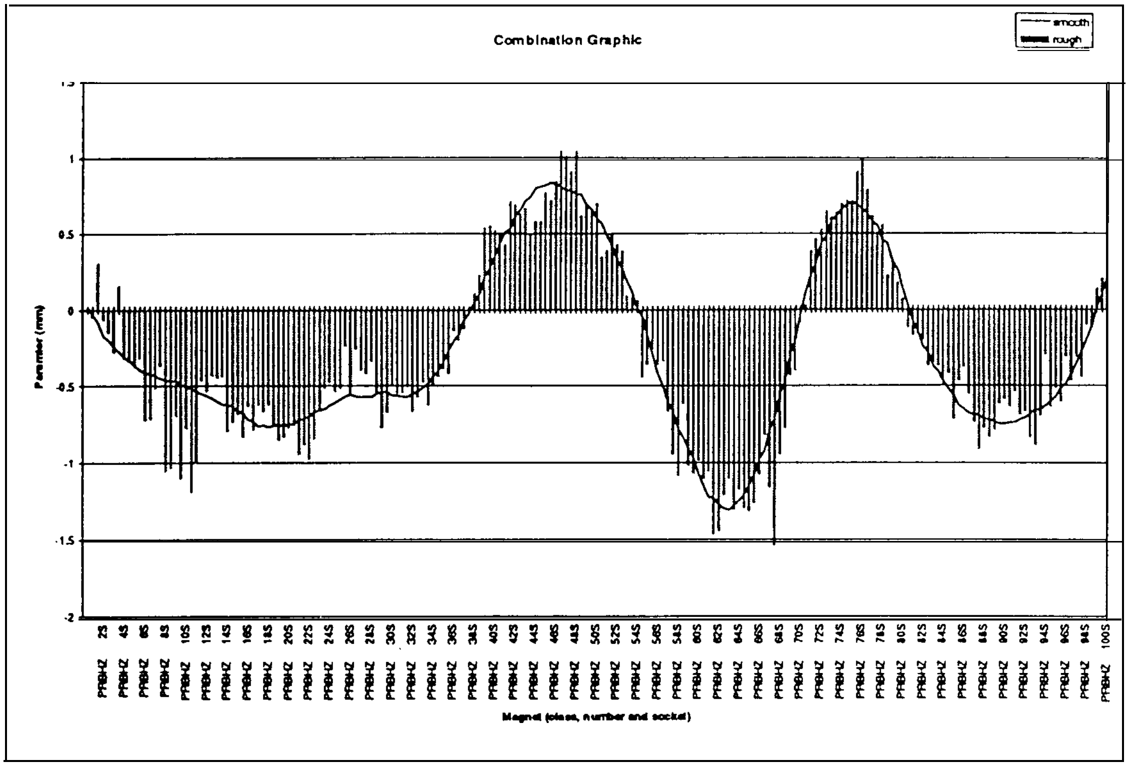


Combination graph



Movement graph

Figure 3 : test on LEP vertical data



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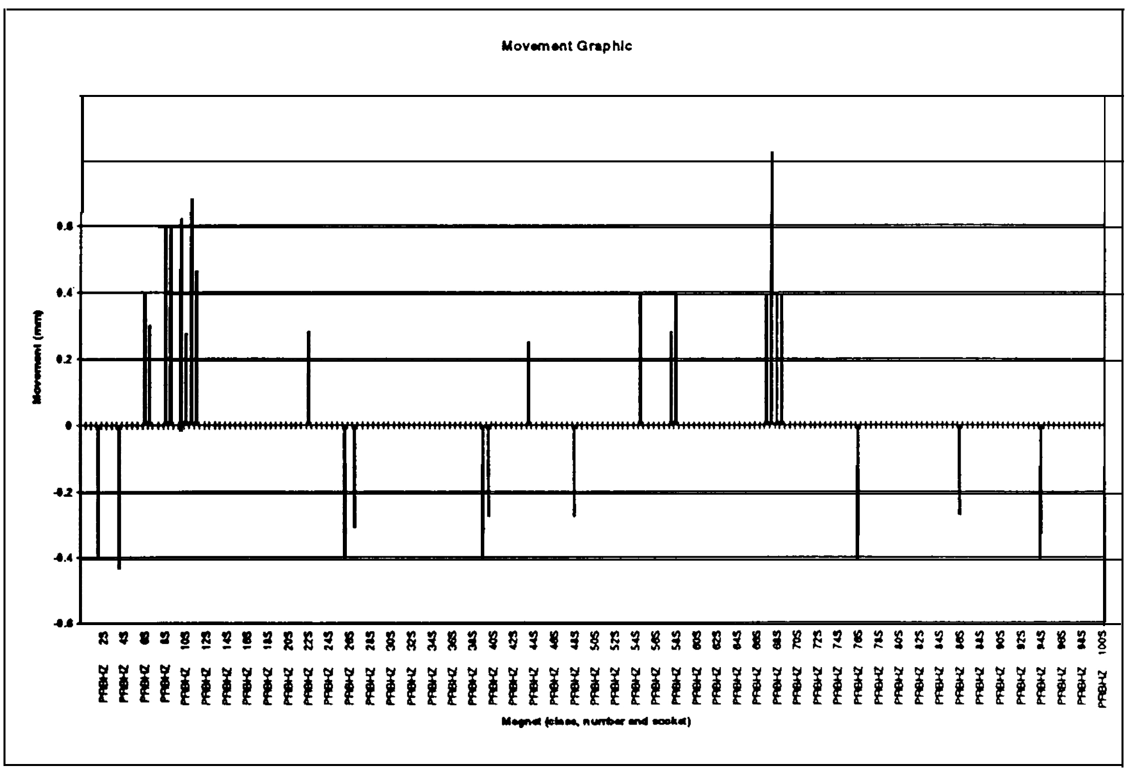

Movement graph

Figure 4 : test on PS radial data

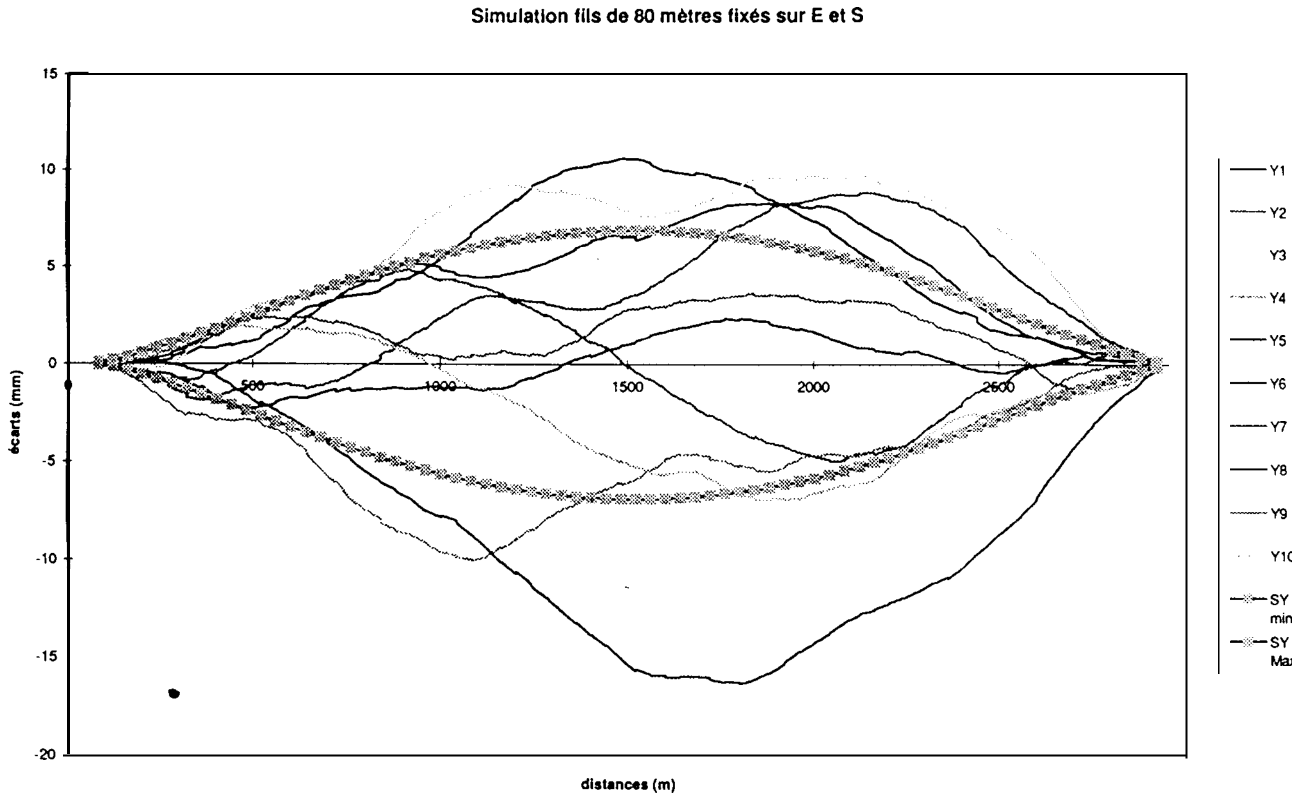

Figure 5 : simulations with standard measurements

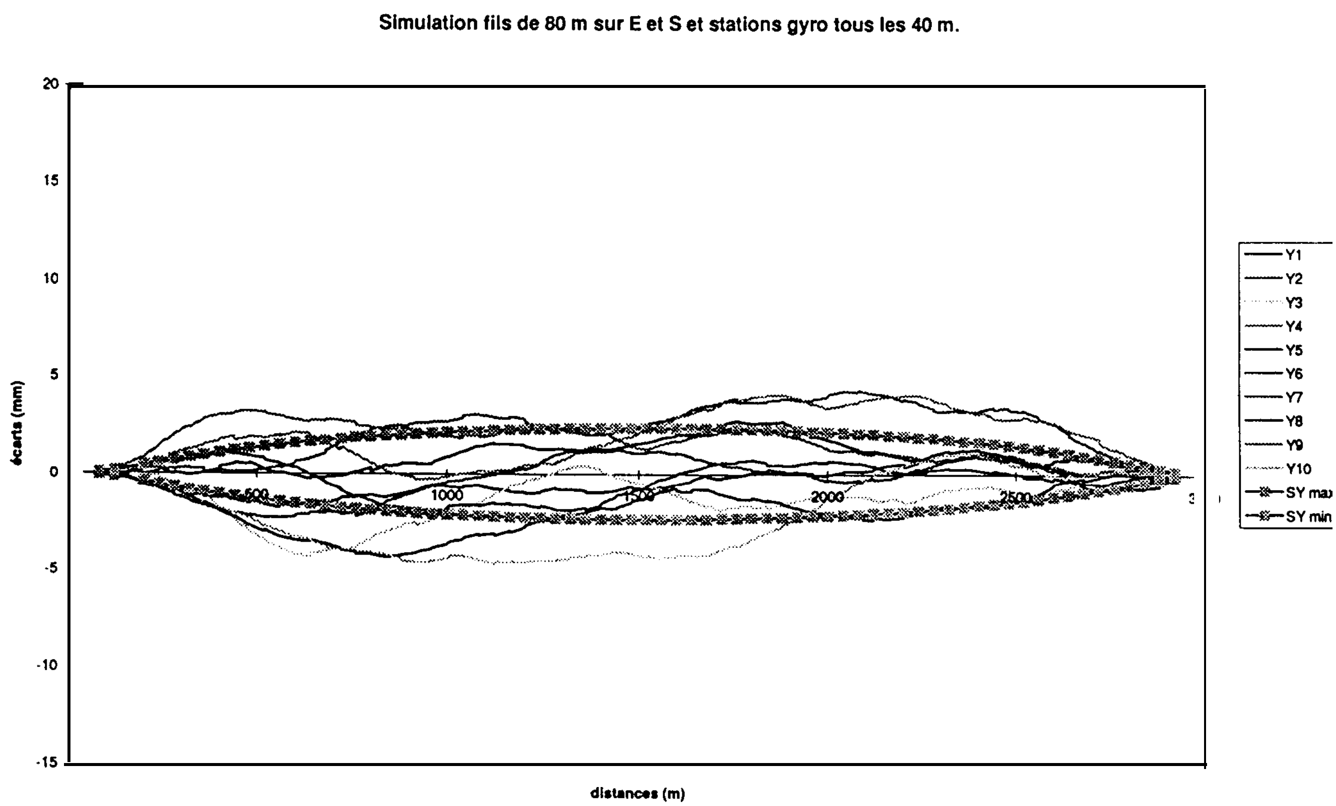

Figure 6 : simulations with added azimuths

It quickly appeared that an exhaustive campaign of radial measurements would be also necessary. This survey was undertaken in 1994 and it is still to be completed (two octants will be measured during the coming shut-down). The initial analysis showed that the local dispersion over a triplet or quintuplet of quads tends to 0.5 mm and 0.7 mm (r.m.s.) respectively - instead of 0.1 mm left at initial alignment - and that the (apparent?) fluctuations of the radial geometry are confusing for the interpretation of the data in connection with orbit simulations. In a first step, only the biggest outliers were corrected.

It also came out that significant improvements could be now introduced by the use of fast & accurate gyrotheodolites. Gyro measurements refer to local meridian and they provide independent azimuths - uncorrelated when corrected from dV effects. Simulations made along one octant show the gain obtained in a standard radial survey (fig. 5) when adding gyro azimuths good to 1 mgon r.m.s. at every cell - nearly 79 m - of the lattice (fig. 6). Such measurements will be experienced during the coming shut-down.

5. ALIGNMENT CONTROL OF LOW BETA SECTIONS

The metrology of low-beta sections calls for two geometrical considerations : straightness of each section and colinearity of these segments - with a good connection to the “smoothed” line of the other quadrupoles, both sides of the experiment. The colinearity requirement leads to the absolute need of a local (going through) reference line, linking the measurements made each side. A possible solution could make use of a laser beam, of which path is brought in the vacuum chamber (proposal for LHC). Another solution is to make use of the beam itself, as already suggested and then experienced for LEP since 1993. The calibration of the related PU’s by means of wobbling, would now give full benefits of the method - which can be considered as a real beam-based alignment process over these low-beta sections of the machine.

Regarding the straightness of each section, it was stated that the radial discrepancies are less likely and less critical than the vertical ones, and we did not consider the monitoring of the radial positions. Alignment is ensured and checked before start-up, and no on-line control has ever been designed. As for the vertical control, we convened that the most useful thing was to check regularly the QS0/QS1 pairs by means of a hydrostatic levelling system (HLS). The initial design of the system has been complemented, in order to cope with the height and temperature differences of the LEP configuration. Adding a pump, a tank (dissipation of heat) and electrovalves, the water is circulated before measurements, in order to regulate the temperatures in all vessels and avoid parasitic thermal expansions of the liquid.

The implementation of this modified system has been first made at Intersection P8. Three vessels were installed on each QS0/QS1 girder, and a fourth one on a reference stand fixed on the floor. The overall noise of the measurements appeared to stay within 10 µm, and data were regularly collected from April to October 1994. As a matter of fact, considering the variations of the average planes of the girders, their changes in tilt or slope or the level of floor points located upstream each side, this area (P8) has to be declared very stable for that observed part of the year. After a small drift (about 100 µm) the first week, the height differences of the QS0/QS1 pairs fluctuate gently within a 100 µm corridor over the six months period recorded by the system. Similar equipment will be installed in other intersections during this shut-down, and the whole investigation will be useful for the LEP2 final stage, and of course for LHC.

6. CONCLUSIONS

The considerable effort in restoring the flatness of LEP plane and bringing the vertical alignment nearly back to its original quality has shown its beneficial effects. The maintenance level of this requirement is since reduced to 70 correcting moves, instead of 450 two years ago and 140 last year.

The main effort applied now to the radial survey of the machine, and a possible improvement is expected by means of accurate gyro measurements. This will constitute a heavy but beneficial addition in the smoothing process.

The on-line metrological control of low beta sections is reasonably limited to the use of hydrostatic levelling systems connecting the QS0/QS1 pairs each side of the experiments. The first measurements in point 8 displayed a pretty good stability of the girders. The other intersection points will be equipped with similar systems.

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