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LEP Vertical Tunnel Movement -- Lessons for Future Colliders

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In Collaboration with the CLIC-Study Group and the
Survery Group of CERN, 1211 Geneva 23, Switzerland

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LEP Vertical Tunnel Movements — Lessons for Future Colliders

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Abstract. The data from 10 years of vertical surveys verify for all of LEP the previous observation, localized to region P1, that LEP floor movements are predominantly deterministic. This rules out the ATL model as being correct for this tunnel. If generalized, for yearly movements a random ATL model underestimates the possible maximum long-term motions. In contrast, extrapolation of the LEP vertical data to the short-term (hours and days) time-scale shows that the random approach predicts larger short-term movements than the deterministic model. This means that simulations using the ATL hypothesis are overly pessimistic with regard to the frequency of operational re-alignments required. Depending on the constants chosen in the models these differences can be large, of the order of a magnitude and more.

This paper deals solely with the directly measured months-to-years tunnel motions in rock, and the extrapolation of such ground motions to hourly or daily time-spans. It does not address the important question of the contribution of hourly-scale movements of the accelerator components, which could have a random part, to the combined motion. Nor does it address the question of movements of accelerator tunnels like HERA or TRISTAN which are built in water and debris, and not in solid rock.

I GENERAL

A Purpose

Analyzing the LEP vertical survey data is more than academic curiosity. Costs of civil and mechanical construction and operational performance of accelerators depend to a large extent on how the tunnel floor, on which the accelerators are built, moves. In the "old" machines tolerances were of the order of 0.3 mm and machines were kept operationally smooth with corrector magnets. Accelerators were realigned mechanically with wrenches whenever the mechanical rms misalignment became larger than ≈1 mm. The "new" machines planned for the future require an intrusive mechanical beam-based re-alignment whenever they wander off by ≈0.01 mm and even less, so the time scales in which those short-term misalignments happen is very important. The SLC as a prototype of the new machines required design misalignments in the arcs genuinely to be below 0.1 mm and luckily bridged this gap with remote magnet movers so that mechanical re-alignment was only required every so often. While beam-based alignment had been used as a stop-gap measure before, this in a sense was the first beam-based alignment planned in advance.

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The short-term movements impact on the performance — long-term movements impact on the mechanical engineering provisions needed for the adjustments.

B The LEP Data

The LEP survey data [1] constitute the largest body of precision survey data available which is applicable to accelerator design and tunnel engineering problems. The only detraction is that the data were taken directly on the quadrupoles themselves, and not on permanent monuments embedded in the tunnel floor or walls. Present day accelerators replace the installation monument system on the floor or the walls with one based on the magnets themselves because the smoothness of the magnet positions is much more important than the absolute positions.

In the LEP arcs the distance between quadrupoles is 39.5 m. Therefore, the "frequency" of measurement is ≈40 m in the average, so finer details in the movement cannot be explored. However, there are enough troublesome questions to be answered for the 50 m to several kilometer scale for which the LEP data can give an answer.

Survey data have their own set of statistical and systematic errors which are sometimes very different from what physicists are used to, and so we will expend some effort on those. This paper takes the data as they are prepared and proposed by the geodesists, and it analyzes them from a physics point of view while at the same time attempting to explain particularities of surveying theory and praxis. Some of the terminology and methods used here are more from the physicist's point of view and are not used, or not used in this way, in geodesy. That means we first try to extract quantitative statistical rules of behavior of the tunnel movements before we try to understand why it moves in a particular fashion in general, and in particular places.

Naturally, in the end we tried to correlate deviations from the "smoothness" of the data with the geology of the site. This turned out to be difficult. Neither known and existing faults, nor layers of troublesome soil encountered in boring the tunnel seem to really line up with areas of change in elevation, in particular did not explain differences in magnitude. Only when also considering the underground hydro geology of the basin of the Pay de Gex did data start to make sense.

This investigation in itself seems to be a worthwhile enterprise. The 27 km long LEP tunnel is completely bored underground in compacted geological strata. Bored tunnels, compared to cut-and-fill techniques, or blasted tunnels, have shown the greater mechanical stability. Deep underground tunnels, which necessarily need to be bored, are quieter with respect to cultural noise [2]. Collider tunnels also need to be geometrically straight, because with the very small vertical emittances needed to achieve a reasonable luminosity, the constant systematic kick needed for a curvature-of-the-earth following beam is too large in most cases [3]. The LEP tunnel is thus a good model for the tunnels needed for the ≈30 km long Linear Colliders planned for the future.

As an introduction to the data we show all existing data from 1993 - 1999, as restored and processed by Jin [4], in Figure 1, before we deal with appropriate subsets of these data. The caption of Figure 1, like many captions later, contains much information. Note that this data set was corrected for all voluntary magnet movements between 1993 and 1999, but not before. Since we did correct for earlier movements in selected cases ourselves, the attentive reader will notice a few differences in the pronounced spikes of the data in different figures, because naturally it was the magnets with the largest movements which were re-aligned (if discovered as misaligned) early on. It is also important to remember that the original

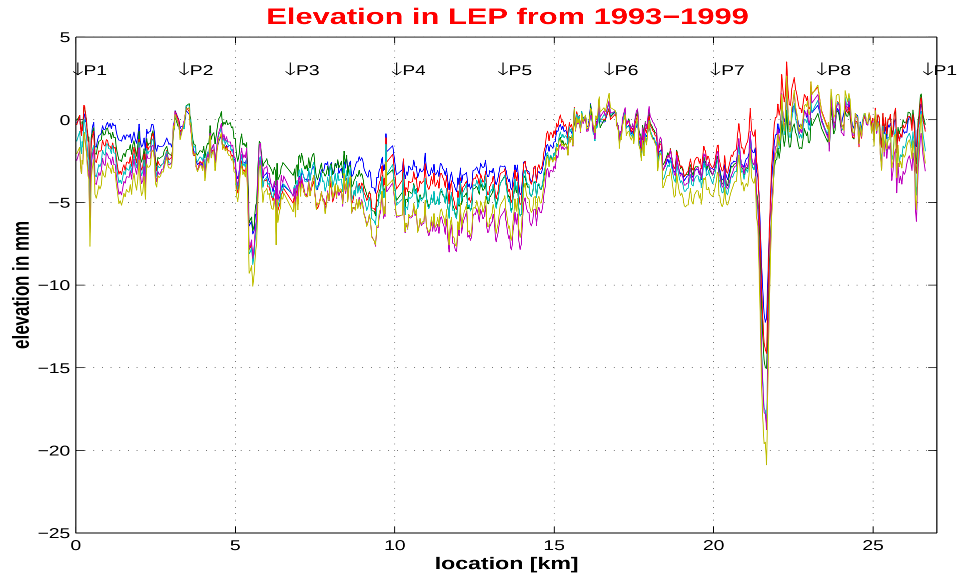

FIGURE 1. Leveling data for all of LEP. We want to point out from the beginning that due to random walk there is about a ± 2 mm flexibility in the smooth features of the data. The humps of many km length are not necessarily due to a real movement of the tunnel, they might come from random walk in the survey process. Some of the characteristics which are real are in particular the sharp local downward movements around 0.5, 3.5, 6, 9, and 22 km. Another interesting feature is the "flat" area between 10 and 14 km (P4-P5), which we will use to extract "normal" movement characteristics. Although in this plot this area seems to be "sinking", other assumptions in the processing of the data led to results that it is very stable, maybe the most stable in all of LEP, see next Figure. But P4-P5 does show the pronounced variation of elevation differences between magnets from year to year typical for LEP as we will see.

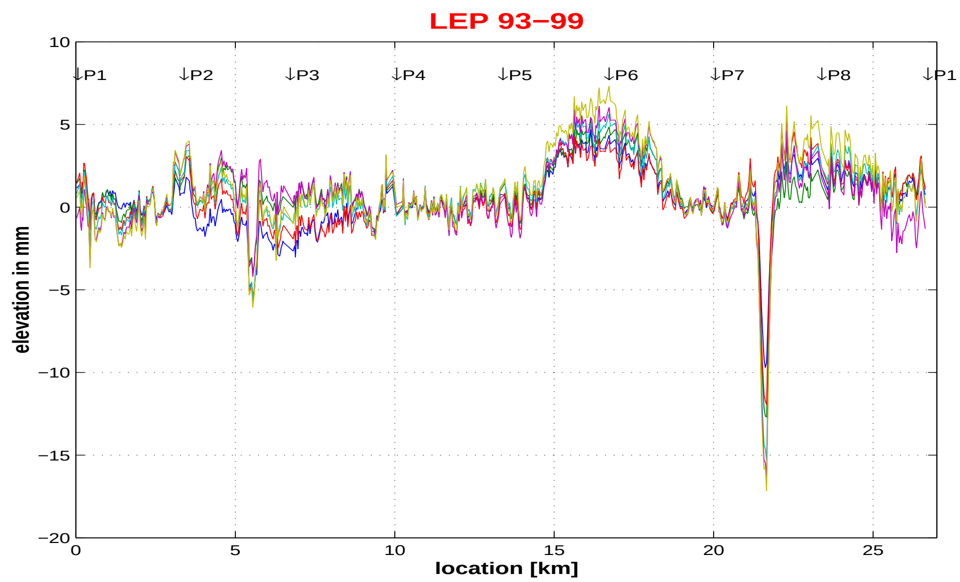

FIGURE 2. In order to extract more meaningful data, various assumptions are being made about the variation of individual points. These assumptions can lead to long wavelength variations in the resulting data from one year and differences in the comparison between different years. So these plot shows the same data as in the previous Figure. Of particular interest is the change in the results for the "flat" area between 10 and 14 km.

installation alignment was to a smoothness of 100 μm or better between adjacent magnets. Since details are difficult to see in this picture, we will show later just the 1993 data, fully corrected (Figure 3). The 1993 data are unique in the sense that for most of LEP this was the first resurvey after installation. One can, therefore, be sure that for these regions there had been no voluntary movements.

Since LEP for good reasons, mentioned above and discussed further later, does not have a permanent monument system, all measurements are referenced on the magnets. So the tunnel movements can only indirectly be inferred from the magnet movements. This entails accurate bookkeeping, because the movements from each re-alignment have to be propagated in the database to keep track of the total movement of a magnet. This process is called data restoration [4]. After restoration an effort is made to remove some of the smooth features, which are due to random walk, and to find the stable areas of LEP. This process does not necessarily lead to unique results - different assumptions during the process may lead to smoothly varying elevations, as shown in Figure 2 as compared to Figure 1. For details we refer to Reference [4] and references therein.

The following work focuses again on vertical movements. Essentially all modern electron accelerators have beams much smaller in the vertical dimension than in the horizontal, with the concurrent much tighter vertical tolerances, so the focus on the vertical is well justified.

This paper deals only with motions in the long-term region and does not address the wide and important field of vibrations with time-scales of 1 sec or less. But we find no reason not to extrapolate the type of motion investigated, which is characterized by a resulting yearly change in terms of rms between 0.05 and 0.20 mm/year, to the low end of validity: hours or days or some such similar time. The extrapolation to short times leads to some interesting conclusions.

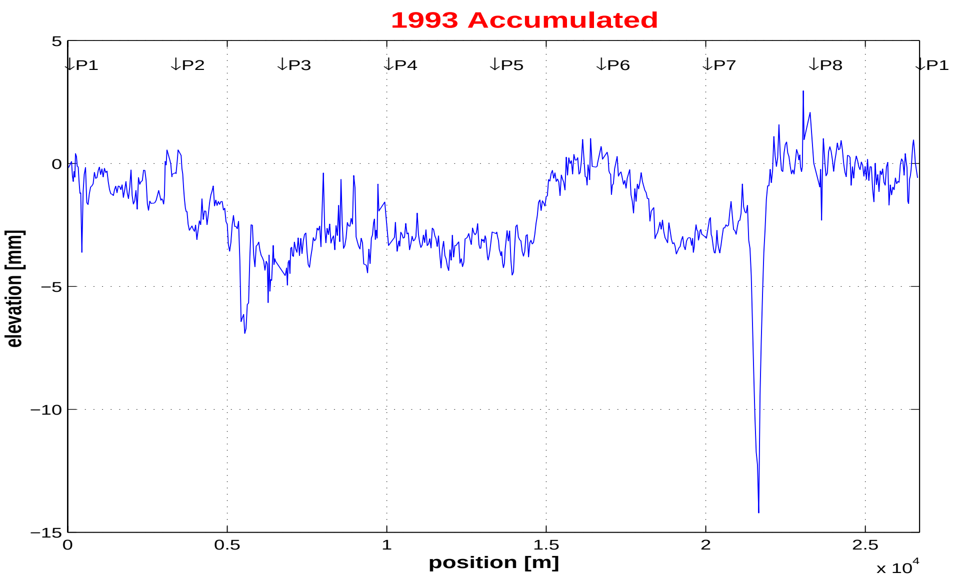

FIGURE 3. The 1993 data show many sharp deviations from a smooth alignment. Unlike the data in the two previous Figures these data have been corrected for re-alignment which happened before 1993. In particular visible are several sharp upward spikes in the vicinity of P3.5 - they are due to the well-known water problems (in the "Renard") under the Jura. These data allow to categorize LEP roughly into three areas: Region P8 to P4 with relative movements away from smooth alignment of up to 4-5 mm, Region P4 to P7 with movements in the 1-2 mm region, and Region 7 to 8 which contains the biggest "break", with absolute movements of up to 15 mm in 1993.

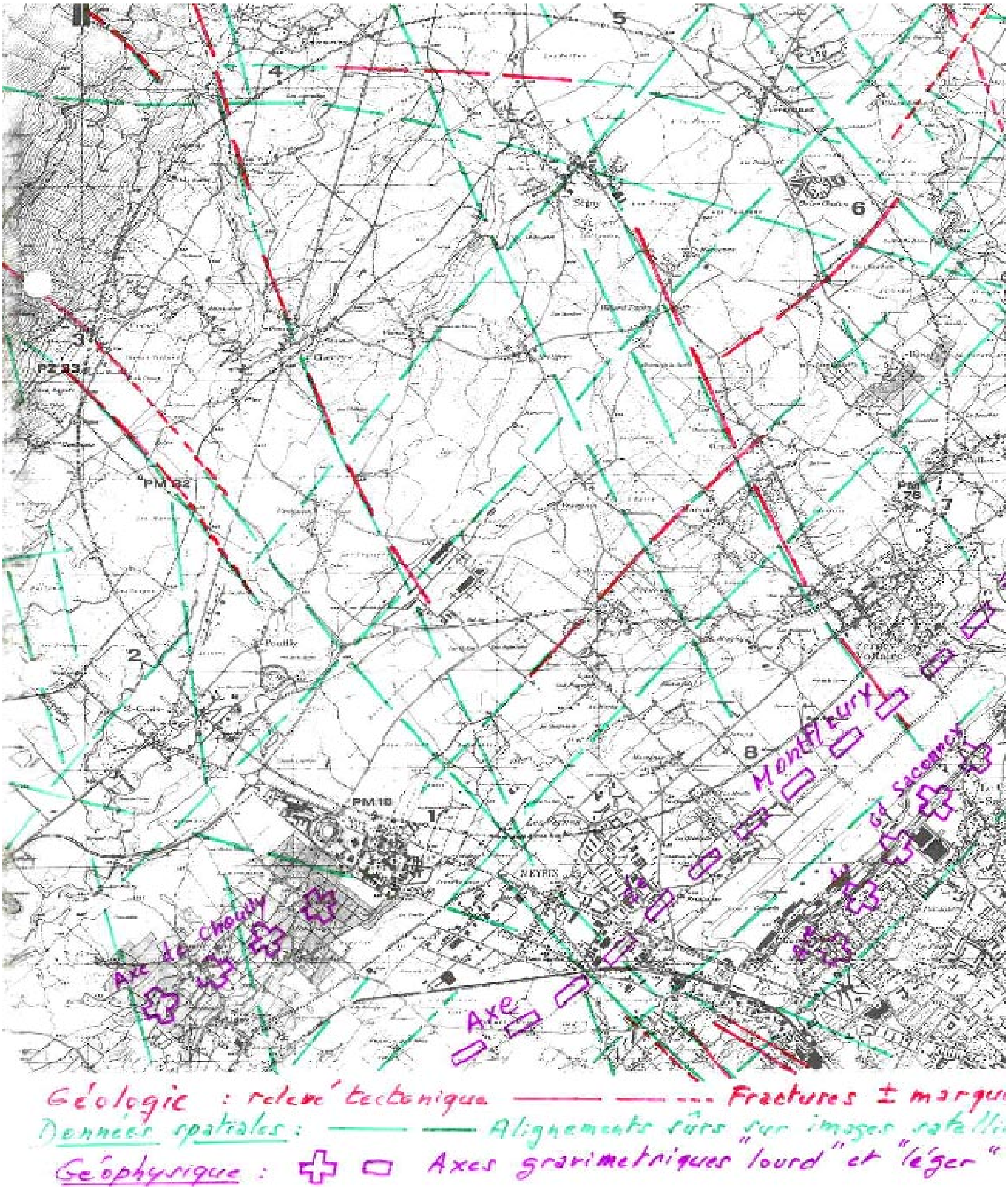

FIGURE 4. Map of the LEP area, with Michel Hublin's enhancements. Geographical north points in the usual direction, straight to the top of the map. The Allondon fault is close to P4, the Ferney fault between P7 and P8. Another important fault (or faults), which is not shown here, crosses LEP at P2.7. It runs strictly west to east down from the Crét de la Neige. There are also the "Fault of the Calame" and/or the "Fault of the Tremblane". As with many pictures in this report color viewing or printing from the post script or pdf files is highly recommended.

C LEP's Physical Environment

LEP construction began 1985; it became operational 1989. Before construction began much exploration and thought went into the siting of the tunnel [5]. Because of concerns about the Limestone and the Moraine, the size, location, and horizontal inclination of the LEP tunnel was changed several times, so that now most of the tunnel is within the Molasse at the southern end of the Swiss Molassic Basin which forms a large bowl, including Lake Geneva. It is a formation similar to the compacted sand stone SLAC is built in. In fact Molasse is a catchword for a variety of sand stones, heterogenous locally but with homogenous properties like tensile strength and hardness over large distances. In some sense it is an ideal rock for tunneling.

Only 3 km of LEP are under the Jura in the Limestone [5]. Molasse and Limestone in the foothills are buried under recent (= the last one million years, Holocene, Quaternaire) deposits from erosive forces, in particular glaciers in this area close to the High Alpes. The glaciers gave rise to deposits called Moraine, but there are other deposits. This Quaternaire overburden over the Molasse is varied, loose and permeable and poses problems when one constructs experimental halls in it and access shafts through it.

As the Environmental Impact Report for LHC phrased it recently [6], the tunnel was constructed in a relatively simple geological context. But what is not "relatively simple" is that relatively deep valleys have been carved into the "roof" of the Molasse under the Moraine. In the French language literature these underground valleys are called "Sillon", which translates as trench, but seems to be used more like describing an (underground) watershed, as in aquifer [1]. This is true in particular if the valleys have been plugged at the exit and underground lakes have formed. And the situation is also more complicated than stated [6] through a number of fault lines which run mostly perpendicular to the Jura in NW to SE direction. Some of the fault lines are immediately recognizable on an ordinary map.

Because the Quaternary deposits are permeable, the water collects on top of the Molasse. It is drained mostly to the south through the Sillon de St. Genis, and the southeast through the Sillon de Montfleury-Ferney. It is believed that these underground valleys follow fault lines, even if those are inactive for the moment. The flow of water under ground now does not always coincide with the above ground creeks and rivers.

On the vertical boundary between the Molasse plain and the Jura mountain, which is also the boundary between Limestone and Molasse for LEP, a layer of a mixed (clay like?) sediment (Gompholite) was encountered in tunneling.

Gompholite, like Butano in California, is known to undergo large swelling if unconstrained and wet, both of which is prompted by tunneling [2]. There is no clear connection to any particular large uplift between the survey data and the Gompholite layer on the south of the Jura section of LEP (P3.1); on the north around P3.9 there is an abrupt uplift probably due to the availability of water through the Allondon fault.

Since this is a vertical boundary, difficult to find with vertical bore holes alone, it is not clear if the existence of the Gompholite layer was known before construction. Gompholite has many different components, making it difficult to identify and is, therefore, given different interpretations and even different names in the literature [6]. Other clay-type formations (Gompholite and Montmorionite) were encountered in the construction of the SPS

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[1] There is generally much confusion over the naming of different geological events. This may explain the cryptic remark encountered: "... names as used in the Canton of Geneva".

[2] The Butano, when penetrated in the tunneling of the North Arc for SLC, swelled so much due to the water coming out of the walls that the tunnel diameter overnight shrunk from 10 to 9 feet such that the tunneling equipment was not able to enter the tunnel the next day.

and caused uplifts later [7], see, e.g. Figure 13 in Reference [8].

CERN commissioned over 100 drill holes of varying depth and an exploration gallery from the "plains" toward the Jura mountain range. In the design report there was mention of only one geological fault: the Allondon Fault [1] , in which the Source d'Allondon (a creek) runs down the Jura from Echenevex and crosses LEP between P3 and P4 (at P3.7). Quote: "To the best of our present knowledge, only one of the known geological faults of the Jura (the Allondon fault) will be intercepted" [5]. A cursory look at Figure 3 shows that there is indeed a dip at P3.7.

During tunneling it was very clear when the northwest part of the Allondon fault was crossed. Despite very close scrutiny the known southeast crossing close to P8.7 could not be identified in the tunnel. Seemingly the fault petered out in the Molasse. But it is now clear from tunnel surveying that what is apparent on the surface does not always vertically match up with what is found below, and vice versa. This makes interpretation difficult except for the most pronounced features.

The area of the largest downward movement, between P7 and P8 close to Ferney-Voltaire, is only mentioned in passing in the Design Report [5] as having one of the three most important features discovered by the exploratory drilling: a strong slope of the molasse/moraine interface which limited the eastwards move away from the Jura of the machine position. As mentioned before, moraine's debris from the ice age is layered above the molasse and one tries to avoid building the tunnel, and in particular the caverns for the experimental halls, in the moraine.

The two other "most important features" mentioned in [5] were two local underground valleys close to St. Genis (P2) and Cessy (P5). These underground watersheds have much influence on the stability of LEP when they cross the tunnel, in particular if they run in new or old fault lines like the Sillon de Montfleury-Ferney, which crosses LEP at P7.5. It is not clear what the precise mechanism is which leads to the downward movement. The most logical would be that the soil was wet and swollen through the faults and that the tunnel drainage system dried it out. So the soil shrank.

There are several upward spikes in the vicinity of P3.5 - they are due to swelling through the well-known water break-in under the Jura, in an area called "Renard". Here magnets moved upwards by about 2 mm at the very beginning. The water problem was known, problems were expected here, hence the area was regularly surveyed. These movements stopped after a few years - it is not clear if due to pumping grout into the ground or due to the self-healing of the Calcaire [9]. We will show later a figure of this area at a larger scale because it contains movements due to the Renard water flooding, and LEP crossing the Allondon Fault, and the Gompholite, all three very clearly separated in the effects on the tunnel.

Since the time of the LEP exploration, mostly due to GEOSAT measurements, [2] more has become known about geotectonic faults, buried or not. Figure 4 as marked up by Michel Hublin from the CERN Survey Group shows many fault lines. One which lines up with a large movement in the tunnel is the one close to Ferney. But others cross the LEP tunnel without effecting misalignments.

We suspect, as stated before, that it is more the availability of water locally then the fault itself, or the withdrawal of water through the tunnel drainage system, which is causing the

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[1] This fault is also called the "Déchrochement du Coin" in geological maps. The Allondon creek only runs in it in the very beginning.

[2] I thank Michel Hublin for marking up in color, based on his vast knowledge, a map of the area (Figure 4) which shows fault lines established by classical geological means and by satellite surveying.

differences. This suspicion is verified by the location of P2.7, the second largest discontinuity in the tunnel. Here LEP is crossed by a west-east fault (or faults?) coming down from the Crêt de la Neige (not marked in Figure 4) and by the Sillon de Sergy which empties into the Sillon d'Allondon. Particular useful for understanding is a longitudinal cut along LEP in Reference [11].

The construction of the tunnel floor, here regarded as part of the environment, took place in 39.5 m sections, separated by polysterine expansion joint. The individual segments were not connected by rebar or other anchors, neither did the floor itself contain rebar. The construction of the floor under the Jura is somewhat different from the construction in the plain, owing to the difference in tunneling method. But the essential part is that in both case the floor was poured in two phases, each of considerable thickness such that the total thickness at the thickest point, approximately under the beam line is about 1.20 m (4 feet). It is also important to know that the concrete was poured on undisturbed solid rock.

For completeness we mention here the construction of the tunnel walls. The diameter of the excavation was 4.40 m, somewhat larger than needed. This allowed for a concrete lining of 15 cm thickness with 10 cm of tolerance for alignment errors of the boring machine. The tunnel lining is made of precast waterproof segments of 9.875 m length, keyed together and rendered watertight by preformed sealing strips and a mastic seal. The lining was then attached to the rock walls by injection grouting. A drainage system behind the walls is designed to prevent any water pressure on them.

Figure 3 shows that from the magnitude of misalignments LEP can be roughly divided into 3 regions:

- Regions 8 to 4 with movements up to 4-5 mm in 1993
- Regions 4 to 7 with movements in the 1-2 mm region in 1993
- Regions 7 to 8 which contain the biggest "break" (fault) in Ferney-Voltaire close to the Geneva Airport, with accumulated absolute movements of 15 mm in 1993, i.e. 3 mm/year.

These regions become even more visible if one plots the movement of a magnet with respect to its neighbor, rather than the absolute elevation, as later in Figure 16. Differently expressed: the northern half of LEP, with the exception of the part under the Jura in the Calcaire, is more stable than the southern half. Since the water in the Pays de Gex generally drains to the south, this supports the thesis that the presence, absence or removal of water is important for tunnel stability.

Much concern rose during the tunneling because one encountered layer after layer of different sand stones. The fear was these would give rise to breaks. None of this has materialized and the tunnel is very stable in general.

D About Models, "Laws", and Principles

A previous paper [8] showed that the magnet movements at each point surveyed in the LEP tunnel were predominantly systematic (= deterministic) [1], and not random, in nature. Expressed differently, the term deterministic means here: if a magnet moves the distance y_1

[1] The proper terminology from the Handbook of Surface Metrology [12] would be deterministic and not systematic, as introduced previously [8], which we will use from now on. We will keep the use of systematic to uses like "systematic error". I am thanking Gordon Bowden of making me aware of Reference [12], a true gem.

in the time t_1, it will move $2y_1$ in the time $2t_1$. The trigger for this conclusion in Reference [8] was the observation that "outliers", known to happen in accelerator surveying since a long time, were not true outliers due to measurement or adjustment errors as had been assumed but could be traced back to deterministic movements of specific points. Figure 5 shows a historical example [13]. Observed in many accelerators, these movements generally seem to go on unabated for 5 or more years, and only slow down somewhat in later years.

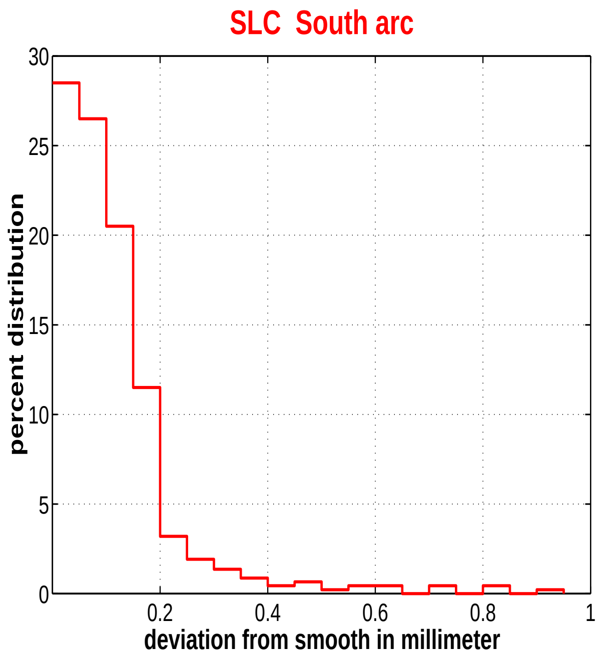

FIGURE 5. Histogram of horizontal adjustments required during the installation of 300 alternate gradient magnets in the SLC South Arc. Outliers are found up to 9 standard deviations. Note that the original figure caption makes reference to a "smooth beam line".

The conclusion that in machines installed in solid rock the dominant long-term misalignments are deterministic (systematic) in nature, from Reference [8], contrasts sharply to the conclusion drawn from the ATL-hypothesis that the "ground points perform Brownian motion characterized by the variance of the relative displacement which scales as a product of temporal and spatial intervals" [14]. In other words, the LEP data show that long-term misalignments from ground motion are deterministic and not random. This does not exclude random contributions to the combined motion of magnets and accelerator elements from other sources like cooling water and air-conditioning equipment, or vibrational ground displacements on a much different time scale.

Reference [8] had been interpreted in the sense that it should be better to build accelerators in loose ground. This is only correct if one focuses solely on the long-term movements. For the daily stability, important for operation, solid rock turns out to be the better material. To research this topic in greater depth we will evaluate and plot long-term rms-values for various areas in LEP, compare them to deterministic and random models, and then try to use these values for short-term (hours) predictions for future accelerators. It has also been found that deep tunnels in solid rock are quieter with respect to vibrations in the many Hz region [2].

But first we must discuss random walk. The random walk problem is important for understanding what might be a "real" change in elevation versus the possible magnitude of random walk-induced "apparent" change. The random walk will play a role in the alignment of future accelerators no matter what the survey and alignment method. It did not play a role in the SLC linac because of the existence and use of the SLAC laser alignment system which gave a straight reference line within the 25μm resolution of this system [15]. The latter was used as a reference even when the beam based alignment was needed to establish accuracies smaller than 100μm between the linac quadrupoles and the laser system [16].

At times the random walk has been confused in the literature [14] with an actual movement, as shown in Reference [17], and a constant A_{LEP} designed to describe the movement in LEP has been derived from it [14].

Since the most complete set of data is available for LEP region P1, more detailed analysis and modeling will focus on P1. The "flat" region in P4-P5 will serve to get a minimum baseline value for movements when nothing special seems to occur.

The rms-values so derived will be compared to two models, the deterministic PT model [8] and the random ATL model [19]; these models then in turn will be used to predict possible ground motion behavior of future colliders and the impact this would have on alignment requirements.

The deterministic model has been explained in Reference [8]; it is parameterized here with the equation

$$Rms = P \cdot T \tag{1}$$

with T = time passed and with the proportionality constant, if derived from the data in P1, P_{P1} = 5.5 $\cdot 10^{-6}\mu$m/sec. Other areas at LEP have to be described by other proportionality constants. That is to say, the constants are local and probably depend on the geology of the location in the tunnel, excavation methods, construction methods, construction quality, and so on.

Note that unlike the ATL model, this Ansatz does not depend on the distance between two points at all. Since we believe, based on the empirical evidence, that each location in an accelerator tunnel (in fact, on earth) has its own history, its movements in general cannot depend randomly on the distance from another far away location. Naturally there are correlations between locations close together. The existence of those correlations is obvious in the LEP data.

The random hypothesis [17], is parameterized usually as

$$Rms^2 = A \cdot T \cdot L \tag{2}$$

with the proportionality constant A for LEP derived by Reference [14] as A_{LEP} = $8 \cdot 10^{-6} \mu m^2/(\text{sec} \cdot \text{m})$, T= time passed, and L = distance between two locations whose Rms is described [1].

To get a feel for the movements involved, we rewrite the proportionality factors for both models, P and A, for the best documented area of LEP, Point P1, the insertion area. In units more obvious for long-term applications these constants can be expressed as

$$P_{P1} = 0.175mm/year \tag{3}$$

[1] Sometimes instead of the actual distance the betatron wavelength is used [18], because the impact of ground motions with longer wavelength on the magnetic elements is suppressed (sometimes called correlated movements).

and

$$A_{LEP} \cdot L_{P1} = 0.415 mm^2/year \quad (4)$$

whereby the half of the length of P1, 680 m, was used in the last equation.

In Reference [8] the Fischer Principle was invoked: "Every Ground Motion has a Definite Explanation" [21]. Following this principle one has to first follow many specific locations in tunnels over a long time before one can make any statement about the statistical behavior of the assembly of all locations. Proponents of the random model [19] have complained that each accelerator builder claims that his or her tunnel is special. Such statements miss the point. It is not only each tunnel which, due to geological or construction uniqueness, is particular, it is each point in each tunnel which is special because of its history [8].

E Problems in the Analysis of Long Survey Runs

Using the LEP 1993 data, Figure 6 shows what can happen with an appearance of component movement, when there is none, and how careful one must be when interpreting data. Leveling distances in LEP are typically 19.75 m (half the Quadrupole spacing in the arcs), so that leveling set-ups were made every 39.5 m. Thus the number of total set-ups is about 675.

For cost reasons no complete LEP survey had been done until 1993, after construction was completed in 1988. For most of LEP this survey was the first post-construction look. It was found that the LEP magnets had been installed in a warped plane (Figure 6). This happened because the automatic compensation of the level was susceptible to the earth's magnetic field, producing a sinus error when making one complete turn with the level in the magnetic field of the earth. One easily concludes from Figure 6 that the sharp spikes in the data are most likely true misalignments.

The question arises: is the broad hump between 14 and 22 km also due to a true movement of the tunnel floor? Probably it is due to random walk during the installation survey which could not unambiguously be removed by the analysis. We will make the case that it is not a true movement through a series of simulations and comparison to differences of data by year, but it is difficult to be absolutely sure.

So in addition to systematic effects of survey instruments, there is the random walk problem one has to deal with. Unlike most measurement processes in physics that we are used to, survey measurements progress from location to location, whereby the results from all previous measurements impact on the next one. A case in point is the well-known problem of angle measurements with a theodolite in a tunnel, where very small systematic errors due to the transverse temperature gradient of the air in each measurement can add up to huge accumulated errors, if not restrained by other methods [1]. For leveling the random walk is more troublesome than the systematic errors, although the latter have to be watched.

For a random walk with an error ϵ in each step (the assumed set-up error in leveling) the expected mean square error after step i is

$$Rms = \sqrt{i} \cdot \epsilon \quad (5)$$

[1] For the relatively short SLC arcs the estimated horizontal closure error without outside constraint was a staggering 180 mm, when the tolerance given was 1 mm. The horizontal coordinate had to be constrained by 14 penetrations [20] to get the closure error down to 1 mm.

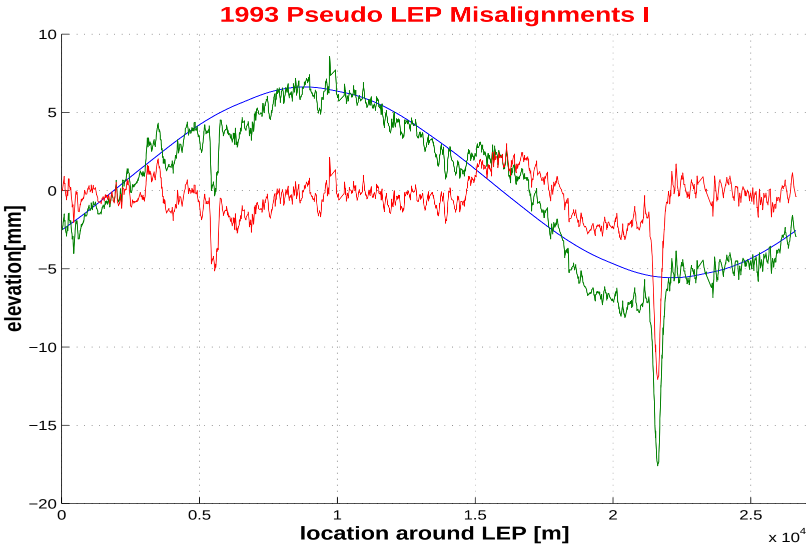

FIGURE 6. The sinusoidal ragged curve shows the raw data as measured '93. It was identified as being around a skewed curve (the second, smooth sinusoidal curve) caused by a systematic error of the leveling instrument with which the original installation was done. That means LEP actually is built in a warped plane with about ±6mm amplitude. The third derived curve, the difference between the two, finally shows the derived position of magnets in LEP in 1993. Intervening re-alignments have not been taken into account here. However, the derived positions are also not quite right due to random walk, as we will show. Does random walk matter for the performance of LEP: probably not. Does it matter for conclusions other people have drawn from the data: yes. One should emphasize here that the agreement of the derived curve with vertical zero (the horizontal axis) is no accident: there is much effort and skill behind it; for further reading see Reference [4].

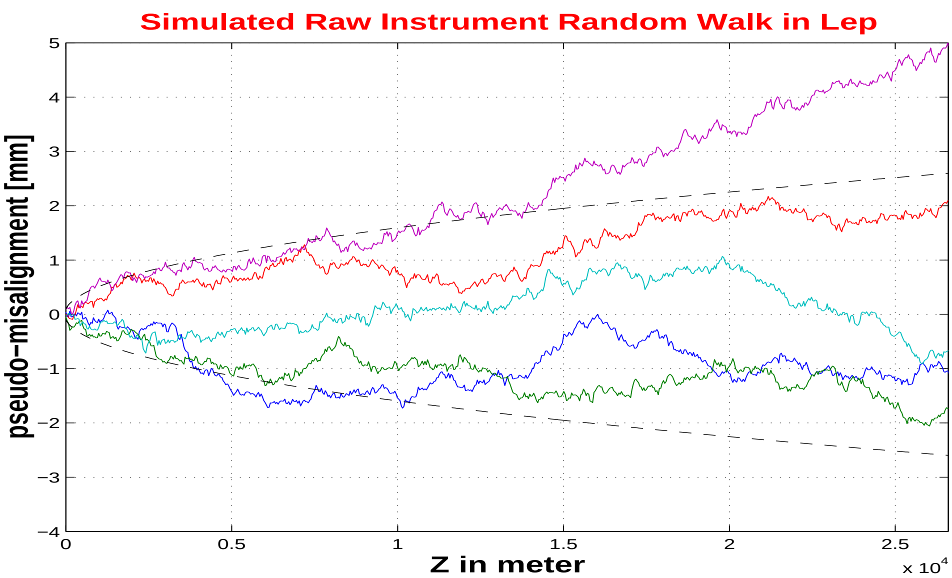

FIGURE 7. Five hypothetical level runs around LEP with open end. This should be interpreted as modeling the variations in a yearly survey of a perfectly aligned machine which does not move at all. The smooth line shows the 2σ expected error curve, for a 50 μm set-up error for each measurement, if one starts the level process from coordinate zero. Note in particular with the top curve how much a random walk can stray from the expected. In Figure 8 we show how well this can be corrected with an end-point adjustment.

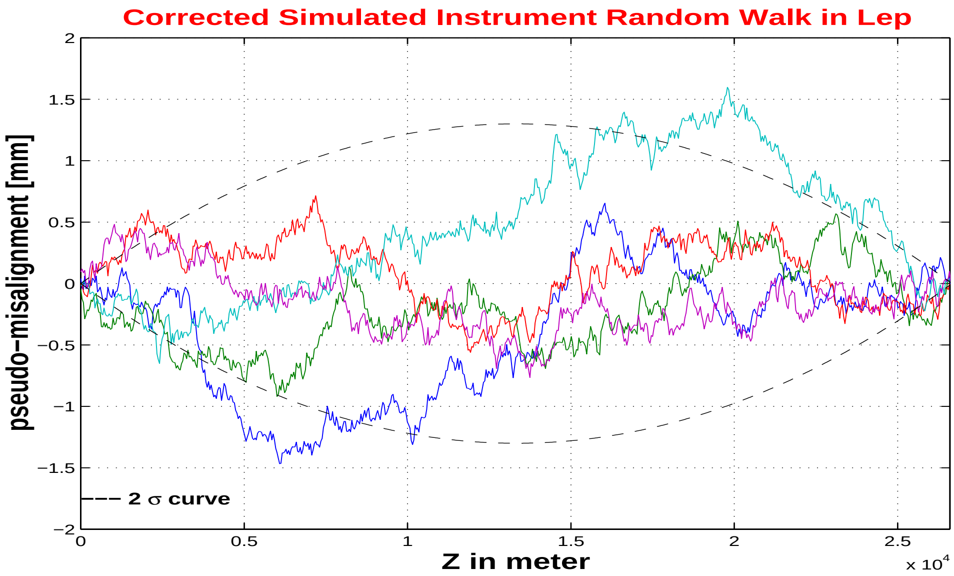

FIGURE 8. This shows the identical 5 (simulated) measurements of Figure 7. The end-point error of each curve is linearly distributed over the run of the survey. The 2σ curves show that 95% of the end-point corrected measurements fall within the curves.

Figure 7 shows a simulation of 5 hypothetical leveling runs around LEP, assumed to be independent work done at different times, for example 1993 - 97. Let us also assume that we have firmly installed monuments in the floor so that arbitrary and willful movements of the magnets have no influence on the result. The simulated data shown are not corrected for the closing (end-point) error; we will show the end-point-corrected data in Figure 8. This expected (theoretical) end-point error can be calculated from equation (5) and with 675 set-ups and a set-up error of 50 μm is 2.6 mm at the 2σ level. The dashed curve shows the expected 2σ error at each point if the leveling starts at coordinate zero.

The simulations were done with the random number generator in MATLAB which produced pseudo-random numbers drawn from a normal distribution with a mean of zero and a variance of one. The state of the generator was coupled to the clock of the computer, making sure that a different sequence of random numbers (seed) was generated each time the generator was used. The relation between the variance and σ (standard variation) is established by normalizing the sum of square deviations by (N-1), where N is the total number of the sequence. This makes σ^2 the best unbiased estimate of the variance if the data are a sample from a normal distribution.

Leveling a circular machine has the advantageous feature that with the last point one comes back to the point of origin. The closure error then can be linearly distributed over the leveling run. Figure 8 might one make believe that the tunnel floor monuments have moved, up to an amplitude of $\approx \pm 1.5$mm, when in fact they have not.

To return to Figure 6: the broad variation between 14 and 22 km is probably a remnant of the random walk during the installation survey. Is there any way to avoid this random walk? Only if one is willing to spend the money and effort to bring in independent measurements from the surface through penetrations. Repeating the surveying would just have led to another random walk. Bringing in independent measurements in the vertical [1] was not

[1] To limit the horizontal systematic deviations, where outside references were needed, a gyro theodolite was used for LEP.

needed for the demands of LEP, but it will probably be necessary for the linear colliders yet to be built. Fifteen years ago this would have been a very expensive proposition. However, the advent of GPS technology means that sub-millimeter accuracy can be achieved horizontally and vertically at a low price, using penetrations to the surface. But there still will be random walk, albeit with a reduced amplitude.

Although there is no direct method to investigate and prevent the random walk from happening, one can get a feel for its magnitude experimentally by comparing the yearly measured differences, since differences between random walks are random walks themselves (except for a $\sqrt{2}$ in the expected error). Figure 9 shows the four difference curves for the five simulated curves of Figure 8. As a reality check Figure 10 then shows the four difference curves for the five actual measurements from the years 1993 to 1997.

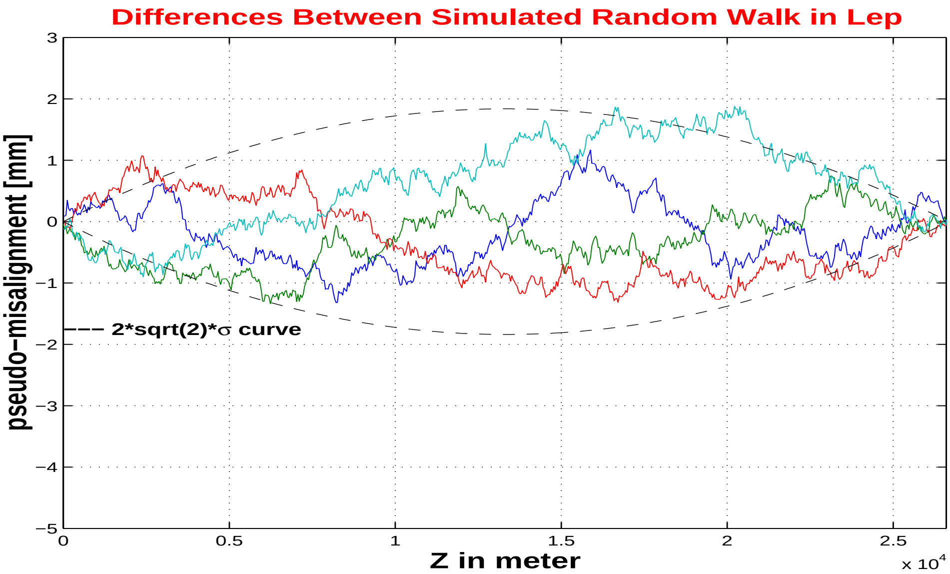

FIGURE 9. The four differences between the 5 simulated measurements of Figure 8. The $2\sigma\cdot\sqrt{2}$ curve shows that 95% of the differences fall within, just like the original random walk.

The agreement between Figures 9 and 10 is good. Maybe the amplitudes of the smooth parts of the curves in Figure 10 are somewhat larger than the simulation in Figure 9, pointing to a set-up error larger than 50 μm, but that is difficult to judge with the small data sample of just four curves. One can identify quite clearly the major real, spike-like, movements, while the more gradual changes are suspect for random walk effects. We will look at a method to get around this ambiguity for a quantitative comparison to models, further below.

What does the random walk of LEP surveying over the years have to do with one of the topics of this paper, namely to investigate the short-term movements? As described previously, the ATL model for LEP [14] has been fitted using the random walk of the survey instrument to get a LEP specific number for A_{LEP}, and had not been fitted to the actual movements of the magnets. One of the tasks below will be to identify the actual movements and then to construct a model.

As noted earlier, not all of LEP was measured annually before 1993. But the injection area (P1) was surveyed each year from the beginning and has the most complete set of data. Therefore, the analysis from Reference [8] is extended below to include all the data available for region P1 through 1999.

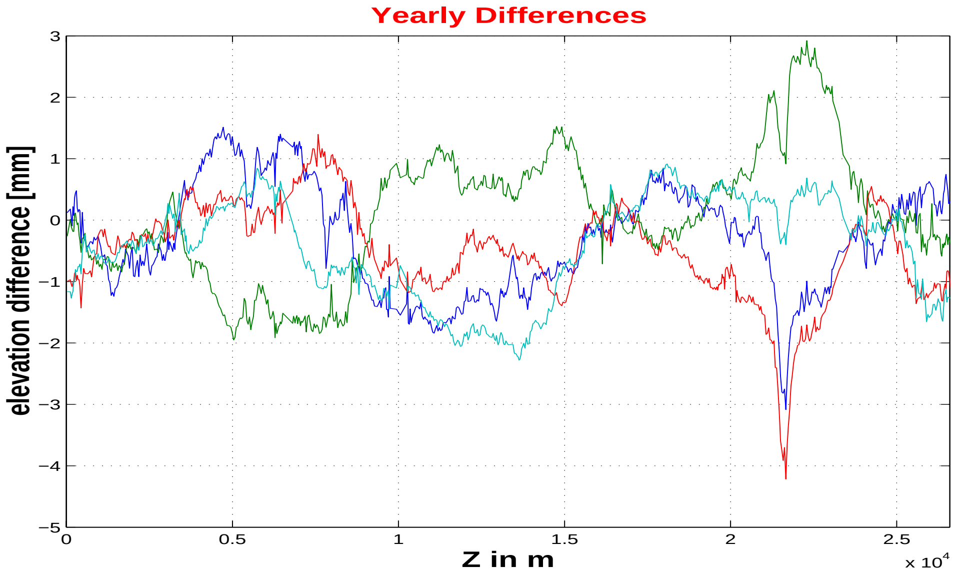

FIGURE 10. The four differences between 5 actual level runs around LEP in the years 1993 to 1997. Differences between random walks are again random walks but with the error larger by $\sqrt{2}$. One can identify quite clearly the major real spike-like movements, while the more gradual changes are suspect for random walk effects.

F Why accelerator misalignments look random
(when in fact they are not)

Since its invention in 1953 by Courant and Snyder [22], strong focusing has been the basis for much of the improvement in the performance of accelerators and storage rings. There were concurrent increased demands on alignment tolerances, but over the years it was recognized that absolute positioning of magnetic elements is not essential, that mainly relative (element to element) smoothness is important, (see e.g., the discussion of smoothing concepts in [23] and [24]).

In the context of smoothing, the alignment rms deviation from an ideal or smooth reference orbit became the important parameter for machine physicists. Accelerator simulations were designed to investigate what rms, independent of source, would be sufficient for satisfactory operation. No particular effort was made to understand the root causes for the movement's underlying deviations.

Tunnel movements are interpreted as random because the misalignments are measured as deviations from a smooth mean curve (defined by the measurements themselves!) and not from some absolute ideal line.

Thus, by their very nature, smoothing methods **produce** deviations (from the thus defined mean) which **look Gaussian** (that is normal) distributed. The deviations seemingly are the result of a random underlying process (the movement), when in fact they are not.

Figure 5 is a perfect example for that effect. This paper will again show, with the enlarged LEP data set, that individual locations in accelerator tunnels for the most part do not move in a random but rather in a deterministic way on each point, probably due to concrete floor settlement and persistent geological and hydrostatic forces.

II TOWARD A DIFFERENT MODEL

A Evaluation of P1 Data from 1989 to 1999

We will first deal with the P1 data before extending the analysis to all of LEP. To understand some of the arguments which follow later one has keep firmly in mind that these leveling "data" are restored data [4], i.e., for each year the plotted data have been corrected for all willful magnet movements (including smoothing re-alignment) known from previous years. Reference [4] restored the survey data for all the LEP magnet movements for the 1993 - 99 period. Corrections to the data for the previous time were taken from Reference [8] and updated taking the data from [25] of all known voluntary movements before 1993, including regions outside of P1; this made a complete yearly set of data for P1 and brought all of the LEP data to the best possible state.

We tried to line up the 2 prominent downward and the 3 upward movements in P1 with known fault lines (see Figure 4. They don't line up. Since P1 is the injection area for LEP the tunnel cross section changes on both sides when the injection tunnels come in. These locations do not line up either with the changes in elevation.

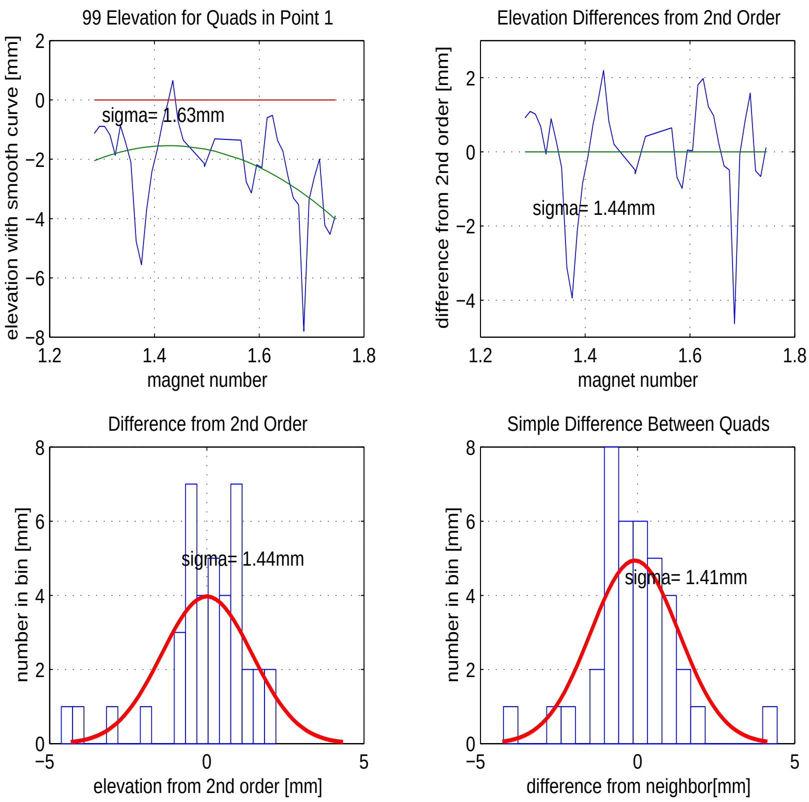

FIGURE 11. Elementary processing of data in P1, shown here for the 1999 measurements. Shown are (a) the original data and their fit, (b) the subtracted elevation, (c) a histogram of these elevations, and (d) a histogram of the simple differences between adjacent magnets. Note that the rms-values for the differences from a smooth curve and the differences between adjacent magnets are very close.

Figure 11 shows, using the example of the 1999 data, how the P1 results were handled. The data for each year were fitted with a 2nd order polynomial to reduce random walk bias from the leveling process. This is not completely accurate, as in all fits the extreme points carry extra weight and bias the average fit. However, it is not bad for Point 1 data in particular, since upwards and downwards movements are somewhat balanced. At the same time, differences between adjacent magnets were evaluated (subfigure (d)). We use here, and only here in this paper, the data with the fit subtracted because this display shows more clearly the deterministic characteristics of the movements.

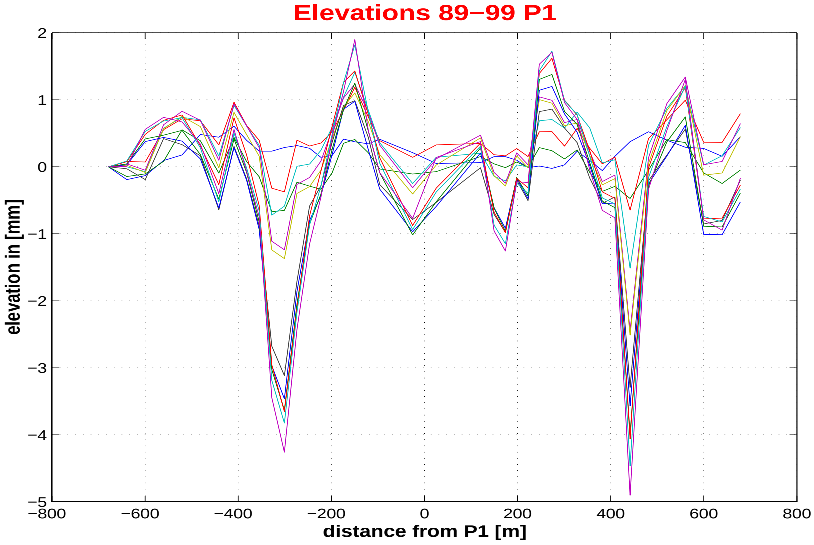

FIGURE 12. Elevation in P1, after subtraction of 2nd order fit, for the years 1989 - 1999. The sequence of curves in the vertical follows by and large the years the data were taken. There are several features in the plot which show that the elevations fall into two groups: one for the years 89-94, and one for 95-99. This is particularly evident around -360m, -50m, +150m, and 650m. The data were normalized to the same value (zero) at -680 m.

First, we will plot the P1 data for all 10 years available in Figure 12. The positions fall into two groups by years, one from 1989 to 1994, and another from 1995 to 1999. For guidance, see the caption of Figure 12. What happened between the two sequences? There is still more work to do before one can address this question.

Even with the method of fitting a polynomial and subtracting the fitted curve, there is still a question of model bias from the leveling process. To eliminate that potential bias, a next step in the evaluation is to examine the differences between one magnet and it's neighbor (simple difference). This has the advantage of eliminating random walk of the leveling process as well as being identical to the original method of measuring elevations directly from magnet to magnet. Thus, if a random component should be found in the data, it could be attributed to the actual movements of the floor. An example for the distribution of differences was shown in Figure 11, subfigure d. This subfigure also showed that the rms value calculated from the deviations from a smooth fit and the rms calculated from the differences are very close, so that for the purposes of rms evaluation both methods can be used interchangeably.

Using this approach, Figure 13 is based on the same data as Figure 12, but instead of fitting and subtracting a smooth curve, a direct subtraction of the elevations of adjacent magnets was done. Figure 13 verifies that the change of differences falls into two groups by years, although not as clearly as Figure 12. We will return to this topic further below in connection with evaluating the rms deviation for P1.

One recurring question is how to ensure that the movements in each location are de-

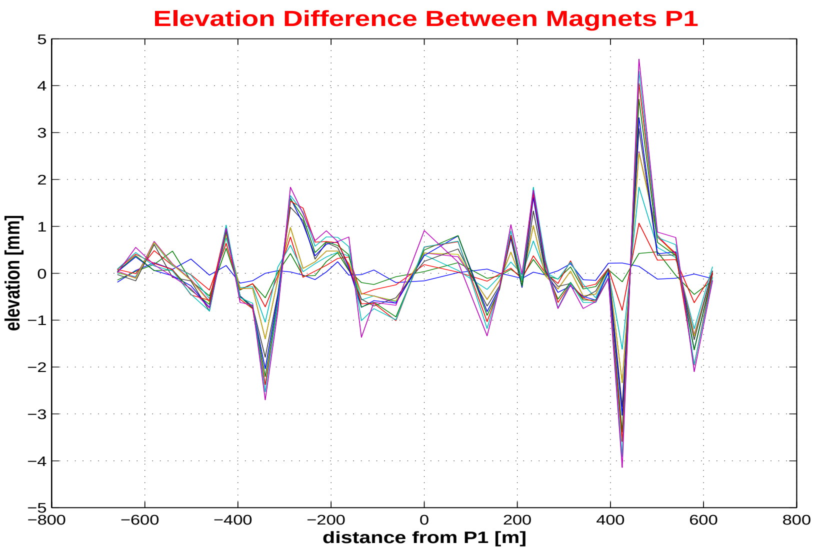

FIGURE 13. Simple differences between adjacent magnets in P1. The sharpness of the difference peaks at 420m underlines the abruptness of the movement, its pitch. The resolution of the pitch is limited by the distance between magnets, that is to say this movement could in actuality be even more abrupt than measured.

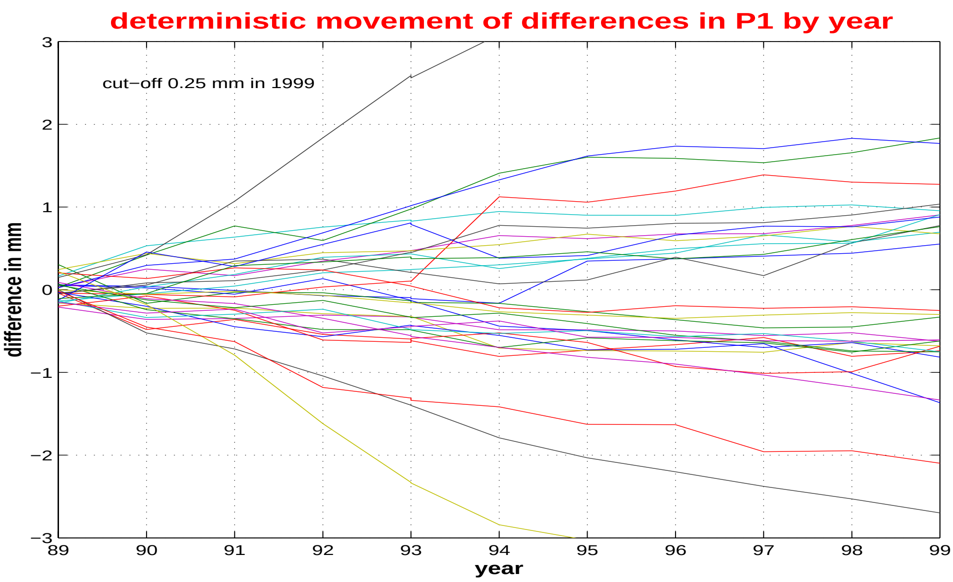

FIGURE 14. From the data of Figure 13 are derived the slopes of movements in mm/year for all magnets with average movements of more than 25 μm/year.

terministic and not random, and in particular how to make this graphically apparent [1]. Figure 14 shows the measured differences in elevation between adjacent magnets as a function of the year measured. Only movements with an average slope of larger than 25 μm/year are shown, because the single set-up error of a measurement in one year is about twice that. Random movements would be indicated by curves going up and down in the plot, which they don't. In particular, it is striking that lines do not seem to cross zero. We will show later that this is a general feature of all of LEP, which means all of LEP behaves in a deterministic manner.

In the next step we will calculate and plot rms-values (in Figure 15) for Point 1 for the differences shown in Figure 13. One could use the rms-values for the elevations themselves; these follow the same trend, albeit they are in general somewhat higher, as should be expected. But using the elevations themselves brings again the random walk bias in. These difference rms-values then will be compared to the two models mentioned, the deterministic model and the random ATL model.

Earlier we defined $A_{LEP} \cdot L_{P1} = 0.415mm^2$/year (in Equation(4) which was calculated by using for L one half of the length of the P1 data in meters, 680m.

Since Reference [14] fitted A_{LEP} to the random walk error of the survey measurement this constant is too large. A better value for the CERN environment probably would be the one derived from the motions of the inverted Pendulum in the PS at CERN, $A_{PS} \cdot L_{P1}=0.255mm^2$/year. Or the value from the ZDR, $A_{ZDR} \cdot L_{P1}=0.105mm^2$/year [26]. Figure 15 shows curves with the two higher values. Neither fit the data.

To summarize the conclusions from the data in Figure 14 and Figure 15: a random model does not describe ground movements on the month-to-year scale.

B Evaluation of data from all of LEP

The next figures will show data for all of LEP, but a complete set is only available for the years 1993 to 1999. We will take the results from P1 for guidance. In general one can say that the large movements for LEP did not occur where expected [5], in the Allondon fault region (Source d'Allondon), but at locations which were not flagged as troublesome at the time of construction.

Figure 16 shows the magnet-to-magnet difference of the data of Figure 3. Similar to the region around P1 shown in Figure 13, a plot of the differences between magnets is very instructive. Features of the movements, which otherwise would be covered by the complexity of the raw leveling data, are more visible.

Even more clearly than Figure 14 for the limited data sample of P1, Figure 17 shows for all of LEP the deterministic nature of the relative movements. More than half of the quadrupoles in LEP have an average relative motion of >0.05mm/year and apparently only one of these, after the 1994 earthquake, reversed direction according to the bookkeeping done by the survey group and crossed the horizontal axis.

Figure 18 then shows a histogram of the differences between all quadrupoles in 1993. It shows very clearly that in addition to a narrow Gaussian distribution there is a wider one with tails. Expressed in numbers for 1993 Figure 18 says: 80% of the movements belong to a distribution with σ=≈0.6 mm and 20% to a wider distribution with σ=≈1.5 mm. It is apparent that the data could be described with more than two Gaussian curves, but more

[1] I thank Daniel Schulte for pressing me on this point. He was not satisfied with the indirect conclusion which Figure 15 allows.

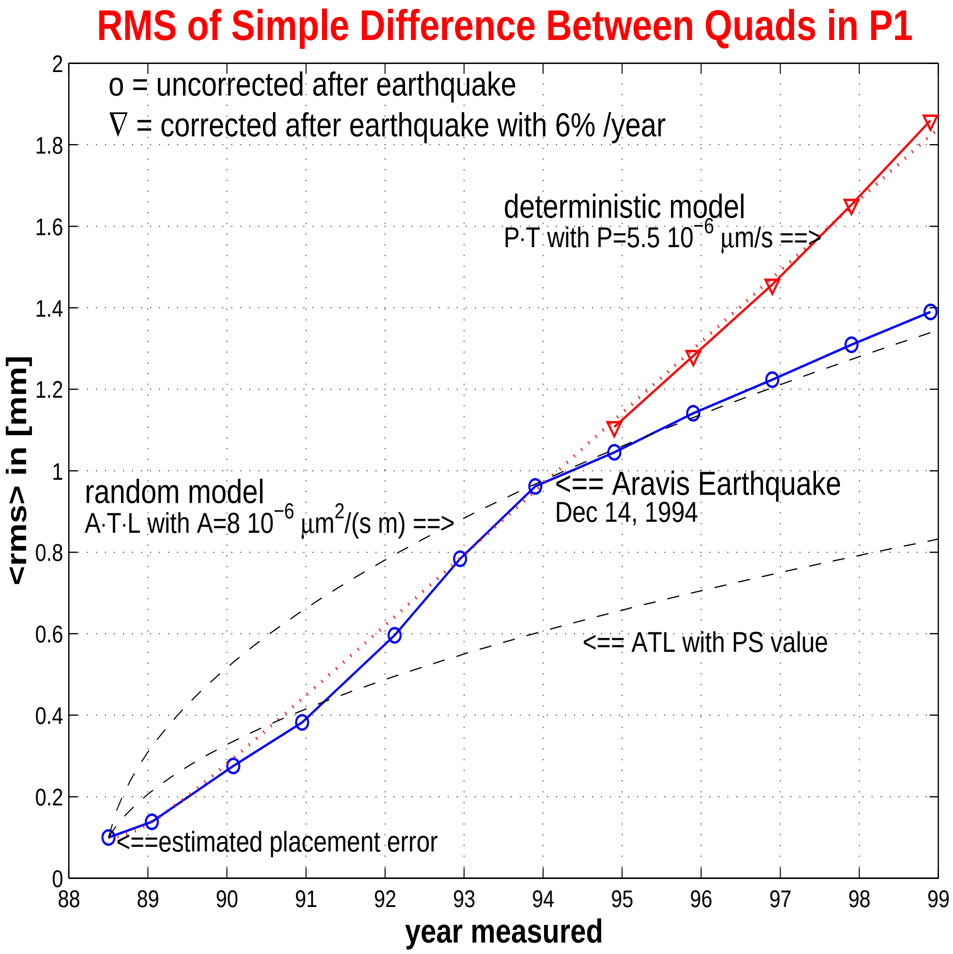

FIGURE 15. Ten-year time dependence for the accumulated rms of magnet off-sets from each other in P1. This busy picture requires explanation. The circles are rms-values calculated by taking the restored difference data as they are. The sharp bend in the curve for the circles in 1994 focused attention on the two groups of curves seen in Figures 12 and 13 and was unexplainable, until the question of an earthquake came up. A fairly large earthquake happened just at the right time to explain the change (December 1994). Two explanations for the mechanism are possible: (1) the tectonic speeds of fault lines was actually changed, making the rms - values grow slower, or (2) a one time change in position of some magnets which was not accounted for in the database because the earthquake happened after the data were taken. The data of Figure 12 support more the second possibility. Rms values are calculated by differences in quadrature. Therefore, in first order a model $(1 + \alpha)^n$, n years passed since the earthquake, seems to be the right Ansatz. From the actual magnet movements by year 10% was estimated for α, a fit gave 12%, resulting in a change of 1.06^n for the change to the rms (∇ symbols in the upper right of the plot).

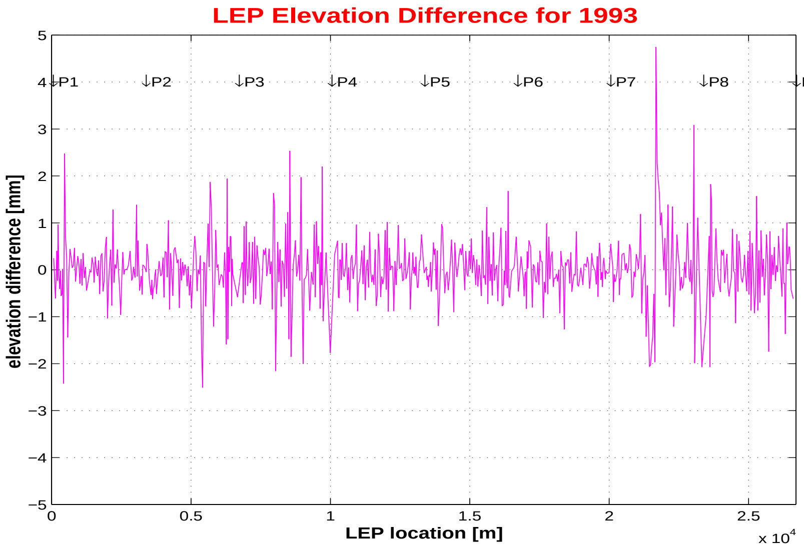

FIGURE 16. The largest differential movements between neighboring magnets are clearly visible and are not always correlated with the raw total excursions from a smooth alignment (or zero). The northern half of LEP not under the Jura, P4 through P7, is clearly more stable than the southern part. The special nature of the movements around 22 km is also evident through the sequence of many differential movements with the same sign. From this figure one can calculate the pitch: if one divides the elevation by the average distance of 40 m between magnets.

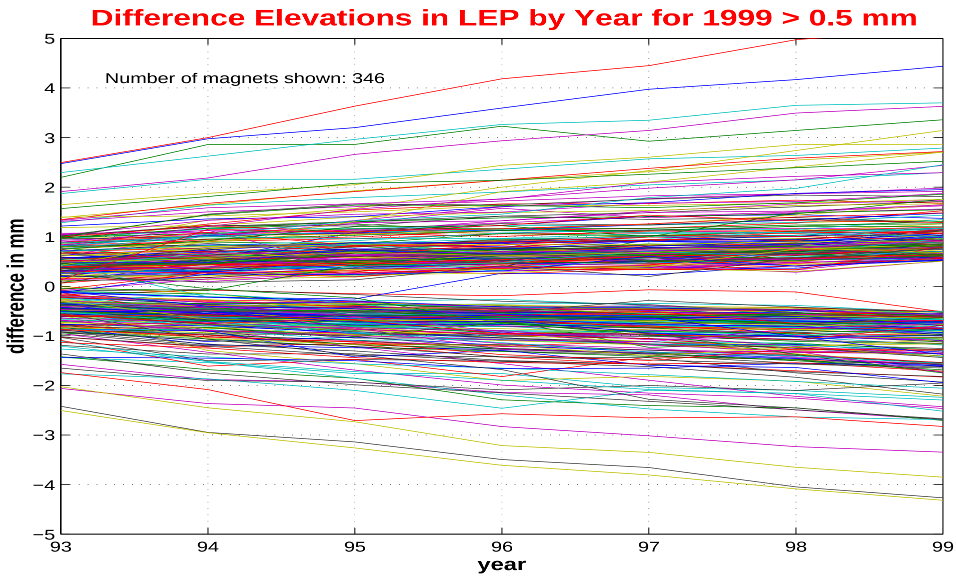

FIGURE 17. From the type of analysis of Figure 16 one derives the slopes of movements in mm/year for all magnets, here limited to magnets with average movements of more than 50 μ/year.

important is that they can not be satisfactorily described with less than 2. Also, because of the minimal structure in the histogram data, the fit errors for correlations between width and strength of the two Gaussian curves are large. A more precise number will be derived later from a deterministic model fit to the variation of rms over the years 1993-1999. For P1 and 10 years this was done already in Figure 15. There is no particular deep physics hidden here: we only try to get the quantitative information for simulations later.

In the same vein, we later will compare deterministic 2-parameter simulations based on these numbers to simulations from random ATL. The latter has been used in the past to make decisions about expected movements for Future Linear Colliders ([26], [27]), making unrealistically pessimistic predictions.

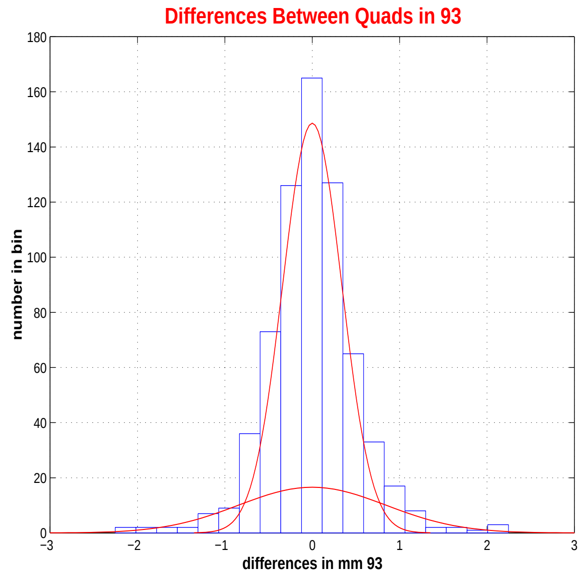

FIGURE 18. Histogram of Movements up to 1993 between quadrupoles for all of LEP shows 2 separate distributions. The 80% in the core have a σ=0.6 mm, the remaining 20% a σ=1.5 mm.

As a preparation we will look again what could be expected in P1 under the ATL model assumption, but with the PS constant. The next two Figures (19, 20) show how elevation and difference distributions would look along P1.

C What is the Right Model Constant? — Evaluation of Region 4

Figure 12 showed graphically the deterministic nature of the LEP quadrupole movements. The maxima of the simulated movements shown in Figure 19 are in sheer numbers close to the amplitude of the measured movements in Figure 12; but they do not replicate the pronounced minima and maxima. In fact, the ATL model with its random walk along the beam line can not produce sharp peaks by definition. While sometimes the random walk leads to a pattern of ever increasing elevation differences as in the 400 to 600 m region in Figure 19, generally the curves are all over the place. Even more instructive are the simulated differential movements between quadrupoles shown in Figure 20 which should be compared with the measured data in Figure 13. The differences between magnets in the simulation are much more underestimated than the elevations themselves, nearly by an order of magnitude, something which would be a most unwelcome surprise for accelerator operation.

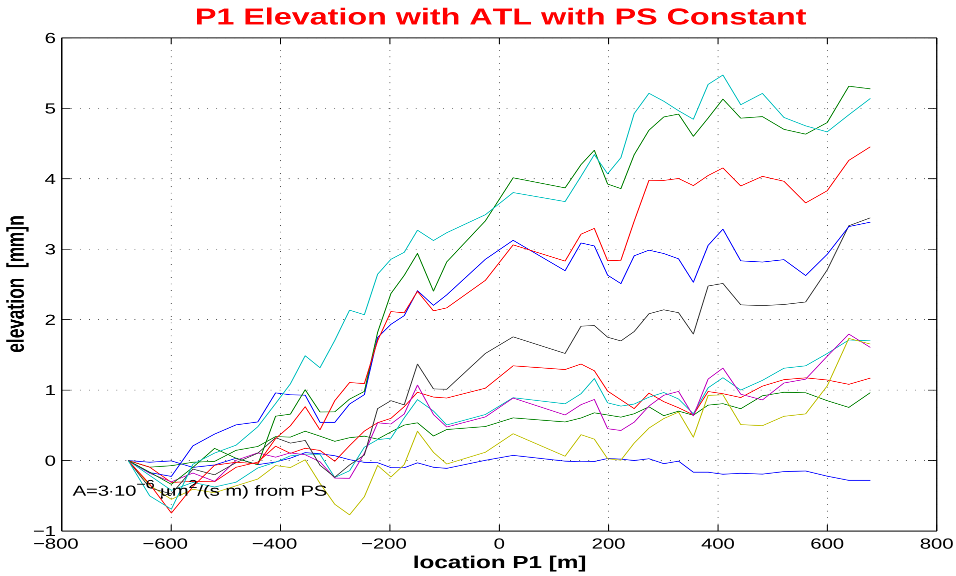

FIGURE 19. Simulation of elevations in P1 over a 10 year time span using the ATL model with the PS constant. Comparison with Figure 12 shows that the typical up and down pattern of the measured data can not be reproduced with a random ATL model.

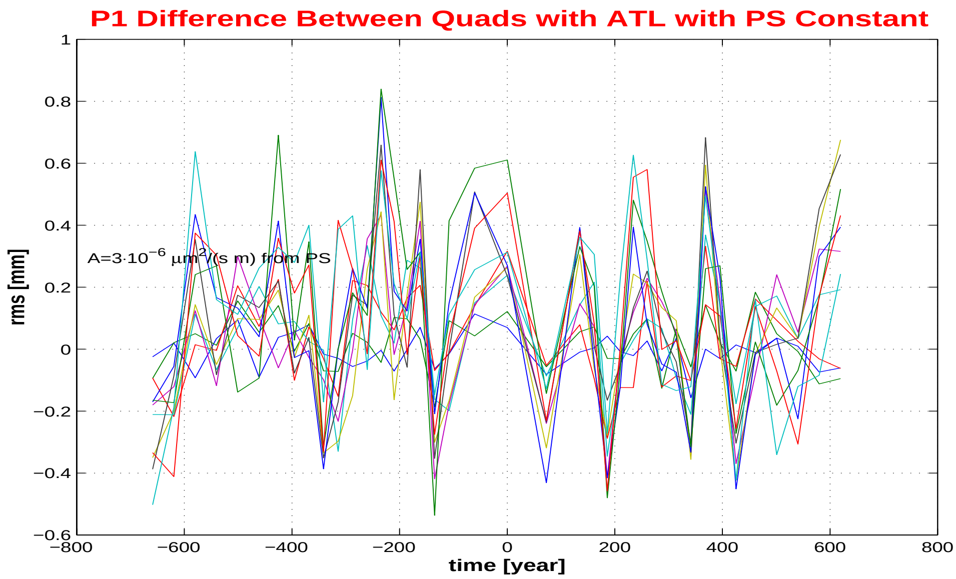

FIGURE 20. Simple differences between the "magnets" simulated in Figure 19. The difference maxima are smaller than the measured movements in Figure 13 by nearly an order of magnitude.

It is probably true that a one-parameter model can not correctly predict or model an actual tunnel. Figure 18 showed that for all of LEP there were two distributions with a different σ. Even using a multi-parameter description, it is difficult to randomly bunch the locations with the larger deviations together, as nature does (see Figures 1 and 12).

The ZDR [26] had modeled ATL diffusion and stated that the short-term alignment drifts probably were overly pessimistic. We will use the formalism developed above to investigate what happens in the short-term with an aligned machine and show that the ZDR statement is true: ATL predictions are too pessimistic.

In Figure 15 random and deterministic curves for the difference-rms had been shown. One striking feature was that at the low end of the time-scale the deterministic model had a much smaller rate of change than the random models, potentially of great importance for operations of future machines. The exact difference depends naturally on the particular constants used.

The equations used in Figure 15 were

$$R_d = \sqrt{R_0^2 + P_{P1}^2 T^2} \tag{6}$$

and

$$R_r = \sqrt{R_0^2 + A_{LEP} L_{P1} T} \tag{7}$$

with R_d the deterministic rms, R_r the random rms, R_0 the placement (or re-alignment or existing) rms, T time (in years in Figure 15). P and A $\cdot$ L were defined in equations (3) and (4).

The ZDR simulated in it's Figure 7-66 [26] the "ATL-like" drift accumulated in 30 minutes from a perfectly aligned machine using an A_{ZDR}=5 10^{-7} μm^2/m·sec. Figure 21 replicates this simulation and adds two more one-half hour intervals. In slow drift and absolute magnitude the first half-hour curve looks very much like the curve in Figure 7-66 of the ZDR. Up to the 5 km point the next two intervals bring not much change, but beyond that distance very much bigger drifts occur randomly. This is not surprising since the ATL approach uses for L the distance from the reference point. The curves here are fairly typical for ATL simulated curves with the random walk-like appearance.

The A-constant used for the random model in Figure 21 and in the ZDR , A_{ZDR}, is on the lower end of constants fitted with this model in the literature [14]. It is not clear how realistic the ZDR constant used for Figure 7-66 in the ZDR is and how it was derived in the ZDR. Appendix C of the ZDR, for example, derives a value of A_{ZDR}=2 10^{-7} μm^2/m·sec. Other A-values for SLAC in Reference [14] were given as the much larger A_{SLC}=20±10 and A_{PEP}=10±5 10^{-5} μm^2/m·sec.

P1 is a region of LEP with pronounced features in misalignment. That means that with P_{P1} as chosen constant in the deterministic model the simulated rms will be larger than in other parts of LEP, so the model is not globally applicable. This approach is consistent with the underlying assumption of the PT model that there is no global law governing ground motions and misalignments.

In order to obtain a better estimate as to the narrower core of the distribution in Figure 18, we will evaluate the "flat" region from 10 to 14 km, in LEP regions P4 and P5, to get an additional data point for the deterministic model, which we call P_{P4}. This factor should be the lowest of P's describing any section of LEP. First we will look at the equivalent of Figures 14 and 17 to see if the slope of movement for this region is deterministic, or if a random component is present for smaller amplitudes in movements.

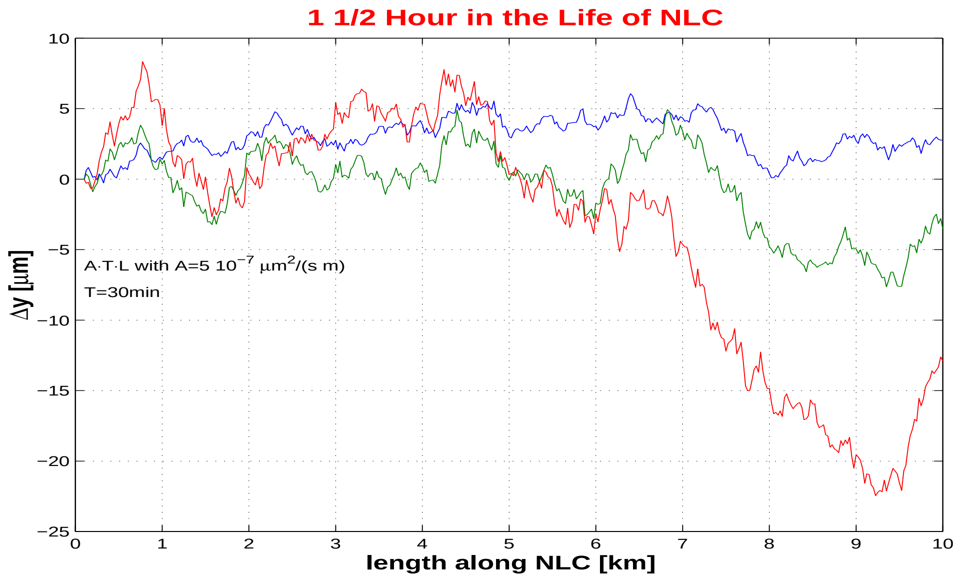

FIGURE 21. Alignment drifts based on the ATL hypothesis for NLC, with the A-constant of the ZDR, for intervals of 0.5, 1, and 1.5 hours. The 1/2-hour curve of this simulation closely replicates in slow drift and magnitude the curve in Figure 7-66 of the ZDR. But further simulation in time (1-hour and 1 1/2-hour lines) show quite different results, reflecting the typical hazards of random walk. To ease comparison all curves are normalized to zero at the beginning.

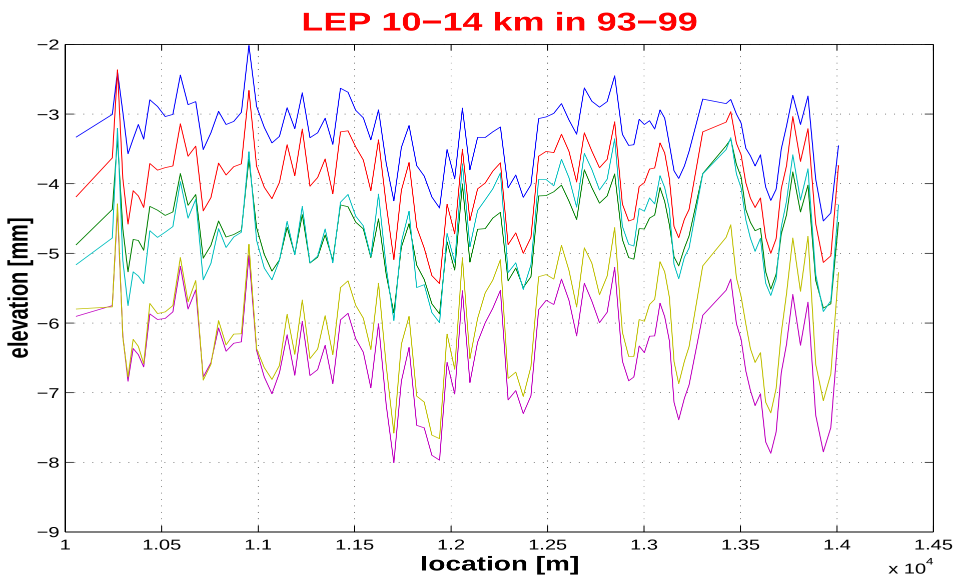

FIGURE 22. Elevations of 102 magnets in regions P4-P5. The elevations appear to change from year to year in a regular fashion (sinking), but as explained earlier in the text different evaluations identify this area as possibly the most stable in LEP. Fourier analysis of the apparent regular up-down pattern along the beam line was without success. See the text for additional explanations.

Figure 22 shows the very regular pattern of the elevations in P4-P5. The pattern of maxima and minima in P4 looks so regular that we Fourier-analyzed an interpolated sample (interpolated, because the positions of the magnets are not all equidistant). We found two spikes in the Fourier spectrum at ≈9.9 m and 52.5 m. The first number was mentioned earlier as known from construction: the shell of the tunnel was pre-cast in 9.9 m sections and grouted to the rocks. However, since the "sampling rate", ≈39.5 m, is larger than the "frequency" of 9.9 m, we feel this "agreement" is interesting, but probably meaningless.

The floor itself was cast in 39.5 m sections with expansion joints on either end. The different concrete segments were not anchored to each other. The dimensions correlate exactly with the FODO cell-length pattern, something one clearly never should do.

It is useful to speculate what brought this "regular" pattern about. We think it is the construction decision which placed each LEP arc quadrupole on its own 39.5 m concrete slab. Future colliders have very stringent short wavelength alignment tolerances. We believe that the vertical movements occur across the joints with a very short wavelength. To ensure greater smoothness for future machines one should forego expansion joints and cast a monolithic concrete slab with a continuous strong rebar skeleton in the floor. This may lead to cracks in the floor, but will keep the relative alignment smooth.

If one insists on expansion joints one must have an irregular expansion joint pattern, or in any case one which is not connected to the FODO cell length. Not having expansion joints is the solution chosen for modern synchrotron light sources. Synchrotron sources, classified by Fischer and Morton as belonging to the same class of "open" machines as linear colliders [18], have also taxing alignment and stability requirements; for the Argonne National Light Source, e.g., see Reference [28].

From the data of Figure 22 we derived the slopes of movements in mm/year for all magnets with average movements of more than 25 μm/year, shown in Figure 23, to answer the deterministic vs. random question. Seventy-eight out of 102 magnets in this section were above the threshold, while none crossed the horizontal axis. Again, there is no sign of random movement.

It is also interesting to look at the rms value of the differences in P4-P5. In P4-P5 the Rms of the differences in 1993 was 0.44 mm. This compares well with the 0.6 mm estimated from Figure 18 for all of LEP for the narrower of the two distributions. [1] We conjecture that for LEP there is a "normal" differential tunnel movement, which in five years accumulates rms deviations of the order of ≈1/2 mm, and then there is a movement, based on particular forces in particular places (tectonic fault lines and hydrostatic pressure among others, for sure), accumulating total rms' in 5 years of the order of 1.50 mm, forces which are apparently not at work in P4-P5.

A histogram of the relative motions in P4-P5 between quadrupoles, Figure 24 bears this out: There is no underlying wider distribution, nor tails of any kind. From the growth of the rms values of the differences between neighboring quadrupoles for 1993-1999 (6 years, curve not shown) we derive the parameter for "normal" movement needed for simulation: P_{P4} = 2.0 10^{-6} μm/sec, which in the practical units used before translates into 0.062mm/year, about 1/3 of the value found for P1.

[1] For the region P4-P5 we equate Rms and σ, a good enough approximation for N=102.

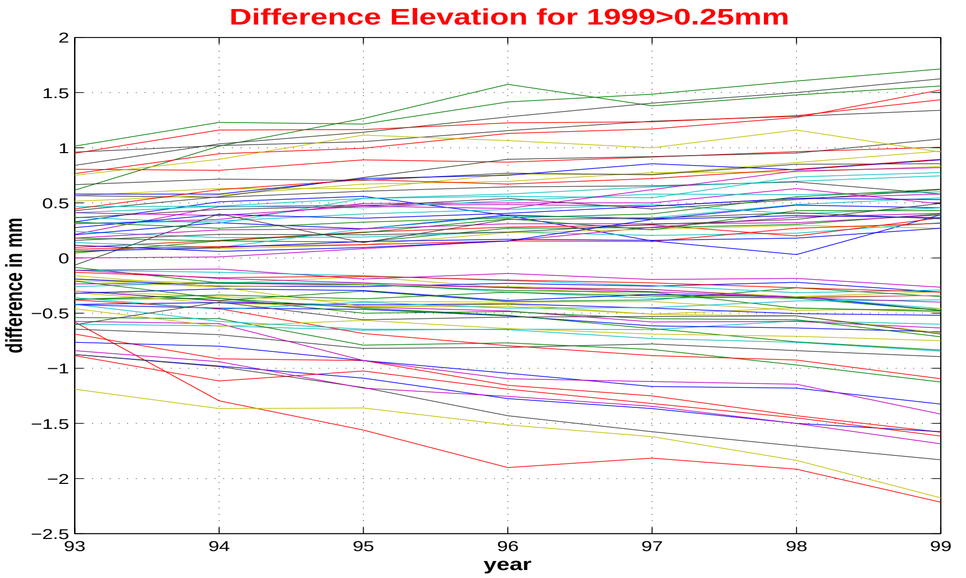

FIGURE 23. Differential yearly movement of 76 the 102 magnets in regions P4-P5. As in other cases in LEP there is no indication of any random movement, which would make magnets change the slope; in particular no magnet crosses the horizontal axis. The cut-off was set to an average speed of 25μm/year, half the single set-up accuracy, which we thought was a sensible threshold to prevent fake-random movements to creep into the data sample.

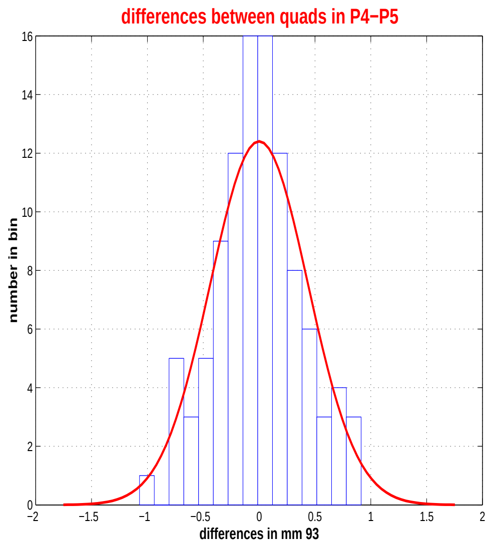

FIGURE 24. Histogram of Movements between quadrupoles in 1993 (from Figure 22) in the "flat" region shows only one distribution, and no tails for region P4-P5. The σ of the distribution is 0.44 mm.

III CONCLUSION

A Short-term Parameterized Simulations

There is a fundamental problem in doing any such simulations at all. The deterministic model has as a built-in assumption that there is no general law governing motions, following the *Fischer Principle* [21] everything depends on local condition and history. Even proponents of a random model acknowledge this implicitly by giving different A-constants for different accelerators, which often, as in the case of SLAC, are located in the same soil and at the same depth [14].

So in principle one could, and maybe should, just take the actual LEP data as an exemplary sample and use it to predict accelerator behavior. Despite these reservations we tried here to extract some general rules from the LEP ground motions, and codify it in numbers because this enables to do simulations tailored to Future LC requirements.

The main reason for trying to extract general rules comes from the data themselves. In addition to some clearly very special local tectonic movements, mainly in P2.7 and P7.5, but also around P3.8, at which we will look later, there are features of LEP misalignments/movements which are more general, and which have been seen in other accelerators [8]. These movements are apparent in an accelerator tunnel from the very first day a floor has been poured. So the strategy for a new tunnel should be to measure a tunnel floor very early on after beneficial occupancy and adjust mechanical and conceptual alignment preparations to the predicted floor movements at each point.

We will now show simulations for alignment drifts, using the features of LEP recognized as general. This then might be applicable for Future Linear Colliders, using the deterministic model and the values for P derived from the LEP data. We will compare a one- and a two-parameter simulation. The jump of faith one has to do is to believe that movements which have been measured on the scale of months with geodetic means are also happening on the scales of days [29]. There are still no believable direct precision measurements of movements on the hours-to-days scale.

There have been efforts to measure total short-term motion [1] of storage ring accelerator components (mostly quadrupoles) by the effects they have on the closed orbit [30], [31]. These are difficult experiments to do with results difficult to interpret. Measurements taken at different times for the same time-scales (hours-to-days) yield quite different results (see, e.g., Figures 3 and 4 in [31]). In addition, instead of measuring ground motions, they measure a combined motion of many things. This includes motion of quadrupoles and their cooling and support systems, which is a very important quantity to measure, but it does not help to disentangle the root causes of movement. It also includes the effects of beam position monitors and their electronic drifts. As a consequence these results have a unique interpretation for time-scales below 0.01 sec (the usual 1/f-law plus cultural noise), but they are compatible with many interpretations for the long-term part, probably because there are just too many dependencies on too many parameters in the operation of the machine.

Figure 25 shows a simulation with one parameter under the deterministic assumptions using the P-parameter derived from LEP area P4-P5. This covers the first three 1/2 hour periods after perfect re-alignment of a 10 km long accelerator (beam) line.

These simulations have to be compared to Figure 21, which was calculated with the ATL model with the constant taken from the inverted pendulum at the center of the PS, rather

[1] One has to be careful with the nomenclature. While here short-term means days and long-term means months and years, short-term in the literature often means vibrations below 1Hz, and long-term means hourly drifts of the orbit.

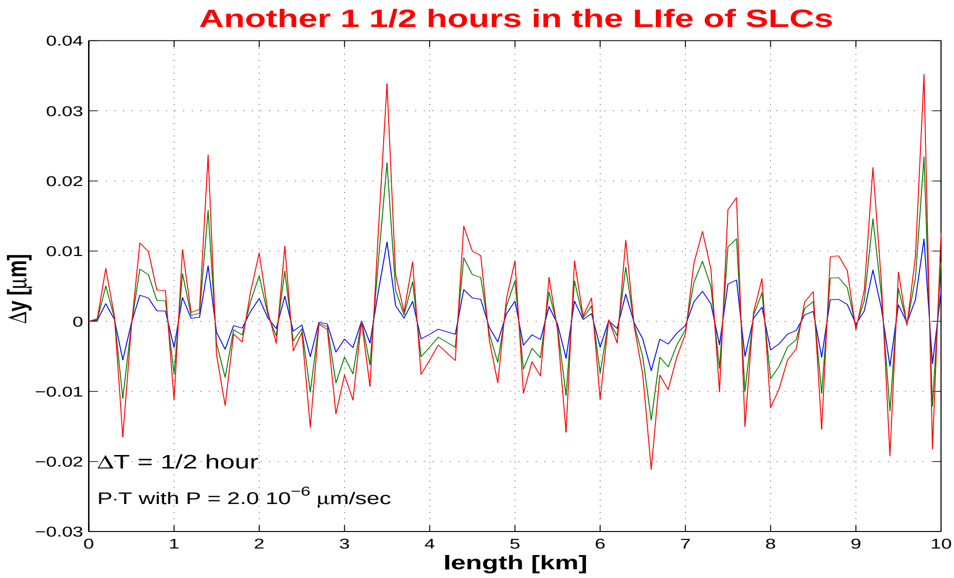

FIGURE 25. One-parameter alignment drifts based on the deterministic PT model, for intervals of 0.5, 1, and 1.5 hours for CLIC/JLC/NLC type accelerators. The constant P = 0.06 mm/year from region P4-P5 was used for the simulation. This would constitute a baseline scenario for the least misalignments in this time span one should expect. When compared to Figure 21 the maximum elevation difference after 1.5 hours is about a factor of 500 smaller.

than the parameter derived specifically for LEP [14], for the reasons detailed earlier [17]. Independent of the absolute magnitude the sheer appearance of the deterministic simulation of Figure 25 looks better than the ATL simulations shown in Figure 21. It has more the appearance of real misalignments as we encounter them in the field.

But it is not yet quite good enough. That is to say, the simulations would describe an accelerator which looks like P4-P5, but not one which includes P1. This comes from using a completely random approach for distributing the misalignments to the individual points in the tunnel (here: magnets), although each point acts in a deterministic way. Deterministic, because if a magnet has moved the distance y_1 in the time t_1, it will move $2y_1$ in the time $2t_1$, but random, because the next magnet may be having the opposite direction of movement.

A look at any of the figures which show LEP data in this paper shows that while it is true that the movement of many neighboring points with respect to one another is randomly up or down, it is not true for all points. There are certain correlations between neighboring points. These correlations generally extend not further than 4-5 quadrupoles, that is 150 - 200 meters. Since this length is the typical betatron wavelength used in simulations in the ZDR [26] these correlations should help reduce the impact of misalignments on the accelerators. We have not tried to incorporate them into the model. Doing so would incorporate ATL behavior over a distance of 4-5 quadrupoles into the deterministic model, which may be the right thing to do in the future, but it goes beyond the scope of this paper.

With the models used the overall magnitude in the deterministic case is smaller by two orders of magnitude but the structure between adjacent points is more pronounced than in the random case [1]. This difference in magnitude for small time spans one could have guessed

1) One should bear in mind that the quantitative aspects of the modeling depend on the constants used. We were not able to make a rational choice between the many A-parameters given in the literature (see, e.g., Reference [14]). In the LEP case, where we could have a good look at the original data, the determination of A_{LEP} is clearly wrong.

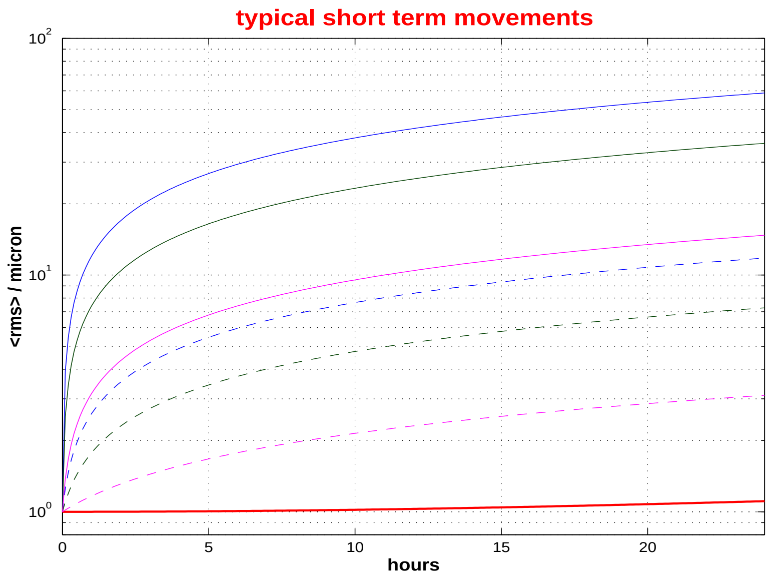

FIGURE 26. Rms values expected from extrapolation of ground motion alone, accrued to a machine aligned to 1μm at T=0. The solid curves starting with an infinite slope are R_r's calculated from equation (7) with A equal to A_{LEP}, A_{PS} and A_{ZDR}, from top to bottom, respectively, as defined previously in the text with L=5 km, half the length of the simulated accelerator in Figure 25. The dashed curves are ATL calculations with the length of one betatron oscillation ≈200 m chosen instead for L. The line on the bottom represents R_d defined in equation (6) with P from the analysis of region P1, the largest P-constant we could identify in LEP, a worst case scenario in our opinion.

from Figure 15; here we enlarge the low end of this figure and replot it with more curves in a semilog plot in Figure 26.

We have plotted in Figure 26 the ATL results for two choices of L. One choice is, following our earlier practice in P1, the half length of the beam line, L=5 km. The other choice is, following the arguments of Reference [32] (but see also [18] [1]) the length of one betatron oscillation $\lambda_\beta = \approx$200 m. The argument is that the effects of ground motions with a wavelength larger than λ_β are effectively suppressed. Figure 26 shows, as suspected in the ZDR, that the ATL approach is overly pessimistic with regard to short-term misalignments, even with the very small value for A_{ZDR}.

The next three Figures (27, 28, and 29), use a two-parameter model with two parameters P_1 and P_2. The parameters are set to P_1 = 0.062mm/year (from Region P4-P5), for the central distribution which comprises 85% of the "data", and P_2 = 0.175mm/year (from region P1), for the wider distribution with tails which makes up the remaining 15%. The values were not taken from Figure 18. Rather P_1 and P_2, which determine the widths, were, as explained before, taken from the change of rms over the years using the deterministic model. With information that in the average the LEP quadrupoles in 1993 had been in place for 6 years this leads to σ's of 0.4 and 1.0 mm, 30% smaller than those derived from Figure 18. Since Figure 18 graphed data from all of LEP, including the prominent "breaks", they agree well enough, in particular if one considers the rather large correlation between strength and width in Figure 18. Note also that the ratio between the two set of widths is about the same.

The points with movements described by P_2 were forced to bunch together in two

[1] In fact, there is very little concerning ground motions the late Gerry Fischer has not thought and talked about, even if not everything was put down on writing.

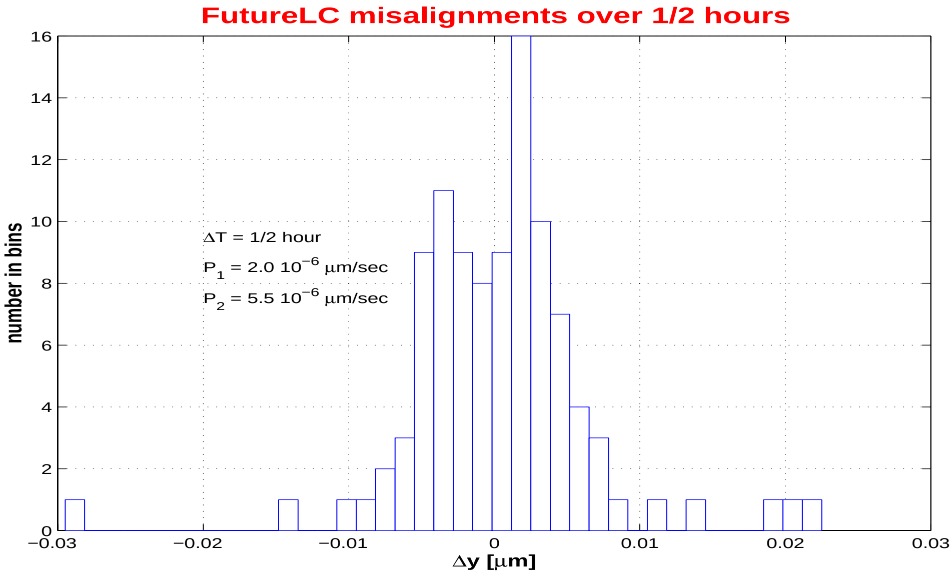

FIGURE 27. Histogram of deterministic two-parameter model calculation for CLIC/JLC/NLC, with P_1 from region P4 of LEP, 0.06mm/year, for the central distribution, and a P_2 from region P1 with 0.175mm/year. That is, the histogram shows by design tails as in Figure 18.

places, just before 5 and 10 km, respectively. But even the case with the P-factor from P_1, 0.175mm/year, the "normal" worst case movement in LEP, will be more than two orders of magnitude smaller than the equivalent simulation from ATL. We call this the "normal" worst case because we will look in the next section in detail at the even larger "breaks" in the floor in P2.7 and P7.5. However, as stated before, there are easy strategies to deal with the very large movements which are limited to just a few places, similar to the "Running With the Wind" strategy used at LEP, but on a daily rather than a yearly basis [1].

B Long-term considerations

The upshot of the previous section was that the random ATL model **overestimates the actual short-term** misalignments of a machine due to ground motion alone by a large amount, because the actual ground motions are not random. A cautionary statement was made that there might be other random contributions to the movement of quadrupoles and acceleration structures which can change the total picture. Nevertheless, "ordinary" movements which impact on the short-term misalignment problem can be parameterized. The "exceptional" movements can not be parameterized and we will discuss them by location in LEP in this section.

If one extends the calculations of Figure 26 (or see Figure 15 for the actual measurements to 10 years) to 20-30 years, assumed to be the typical life-time of a Future Linear Collider, the random model now **underestimates the long-term** movements by up to an order of magnitude.

The problem created is that the range of built-in adjustments for re-alignment, if designed following the ATL model, will not be large enough and the delicate set-up will have to be disturbed at a later time with jack-hammer work to make room in the floor for the

[1] Running With the Wind, CERN Courier, **34,4** (1994) p. 19

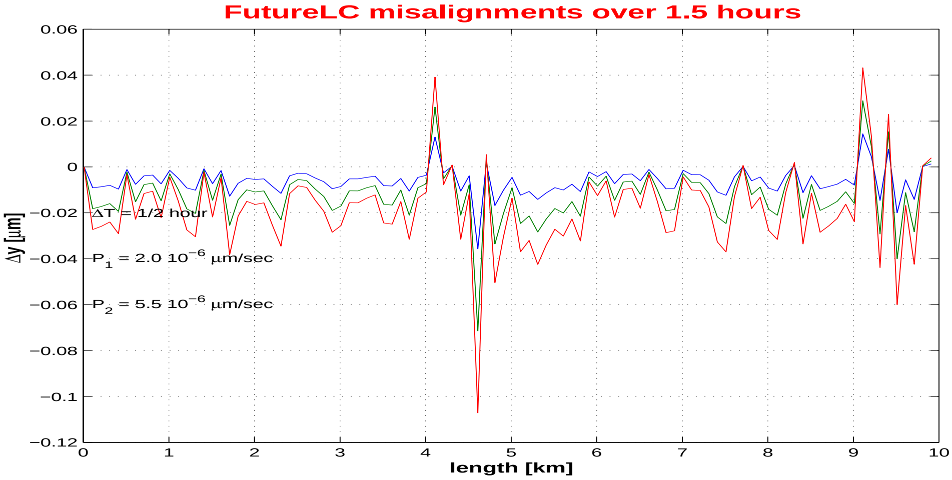

FIGURE 28. Deterministic 2 parameter model calculation for CLIC/JLC/NLC, with the parameters and the distributions from Figure 27. The misalignments have the look and feel of the LEP P1 movements, as they should, because the model was tuned up on P1. As in previous Figures the curves were normalized to zero at the coordinate origin; in this case it resulted in most points being negative. P_2 was used for simulation of the 15% of the magnets between 4-5 km, and 9-10 km, creating a "normal" worst case for misalignment.

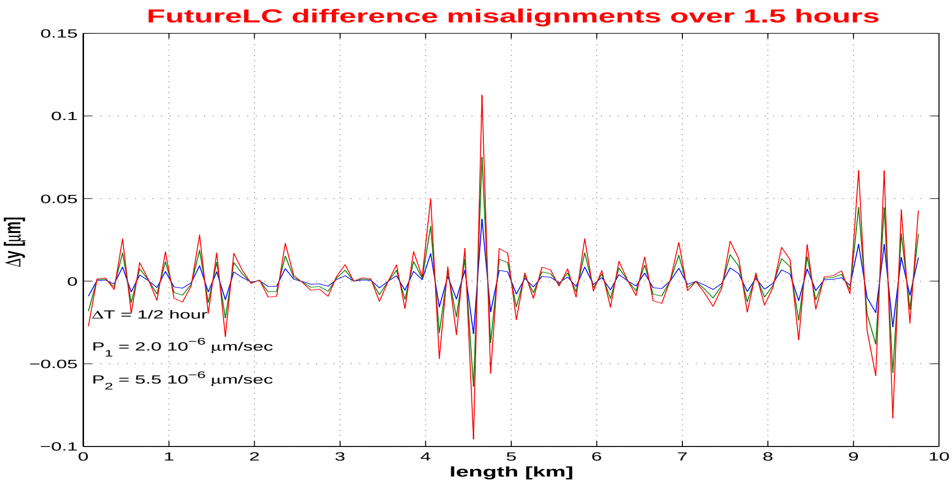

FIGURE 29. Deterministic 2 parameter model calculation of the differential movements between neighboring magnets for CLIC/JLC/NLC, with the parameters and the distributions from Figure 27.

support if the floor goes up. Or the support will need to be dismantled to put in longer adjustment bolts if the floor goes down. One tries to keep the adjustment mechanisms as short as reasonable to keep the eigen-frequencies of the support high. So one wants to properly optimize the bolts for the local conditions.

One could declare by fiat that there will be no tectonic faults on a future collider site. But in reality there seems to be faults nearly everywhere on earth. CERN was not known to be an especially seismic active place, and even the quiet Fermilab site has side branches of the New Madrid Fault. And California and Japan...?

And similar to the LEP site, it may not be real tectonic movements of active faults which drives tunnel movements but rather water penetrating through fault generated cracks in the rock, or the removal of this water. So one has to watch out for the combination of aquifers and (old or new) fault lines.

1 *The Subsidence at Point P7.5 – Ferney*

To restate: The long-term (here: years) considerations are dependent on the fastest movements. The most prominent feature of LEP tunnel floor movements is obviously (see Figures 1 and 2) the subsidence close to Ferney-Voltaire, in P7.5. Figure 30 shows the elevations measured in 1993. This fault area was not suspected before construction as something to watch out for. One should remember that Figure 30 describes the movement of a 1.2 m thick tunnel floor, cast in two layers, each about 60 cm thick, so the forces at work are considerable.

But P7.5 sits at a point where an underground valley, the water-carrying Sillon de Montfleury-Ferney, crosses LEP and the Geneva Airport. Presumably the water penetrates through the fault to the tunnel level, or in past time the water followed the fault weakening the structure of the Molasse, or the ground was wet and the LEP drainage system dried the soil out. However, the Sillon de Montfleury-Ferney is a very wide structure ([10], p. 51, [11]) so that the impact on the LEP tunnel is more like that of a crack in the rock, and less of a trench as in P2.7 (see next section).

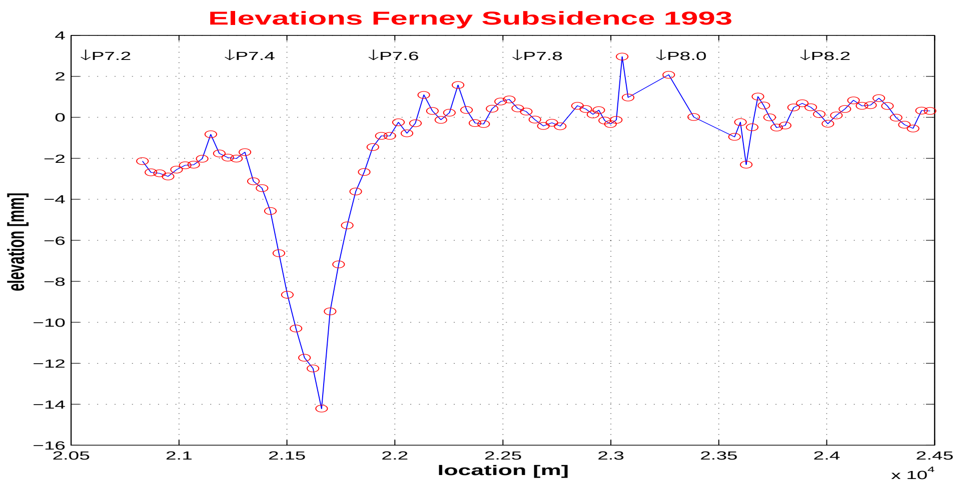

FIGURE 30. The strong subsidence of LEP close to Ferney-Voltaire gives rise to a change of ≈2.5 mm/year over a distance of 200 m.

It is easy to calculate from this maximum movement, ≈3 mm/year, that the daily maximum movements are 8μm/day, or 0.35μm per hour. Thus the simulation in Figure 28 underestimates the maximum movement by a large factor. We explained earlier that part of such difference comes from the lack of spacial short-range correlations in the model.

However, the general model used to predict typical movements should in fact underestimate the movements. As the maximum movements will be rare, they will be easy to handle in daily operation because of their predictability. Thus, they will have no impact on hour-to-hour operations if handled right.

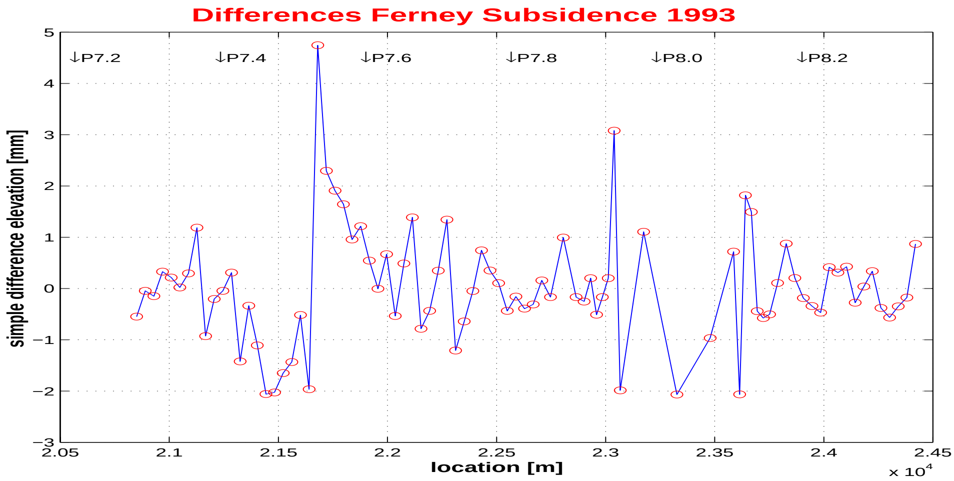

FIGURE 31. Difference movements in the Ferney fault. Comparing the two Figures describing the Ferney fault, one should notice that the differences are signed differences, more like a pitch. That way movements are more accentuated in the graphical representation.

In 1988 Gerry Fischer singled out the fastest regular movement of SLAC, LINAC-Sector 13, with Δy=100μm/month (measured), as something to watch out for, requiring maybe daily corrections of 3μm/day (inferred) [29]. The Ferney fault gives rise to a movement of 3 times that number, $\approx$8μm/day, over about 200 m distance. This has to be compared to a typical transverse vertical tolerance of a few micron for a 25% emittance growth over a betatron wavelength at the end of Future Colliders of the same 200 m (see, e.g., Figure 7-24 of Reference [26] [1]). So this movement would have to be taken care of about two times a day to prevent emittance blow-up. However, since this is a regular movement, deterministic as we called it, it easily can be taken care with the data from the preventive survey measurements immediately after construction, as explained in the previous section.

Despite this striking absolute elevation change, Figure 31 demonstrates that the local differential movements between neighboring magnets are quite normal and within the boundaries mentioned before: an accumulated 1-2 mm over a five year time span, with a few exceptions. This once more speaks for the high quality of the LEP tunnel floor construction.

2 *The Subsidence at Point P2.7 – Villeneuve*

This tunnel movement is due to another important fault (or faults) which crosses LEP at P2.7 and creates the second largest absolute movement. While most faults originating in the Jura run from NW to SE, this runs strictly west to east down from the Crét de la Neige. In the original documentation for LEP [10] the area is described as the crossing of the "Faille

[1] The vertical scale label in Figure 7-24 of the ZDR has to be read as μm and not mm.

de la Calame" and the "Faille de la Tremblaine"; it was also noted that several visible earth movements are connected with it and that it is an important water drainage zone.

This makes all the ingredients of large tunnel movements as explained before: fault lines and availability of water. The corresponding underground valley ("Sillon de Sergy") is known to have a width of 300 m, in good agreement with the subsidence of LEP shown in Figure 32. From the appearance of the subsidence it is possible, but not proven, that it is indeed created through two faults close together, particular if compared to P7.5, the Sillon de Montfleury-Ferney.

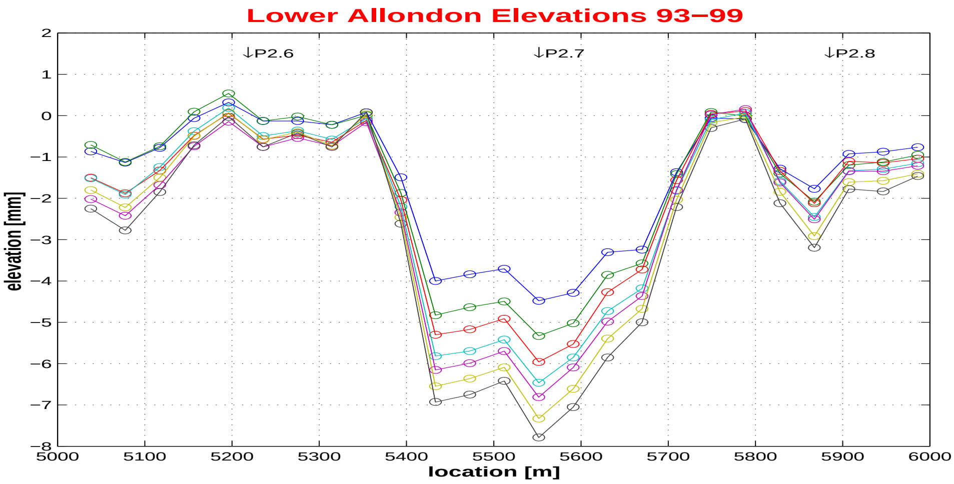

FIGURE 32. Subsidence in LEP Point 2.7, the crossing of LEP with probably two geological faults and the Sillon de Sergy. The curves were normalized to the average of the highest points next to the break (5350 and 4750 m). The width of the subsidence agrees with the known width of the underground valley.

Figure 33 shows that the differential movement belongs to the five largest such groups in LEP, see also Figure 16.

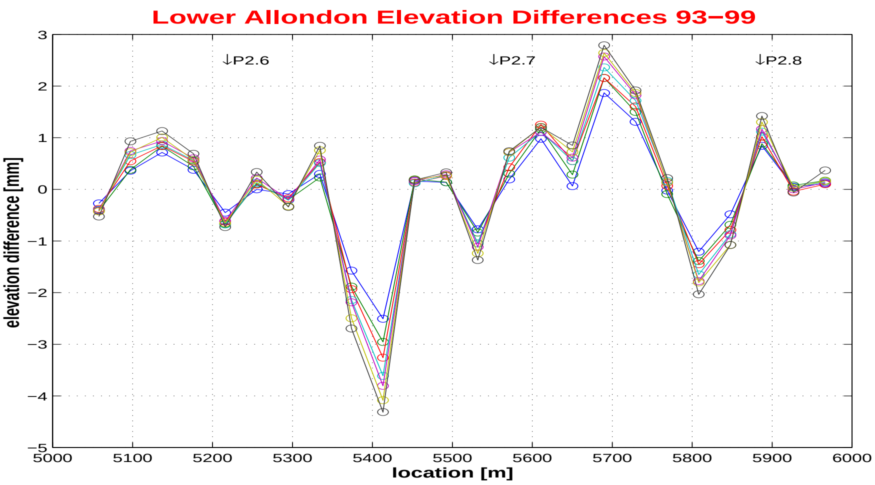

FIGURE 33. Difference in Elevation between neighboring magnets in P2.7. Despite the special nature of this break the differences fall into the general magnitudes of such differences at LEP.

3 P3.8 Three Different Effects

The effects around P3.8 could serve as a schoolbook example how important it is to know the actual history of each point measured in the tunnel, and also to know the geology of the environment.

From left to right in Figure 34 we see:

- three sharp peaks around 8000, 8600 and 8950 m,
- a subsidence around 9300 m,
- a broader peak at 9800 m.

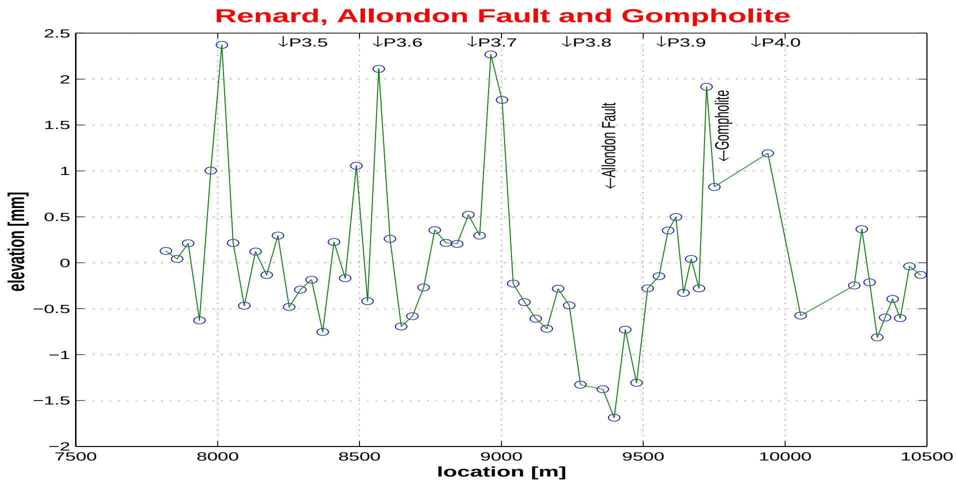

FIGURE 34. Confluence of three different effects leading to accumulated tunnel movements in 1993. All effects depend on the availability of water. As in Figure 3 these data have been corrected for re-alignment actions before 1993. The three sharp peaks around 8000, 8600 and 8950 m are due to water intrusion into the tunnel and it's environment during tunneling, the subsidence around 9300 m is due to the Allondon fault, and the broader peak at 9800 m due to the Gompholite layer traversed here in tunneling.

Just naively looking at the data one could easily and justifiably conclude that ≈2 mm is the normal tunnel height and that everything below are places where the tunnel floor sagged to a varying degree. Putting all the information together the following picture develops:

1. As reported earlier the "Renard" is the area where the tunneling hit water carrying strata. It took a while to stop the water and to continue with tunneling, mainly by injecting cement into the soil. Still, after the floor had been poured and the magnets had been installed and aligned, they rose yearly for a number of years until the movement stopped. This is the reason for the three sharp peaks.

2. The Allondon Fault crosses LEP at 9300 m. This fault carries plenty of water, the Source d'Allondon, making the two ingredients we think are necessary for creating a sinking.

3. At the place where LEP crosses the boundary between Molasse and Limestone, at ≈9800 m, a layer of Gompholite is located. Since Gompholite swells when it becomes wet, the water from the Allondon made the tunnel go up. Interestingly enough, the corresponding Gompholite layer on the southern end of the Jura section of LEP, at P3.1, does not show any signs of up-lift.

C Summary of Conclusions

No sign of random movements of the ATL-type of the LEP tunnel floors were found in yearly vertical surveys over 10 years. It is possible that below the concrete floor the mountain does "Space-Time Ground Diffusion" (ATL-model), but these movements have not been able to penetrate through the concrete floor in any observable way.

It is important to keep the following points in mind while trying to understand the data:

- 1. Distinguish between the random walk of the survey process and the search for random movements of the floor through the movements of the quadrupoles attached to the floor.
- 2. We used a fit to suppress random walk of the survey process only in P1. Otherwise differences were used because a fit for all of LEP would have required arbitrary choices on which data to exclude from the fit.
- 3. Different areas in an accelerator have different model constants. We found we needed at least two; a more refined analysis might decide more are needed.
- 4. The evidence is overwhelming that there is no trace of random movements of quadrupoles over the years.
- 5. We conclude (or conjecture, as the skeptic might prefer) that the ATL model overestimates the short-term movement on the scale of hours, but underestimates the long-term movement on the scale of years.

We expand somewhat on the last point above including some recommendation for construction and drainage below.

1 The Long-term Effects

Long-term effects on the accelerator are determined by the maximum excursions due to swelling clay, tectonic faults, underground valleys, etc. This paper has shown that the "maximum excursion" effects, even when extrapolated to short-term time-scales, can easily be handled in daily operation of the machine since they are deterministic and, therefore, predictable. Care has to be taken in the mechanical design to be able to accommodate reasonable maximum excursion over years without having to dismantle a delicate set-up.

We suspect certain typical ("normal") LEP movements to be due to the way the floor was constructed in disjointed slabs, as discussed earlier. Here is what we would recommend for the construction of Future Linear Collider tunnel floors, with vertical tolerances of a few meter lengths:

- Forego expansion joints and cast a monolithic concrete slab with a continuous strong rebar skeleton in the floor. This may lead to cracks in the floors but will keep the alignment smoother, because it is assumed that movements happen across the joints.
- Establish a permanent monument system and measure early to calibrate maximum movements. Maintain that monument system through the life of the machine. Keep random walk below acceptable tolerances.
- Adjust the design of the mechanical support systems locally to maximum expected excursions, otherwise minimize bolt length.

- Tunnels act like wells which collect water. This works both ways. On the one hand it is important to have a drainage system similar in quality to LEP's, which keeps the tunnel dry and keeps surplus water low in its environment. On the other hand if the rock was wet when bored or when the concrete was poured, it should stay wet to prevent shrinkage. With other words, the drainage system has to be intelligent.

2 The Short-term Effects

Short-term effects on the accelerator alignment under the deterministic behavior have been shown to be more benign than under a random model. Stronger focusing (a shorter FODO cell length) results in a tighter tolerance for quadrupoles but in a looser tolerance for accelerating structures, and vice versa. The tolerances we have picked in the table below are an arbitrary compromise between the two, but the results can easily be re-calculated by anybody not satisfied with the choice. For the ATL model also a length L needed to be chosen. We choose here the typical length of a FODO cell, rather than the average length of an accelerator. This does favor the ATL model by $1/\sqrt{L}$ in comparison - nevertheless ATL reaches the alignment limit by an order of magnitude earlier than the PT model, as it does in any reasonable combination of parameters.

In tabular form:

	CLIC	JLC_X/NLC	JLC_C
λ_β /meters	36	180	360
${\Delta_y}^{Quad}$ / μm	1	5	10
τ_{ATL} / hours	2.6	13	26
τ_{PT} / hours	50	250	500

Table of short-term time tolerances: ${\Delta_y}^{Quad}$ denotes the acceptable rms motion of the magnets from the last beam based alignment. τ_{ATL} and τ_{PT} are the times in hours until the misalignment reaches this rms alignment limit, the so called stable time, under the random and the deterministic assumption, respectively. The constants used were A_{PS}=$3{\cdot}10^{-6}\mu m^2$/(sec · m) for the ATL model (from the inverted pendulum in the PS, a midrange value from the literature), and $P_{P1} = 5.5 \cdot 10^{-6}\mu$m/sec for the PT model (from our evaluation of LEP P1, a "normal" worst case), respectively.

We have not found any movements with this study of LEP which could not be handled with proper care and foresight.

Acknowledgments My connection with the CERN Survey Group, then still under Jean Gervaise, goes back to a SLC pre-construction visit here in 1982, when they kindly helped the SLAC alignment greenhorn to get going. The foundation of this particular work here in the form of a collaboration with the CERN Metrology Group was laid during a sabbatical stay in the SPS/LEP Accelerator Physics Group at CERN in 1991. It was continued in the interim and was again intensified during my present stay with the CLIC Study Group. My gratitude goes to my old CERN colleagues in Metrology Michel Hublin, Michel Mayoud, Jean-Pierre Quesnel, and newly also Fengxiang Jin, who were very generous in discussing and sharing their painstakingly collected and documented data. I thank Burt Richter for his encouragement to continue this work.

Many discussions and exchanges with Gordon Bowden about alignment problems over more than 17 years have helped to sharpen my focus and understanding. I thank Gilbert Guignard and André Verdier for proposals which contributed greatly to the clarity of presentation (just imagine how bad it was before). I am indebted to Cris Oppenheimer and Frank Zimmermann for excellent editing and proofreading.

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