SSCL-Preprint-505

SPS Data on Tunnel Displacements and the ATL Law*

V. Shiltsev† and R. Stiening

Superconducting Super Collider Laboratory‡
2550 Beckleymeade Ave.
Dallas, TX 75237

September 1993

*Submitted to the Third International Workshop on Accelerator Alignment, CERN, September 28–October 3, 1993.
†Guest scientist from Budker Institute of Nuclear Physics, Novosibirsk, Russia.
‡Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

SPS Data on Tunnel Displacements and the ATL Law

V. Shiltsev and R. Stiening

Abstract

In this article we analyze data from long-term measurements of quadrupole displacements in the Super Proton Synchrotron ring at CERN. The variance of displacement can be approximated by ATL law with coefficient $A = (0.1\text{–}0.4) * 10^{-4}\ \mu m^2/s/m$, with T the time interval between measurements and L the distance between two points of the tunnel. The shape of the distribution function is found to be close to Gaussian. The results of the analysis are compared with other data on slow ground motion.

1.0 INTRODUCTION

In an ideal accelerator with well-aligned magnetic elements, the closed orbit passes through the centers of the magnetic elements (bending magnets, quadrupoles, sextupoles, *etc.*) to provide optimal conditions for the operation of the machine. Any alignment errors cause a closed orbit distortion (COD) that leads to reduction of the dynamic aperture of the machine, additional increases in particle loss, limitations on the maximum current of charger particles, and—in extreme situations—an inability to run the machine. Usually, a correction scheme is used to counteract the errors that accumulate during the operation of the machine. In large accelerators, such as the Superconducting Super Collider (SSC), Large Hadron Collider (LHC), HERA, and TeV linear electron-positron colliders, which have several hundreds or even thousands of magnetic elements, one of the most important sources of magnetic errors on a long time scale is the slow ground motion that displaces the elements from their original position. Quantitative parameters of such motion should be taken into account during design so that a correction system of sufficient strength is provided.

The first such parameter is the value of displacement of the ground during the time interval T. Numerous measurements of the power spectral density (PSD) of the ground motion in the very broad frequency band 10^{-8}–10^{3} Hz (see, for example, References 1–7) have shown that amplitudes of displacement grow with a decrease of frequency (*i.e.*, at longer T) and the process is non-stationary or time-divergent. The second parameter is space and time correlation of ground motion. It is well understood that in the case of full space correlation of ground motion over scales of more than betatron wavelength of particles in an accelerator (for example, plane ground wave with large wavelength and low frequency, as was considered in Reference 8), the amplitudes of the COD are small in comparison with the amplitude of ground motion, because the magnetic elements and the beam move together. So, uncorrelated displacements of magnets are the most dangerous for accelerators.[9] Correlation properties of seismic vibrations in the frequency band 0.05–1000 Hz were investigated in References 1, 2, 5, and 6. It was shown that depending on conditions only vibrations below about 2 Hz may be significantly correlated over several hundreds or even thousands of meters, and at higher frequencies the correlation is practically absent. Correlation of slow ground motion with a time scale from 100 s up to several years was usually measured in geophysical experiments where relative positions of two or more monuments were measured over a long time (see References 1–4, 6). It was found that motion due to daily and seasonal variation of ground temperature, atmospheric pressure variation, groundwater-level variation, earth tides, and other regular processes have a large correlation length but disappear if the source is removed. Besides those displacements, another type of diffusive ground motion was observed that has a noise character similar to Brownian random walk. Such a motion is responsible for the non-correlated displacement of points of the ground.

Because of the special interest that accelerator physicists have in the issue, several similar measurements were provided from several accelerator sites, including UNK in Russia, Stanford Linear Accelerator Center, and CERN, where displacements of magnetic elements were observed over several years. (See References 1, 2, 10–12.) Another source of information about slow ground displacements is long-term data on COD in large accelerators when all other machine parameters are precisely controlled. (See References 13 and 14.)

For approximation of these data an empirical formula for slow diffusive ground motion was proposed in References 1 and 2. It was further developed and applied to estimations of COD in References 12, 15, and 16, and it is now often referred to as the "ATL law."

According to this law, the relative rms displacement δx of two points located at distance L grows with the time interval between observations T as:

$$<\delta x^2> = ATL, \quad (1)$$

where A is a constant. Originally it was found that Eq. (1) with factor $A = (1.0 \pm 0.5)\cdot 10^{-4}\ \mu m^2/(s\cdot m)$ is in good agreement with data from accelerator sites within a broad range of time intervals T, from hours to a dozen years, and distances L, from a few meters up to a few kilometers. (See review in Reference 9.)

The PSD $S(f)$ in the frequency domain that corresponds to the ATL law is inversely proportional to the frequency squared:[9]

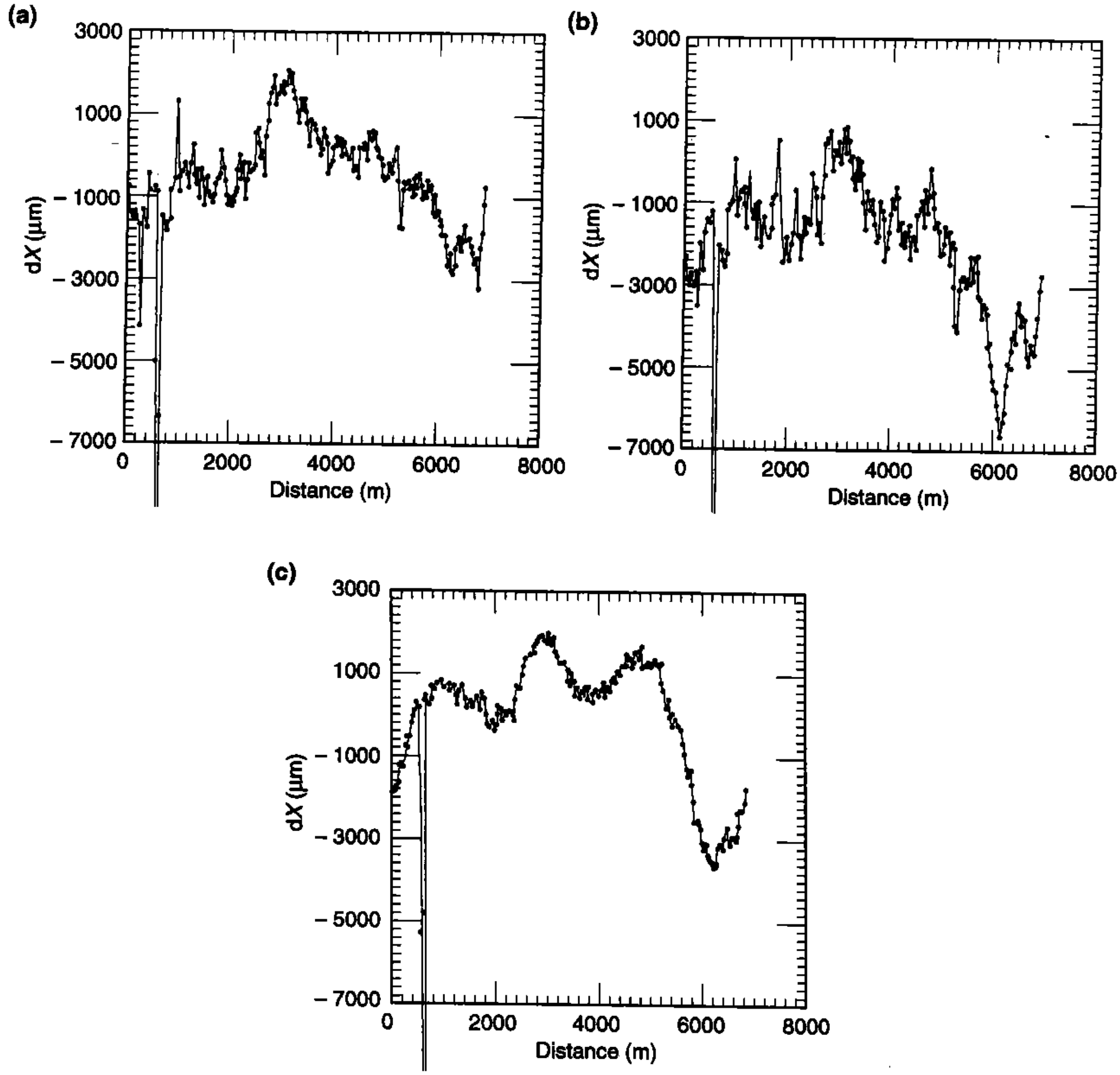
$$S(f) = \frac{AL}{2\pi^2 f^2}, \quad (2)$$

and the measurements in Reference 6 (L = 48 m) confirmed this, but there was mention that slow drifts in a 100-m-deep mine are about 10–20 times less than the same values in the TRISTAN tunnel at KEK.

This article is devoted to analysis of data from Reference 17 on displacements of quadrupoles in the tunnel of the Super Proton Synchrotron (SPS) at CERN, which lies at a depth of about 100 m in rock earth. In Section 2, we give a brief description of the SPS ring and the data observed. Methods and results of data analysis are contained in Section 3. Section 4 presents a discussion of results, comparison with other data and the ATL law, and brief conclusions.

2.0 SPS DATA ON QUADS DISPLACEMENTS

The SPS is an alternating gradient synchrotron constructed at CERN in the mid-1970s. It consists of M = 744 dipoles and N = 216 quadrupoles placed practically uniformly over the ring, with a mean radius R = 1100 m.[18] Primary data from an optical survey[17] represent the vertical displacement of two ends of each quadrupole relative to the theoretical "ideal" position of 1976. These values were measured three times at about 3-yr time intervals: March 1, 1985; February 3, 1988; and January 7, 1991. Accuracy of measurements is estimated to be within a few dozen micrometers. In this article we will refer to the measurements by the year in which they were taken. Values of drifts of two ends of each quadrupole differ from each other. Therefore we used the mean value for further analysis. Figure 1 shows the primary measured values of displacement x (in micrometers) along the circumference of the ring (*i.e.*, the point at 0 m placed close to the point at 6912 m). The values for a few quadrupoles at about 600 m are due to artificial displacement for the $p\bar{p}$ project at the injection point, and we didn't take these into consideration. A very few quadrupoles were especially displaced by much lower values during 1985–1991, and these were taken into account.



TIP-04872

Figure 1. (a) Displacements of quads along the circumference of the SPS in 1985.
(b) Displacements of quads along the circumference of the SPS in 1988.
(c) Displacements of quads along the circumference of the SPS in 1991.

3.0 METHODS AND RESULTS OF ANALYSIS

First we checked how the variance of relative displacements $(x_i - x_j)$ of two points i and j depends on the distance between them. The value, found mathematically, is represented as

$$\left\langle \delta x(L)^2 \right\rangle = \frac{1}{N} \sum_{(i,j)}^{N} \left(x_i - x_j\right)^2 , \tag{3}$$

where a summation was made over all possible $N = 216$ different pairs of points that are set L m apart. The natural quanta for $L << R = 1100$ m is the distance between two neighboring quadrupoles, 32 m. For bigger L, we took into account that an arc is always longer than a corresponding chord. It's easy to understand that the maximum distance that can be considered is equal to $2R = 2200$ m. During the development of data few relative displacements were found above the "3-sigma" threshold for statistical analysis, and they were not taken into account.

Figure 2(a) shows L dependence of the variance of quads motion that occurred from 1985 until 1988—*i.e.*, we investigated values $X = x_{1988} - x_{1985}$ for all magnets. The function that we found is well approximated by linear law BL. (See dashed line at Figure 2(a).) The best fit gives a coefficient $B = 1190\ \mu m^2/m$ for L smaller than 1000 m. (Best fit for L smaller than 500 m gives $B = 1830\ \mu m^2/m$.) The corresponding coefficient A in the ATL law may be calculated as $A = B/T$ ($T = 35$ months) and is equal to $A = 0.13 \cdot 10^{-4}\ \mu m^2/(s{\cdot}m)$. ($A = 0.2 \cdot 10^{-4}\ \mu m^2/(s{\cdot}m)$ for 500 m best fit.)

Figure 2(b) presents the same function for motion during $T = 3$ yr, from 1988 to 1991. The best linear fit gives $A = 0.13 \cdot 10^{-4}\ \mu m^2/(s{\cdot}m)$. This curve has significant deviation from the best linear fit. For example, the variance of relative displacements at 200 m is 3 times larger than the value of the best fit line (corresponding to $A = 0.4 \cdot 10^{-4}\ \mu m^2/(s{\cdot}m)$).

Similar calculations for motion during $T = 6$ yr, from 1985 to 1991, are summarized in Figure 2(c). Here the best linear fit with $A = 0.1 \cdot 10^{-4}\ \mu m^2/(s{\cdot}m)$ (see corresponding dashed line) perfectly approximates experimental data up to 1500 m.

Finally, a similar analysis was done for the 12-yr time interval from 1976 to 1988. (See Figure 2(d).) It was assumed that in 1976 all quads were set at "ideal" orbit positions. In spite of the fact that the best fit coefficient, $B = 3700\ \mu m^2/m$, is much bigger than that for the 3-yr measurements, the corresponding coefficient A in the ATL law has practically the same value, $A = 0.1 \cdot 10^{-4}\ \mu m^2/(s{\cdot}m)$.

Let us consider effects that may interfere with our analysis. Let us assume that a big part of the ring has a constant trend in magnet displacements due to measurement errors or tilt (or even that all the ring is tilted on some angle). It is easy to see that in this case the variance (Eq. (3)) will be proportional to the squared distance between points, L^2, especially at L more than R. None of the pictures presented in Figure 2 shows such a behavior; therefore, we may conclude that this effect is negligible. The second effect occurs if one erroneously takes into account one or a few points that strongly dropped from the array of other data and have no natural origin (like a big drop in Figure 1 around 600 m). This drop increases the variance at all values of L on the same value (even at small distances), and the best fit approximation will predict an unnatural non-zero value of the variance at $L = 0$ m. Again, Figure 2 shows that even if this effect exists it is pretty minor. Finally, a distortion of analysis may come from an absence of uniformity of quad settings along the circumference, which we took as an assumption. But in the case of SPS, where the number of non-regularly settled quads is negligible, the errors caused by them are also minor.

Figure 3 presents results of a Fourier transformation of the 1988 data—power of harmonics vs. its number m (the m-th harmonic has m wavelength over the circumference of the ring). For example, the harmonics number 1 with wavelength equal to the SPS circumference has rms amplitude of about 1 mm = 1000 μm, *i.e.*, its power is equal to $10^6\ \mu m^2$ (see Figure 3). This figure is interesting for two reasons: at first, it shows that the power of m-th harmonics is approximately inversely proportional to m^2, as it must be according to ATL law predictions.[9] (See dashed line at Figure 3.) Then, as was analytically shown in Reference 9, the COD is determined mostly by harmonics with numbers [ν] and N/2–[ν], where ν is the tune of the machine, N is the full number of quadrupoles, and the brackets mean the closest integer. Therefore, Figure 3 allows us to compare the strength of these two harmonics. The resonance harmonics for the SPS with ν = 26.6 (see Reference 18) are numbers 27 and 81. Resonant harmonics for the SSC with tune ν = 123.65 at this plot have effective numbers 10 and 64.

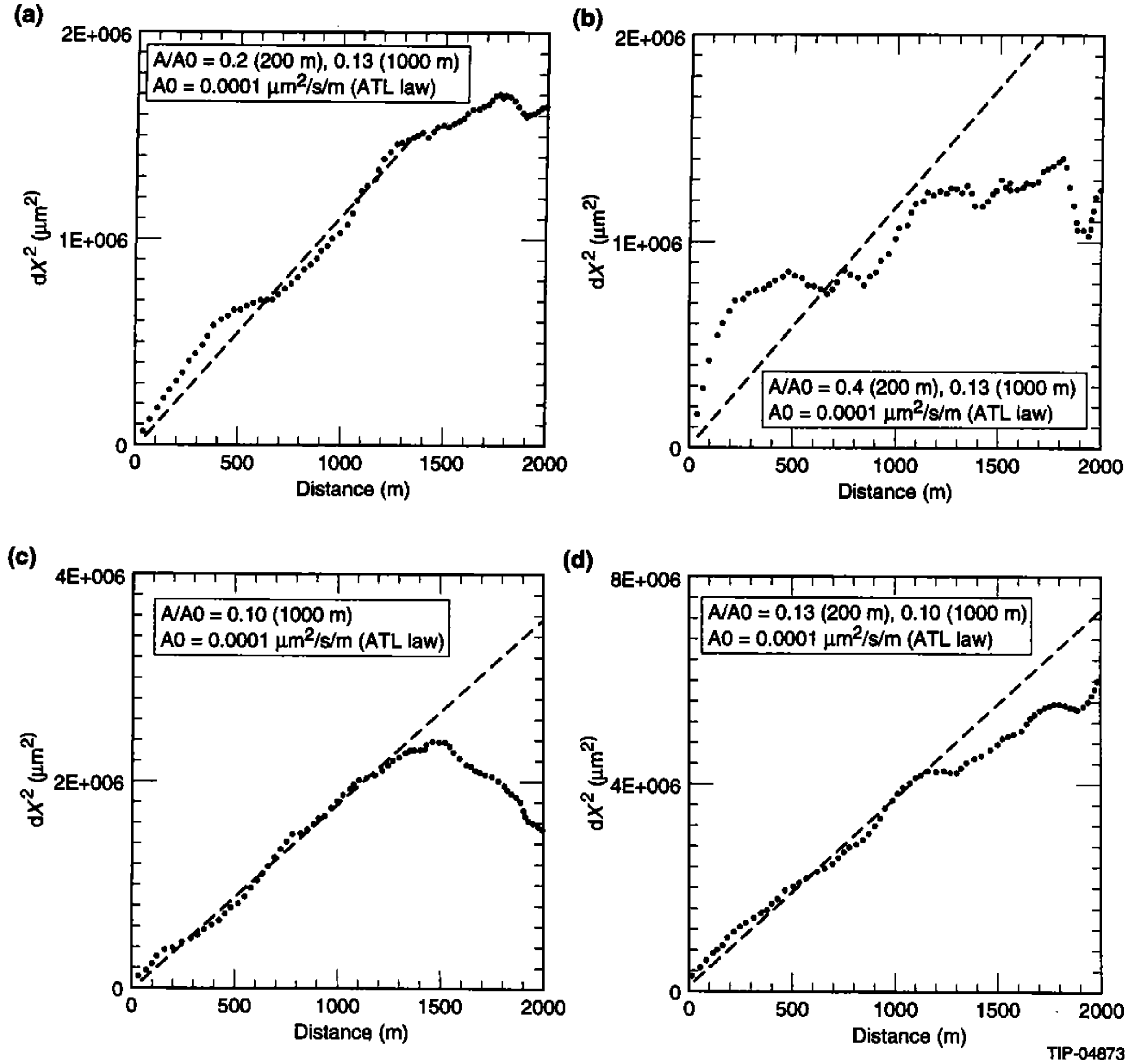


Figure 2. (a) The variance of relative displacements of quads that occurred 1985–1988 vs. distance between quads. (b) The variance of relative displacements of quads that occurred 1988–1991 vs. distance between quads. (c) The variance of relative displacements of quads that occurred 1985–1991 vs. distance between quads. (d) The variance of relative displacements of quads that occurred 1976–1988 vs. distance between quads.

Another result of data processing is distribution functions (probability densities) of relative displacements, for which the variances (Eq. (3)) were discussed above. This information is very useful for designing *maximal* strength of correctors for a machine. The distribution function of relative displacements for points distanced at 192 m and for motion from 1988 to 1991 is shown in Figure 4(a). Gaussian fit with the rms value found from this distribution function is also plotted. The lack of statistics (only 216 samples) allows us to make only general conclusions about the distribution. Nevertheless, if one assumes that the distribution functions have the same character for all distances L, then one can increase statistics by averaging all the distribution functions. However, each should be normalized on its own variance (as shown in Figure 2). As a result one can obtain the distribution function like that in Figure 4(b), but when the random variable is measured in units of rms value. The Gaussian fit in Figure 4(b) approximates well the 1985 experimental data. For a more detailed presentation of tails of distribution above 3 sigma, see Figure 5, where we present densities of probability for 1985, 1988, and 1991 measured values in logarithmic scale. One can see that the Gaussian function satisfactorily describes the core of the distribution, but the experimental results have tails above 3 sigma that are at least 2 times more populated.

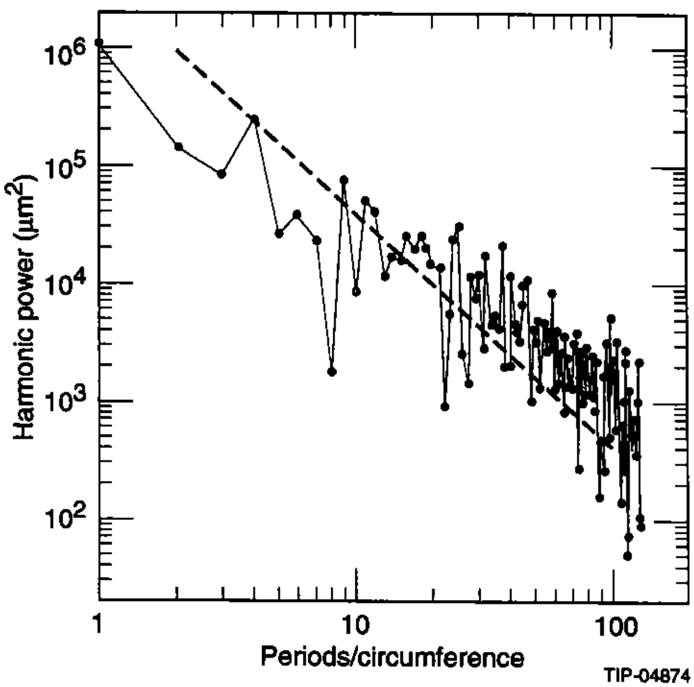


Figure 3. Spectrum of space harmonics found by Fourier transformation of primary 1988 data (*i.e.*, FFT of Figure 1(b)).

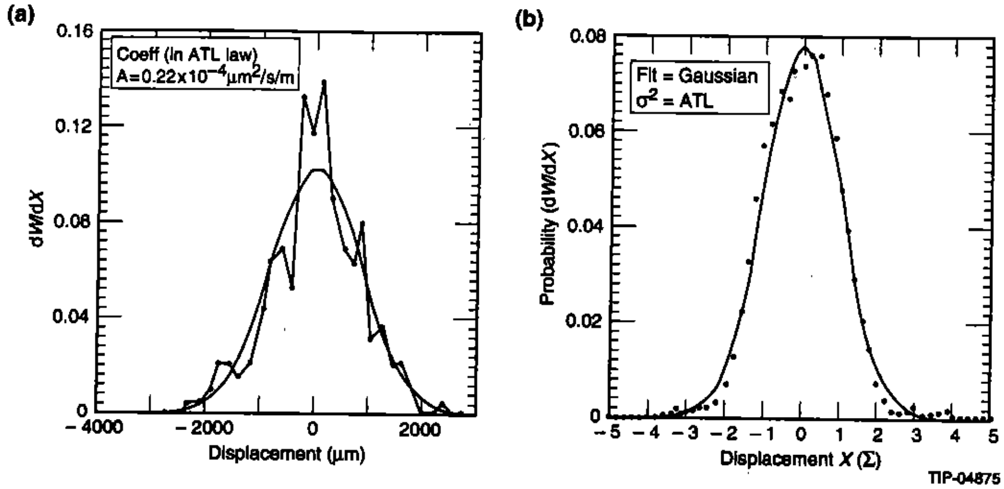


Figure 4. (a) Probability density vs. relative displacements of quads that occurred 1988–1991 for pairs of quads placed 192 m apart. (b) Probability density vs. normalized relative displacements of quads that occurred 1988–1991 for pairs of quads placed from $L = 32$ m to $L = 2200$ m apart. For each L, relative displacement was normalized on its own rms value (see Figure 2(b)).

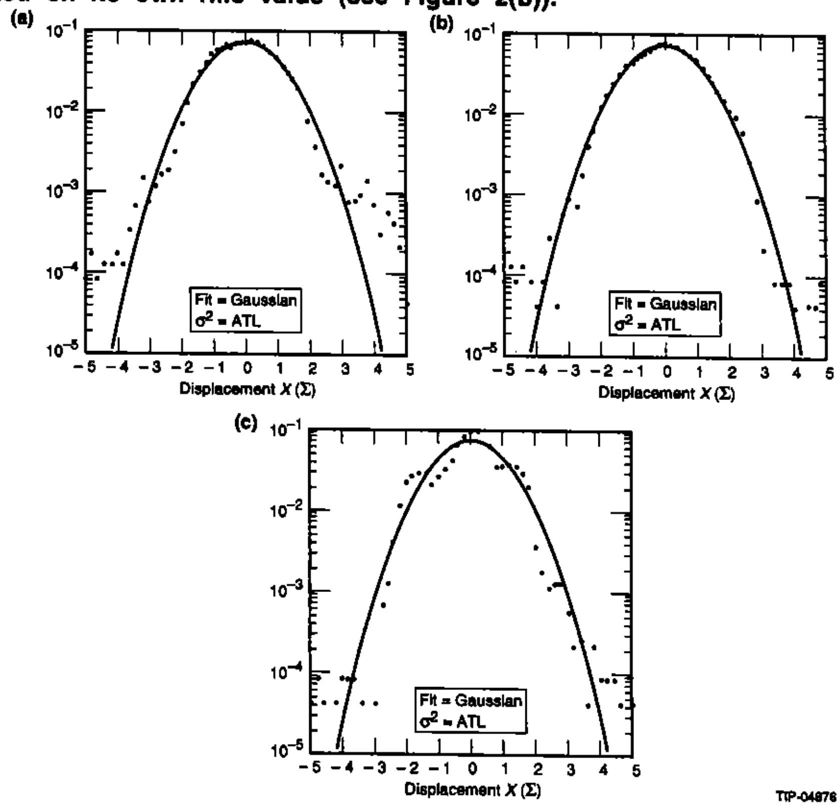


Figure 5. (a) Probability density vs. normalized relative displacements of quads that occurred 1976–1985 for pairs of quads placed from $L = 32$ m to $L = 2200$ m apart. For each L, relative displacement was normalized on its own rms value.
(b) Probability density vs. normalized relative displacements of quads that occurred 1976–1988 for pairs of quads placed from $L = 32$ m to $L = 2200$ m apart. For each L, relative displacement was normalized on its own rms value.
(c) Probability density vs. normalized relative displacements of quads that occurred 1976–1991 for pairs of quads placed from $L = 32$ m to $L = 2200$ m apart. For each L, relative displacement was normalized on its own rms value.

4.0 DISCUSSION, COMPARISON WITH OTHER DATA, AND CONCLUSIONS

Analysis of data from SPS has shown that the ATL law can be used to satisfy the model for the slow ground motion. The coefficient A was found from the range (0.1–0.4) $\cdot 10^{-4}$ $\mu m^2/(s \cdot m)$, with mean value of approximately $A_{SPS} = 0.14 \cdot 10^{-4}$ $\mu m^2/(s \cdot m)$.

In Figure 6 we present SPS data from 3 yr of observations (1985–1988), together with data from other accelerator sites (taken from Reference 9). Because of different times of observation for these data, they are presented as functions of the variance of displacement divided by time of observations vs. distance L between points of the ground. For comparison, the ATL law with coefficient $1.0 \cdot 10^{-4}$ $\mu m^2/(s \cdot m)$ is also shown by a dashed line. One can see that diffusive ground motion at the SPS is several times less than at other places. This can be explained by the comparably low depth of the SPS tunnel and the relatively hard rock at the CERN site. No measurements have yet been made in the SSC tunnels. When such measurements are made, we would expect that the value of A will lie between the value $0.14 \cdot 10^{-4}$ $\mu m^2/(s \cdot m)$ measured at the SPS and the value $1.0 \cdot 10^{-4}$ $\mu m^2/(s \cdot m)$ measured at the Positron-Electron Project (PEP) ring at Stanford.

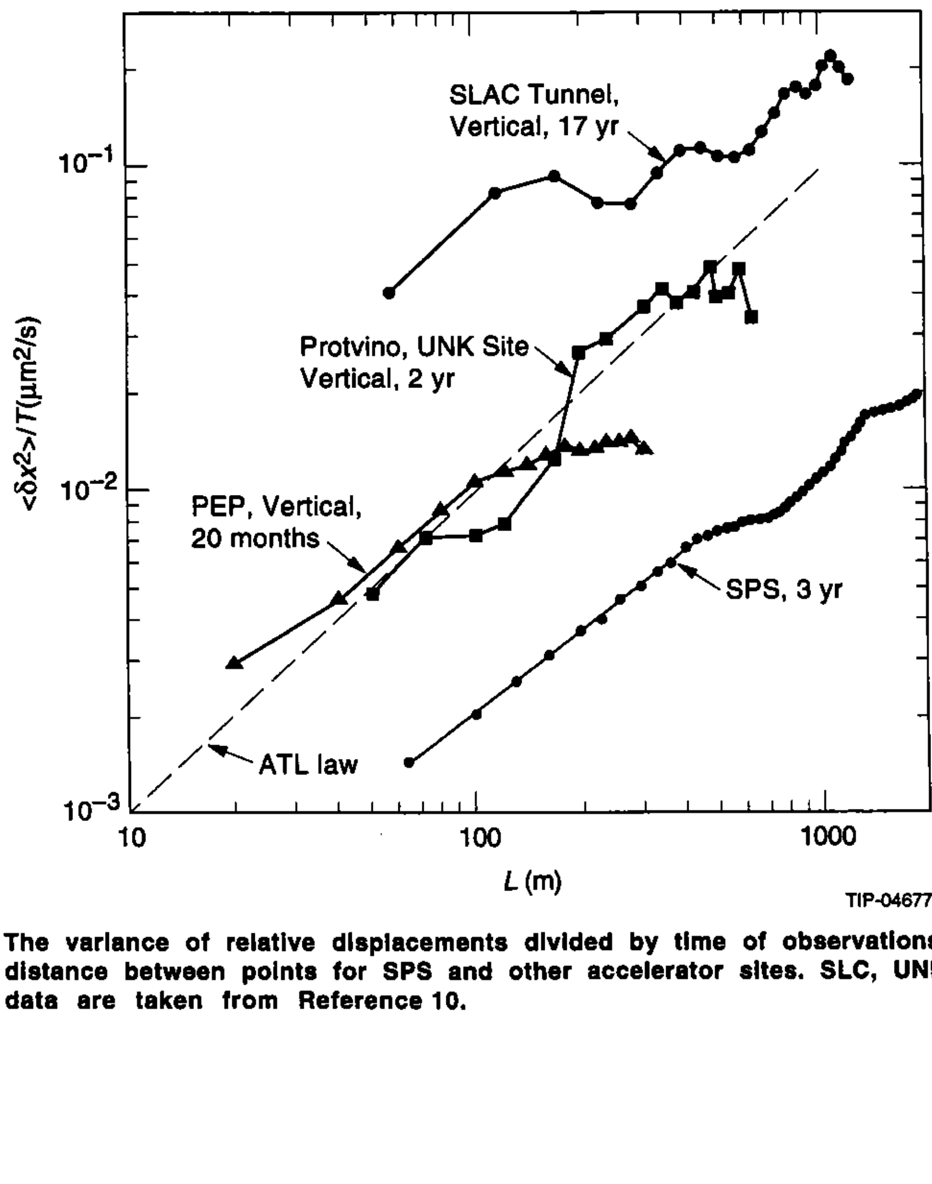


Figure 6. The variance of relative displacements divided by time of observations vs. distance between points for SPS and other accelerator sites. SLC, UNK, and PEP data are taken from Reference 10.

ACKNOWLEDGMENTS

The authors are grateful for many discussions with and suggestions from G. Bourianoff, M. Syphers, G. Stupakov, Y. Cai, and other participants of the SSC Interaction Regions weekly meetings. We thank J.P. Quesnel (CERN) for his kindly permission to use SPS data in our analysis. We are grateful to R. Meinke and D. Johnson for their steadfast interest in this work.

One of us (V.S.) deeply appreciates the constant collaborative work on long-term position stability of elements of large colliders with Vasily Parkhomchuk and Andrey Sery (Budker INP, Novosibirsk, Russia) and information exchange with Shigeru Takeda and Noboru Yamamoto (KEK, Japan) in the field of slow ground motion measurements at accelerator sites.

REFERENCES

1. B. Baklakov, P. Lebedev, V. Parkhomchuk, A. Sery, A. Sleptsov, and V. Shiltsev, "Investigation of Correlation and Power Characteristics of Earth Surface Motion in the UNK Site," Preprint INP 91-15, Novosibirsk, 1991 (in Russian).
2. B. Baklakov, P. Lebedev, V. Parkhomchuk, A. Sery, A. Sleptsov, and V. Shiltsev, "Investigation of Seismic Vibrations and Relative Displacements of Linear Collider VLEPP Elements," *Proc. of 1991 IEEE Part. Acc. Conf.*, San Francisco, 1991, p. 3273.
3. F. Wyatt, "Displacement of Surface Monuments: Horizontal Motion," *Journ. of Geophys. Res.*, Vol. **87**, No. B2, p. 979, February 1982.
4. S. Takeda *et al.*, "Vertical Displacement of the Base in TRISTAN," *Proc. of HEACC'92*, Hamburg, p. 406, July 1992.
5. V. Parkhomchuk, V. Shiltsev, and H.J. Weaver, "Measurements of Ground Motion Vibrations at the SSC," SSCL-Preprint-323, May 1993, and *Proc. of 1993 IEEE Part. Acc. Conf.*, Washington, DC, May 1993.
6. S. Takeda *et al.*, "Slow Drift and Frequency Spectra of Ground Motion," KEK-Preprint 93-61, July 1993.
7. V. Balakin *et al.*, "Measurements of Seismic Vibrations in CERN TT2A Tunnel for Linear Collider Studies," CLIC-Note-191, 1993.
8. J. Rossbach, "Closed Orbit Distortions of Periodic FODO Lattice Due to Plane Ground Waves," *Particle Accelerator Journal*, 1988, Vol. **23**, p.121.
9. V. Parkhomchuk, V. Shiltsev, and G. Stupakov, "Slow Ground Motion and Operation of Large Colliders," SSCL-Preprint-470, July 1993.
10. V. Parkhomchuk and G.E. Fischer in *Proc. of Workshop on Vibrational Control and Dynamic Alignment Issues at the SSC*, H.J. Weaver, ed., SSCL-SR-1185, Feb. 1985.
11. G.E. Fischer, "Ground Motion and Its Effect in Accelerator Design," SLAC-PUB-3392 Rev., 1985.
12. D. Martin, "Alignment at the ESRF," *Proc. of European Part. Acc. Conf. 1992*, p. 141.
13. R. Brinkmann and F. Willeke, "First Experience with Colliding e-p Beams in HERA," *Proc. of 1993 IEEE Part. Acc. Conf.*, Washington, DC, 1993.
14. H. Koiso, S. Kamada, and N. Yamamoto, "Observation of Changes of the COD in TRISTAN Main Ring," *Particle Accelerators Journal*, 1990, Vol. **27**, p. 71.
15. V. Parkhomchuk and V. Shiltsev, "Fractal Model of Ground," Preprint INP 92-31, Novosibirsk, 1992.
16. V.A. Lebedev, V.V. Parkhomchuk, V.D. Shiltsev, and A.N. Skrinsky, "Suppression of Emittance Growth Caused by Mechanical Vibrations of Magnetic Elements in Presence of Beam-Beam Effects in the SSC," Preprint INP 91-120, Novosibirsk, 1991.
17. J.P. Quesnel, Survey Group (CERN), private communication.
18. J. Bosser, ed., "Beam Instrumentation," CERN-PE-ED 001-92, p. 34, 1992.