SLAC-PUB-8595
August 2000
physics/0008192

Ground Motion Model of the SLAC Site

Andrei Seryi, Tor Raubenheimer

Presented at the 20th International Linac Conference (Linac 2000),
8/21/2000—8/25/2000, Monterey, CA, USA

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Work supported by Department of Energy contract DE–AC03–76SF00515.

Ground Motion Model of the SLAC Site *

Andrei Seryi, Tor Raubenheimer

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309 USA

Abstract

We present a ground motion model for the SLAC site. This model is based on recent ground motion studies performed at SLAC as well as on historical data. The model includes wave-like, diffusive and systematic types of motion. An attempt is made to relate measurable secondary properties of the ground motion with more basic characteristics such as the layered geological structure of the surrounding earth, depth of the tunnel, etc. This model is an essential step in evaluating sites for a future linear collider.

1 INTRODUCTION

In order to accurately characterize the influence of ground motion on a linear collider, an adequate mathematical model of ground motion has to be created. An adequate model would require an understanding of the temporal and spatial properties of the motion and identification of the driving mechanisms of the motion. Eventually these must be linked to more general properties of a site like geology and urbanization density. In this paper, we consider one particular model based on measurements performed at the SLAC site [1, 2, 3, 4, 5]. We use this model to illustrate existing methods of modeling, as well as potential problems and oversimplifications in the modeling techniques. In our particular case, the representation of the cultural noise, especially that generated inside the tunnel, is difficult to incorporate. However, the model provides a foundation to which many additional features can be added.

In general, the ground motion can be divided into 'fast' and 'slow' motion. Fast motion ($f \gtrsim$ a few Hz) cannot be adequately corrected by a pulse-to-pulse feedback operating at the repetition rate of the collider and therefore results primarily in beam offsets at the IP. On the other hand, the beam offset due to slow motion can be compensated by feedback and thus slow motion ($f \lesssim 0.1$) results only in beam emittance growth. Another reason to divide ground motion into fast and slow regimes is the mechanism by which relative displacements are produced that appears to be different with a boundary occuring around 0.1 Hz. In the following, we will first describe the 'fast' motion and then we will present the 'slow' motion which includes both diffusive and systematic components.

2 FAST GROUND MOTION

Modeling of the ground motion requires knowledge of the 2-D power spectrum $P(\omega, k)$. The fast motion is usually represented by quantities that can be measured directly: the spectra of absolute motion $p(\omega)$ and the correlation $c(\omega, L)$ which shows the normalized difference in motion of two points separated by distance L. The spectrum of relative motion $p(\omega, L)$ can be written as $p(\omega, L) = p(\omega)2(1 - c(\omega, L))$ which in turn can be transformed into $P(\omega, k)$ [9].

Measurements [2, 6] show that the fast motion in a reasonably quiet site consists primarily of elastic waves propagating with a high velocity v (of the order of km/s). The correlation is then completely defined by this velocity (which may be a function of frequency) and by the distribution of the noise sources. In the case where the waves propagate on the surface and are distributed uniformly in azimuthal angle, the correlation is given by $c(\omega, L) = \langle \cos(\omega L/v \, \cos(\theta)) \rangle_\theta = J_0(\omega L/v)$ and the corresponding 2-D spectrum of the ground motion is $P(\omega, k) = 2p(\omega)/\sqrt{(\omega/v(f))^2 - k^2}$, $|k| \leq \omega/v(f)$.

The absolute power spectrum of the fast motion, assumed for the SLAC model, corresponds to measurements performed at 2 AM in one of the quietest locations at SLAC, sector 10 of the linac [2], (see Fig.1). The spatial properties are defined by the phase velocity found from correlation measurements $v(f) = 450 + 1900\exp(-f/2)$ (with v in m/s, f in Hz) [2].

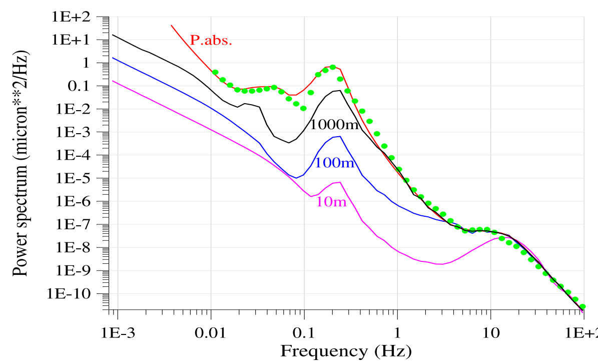

Figure 1: Measured [2] (symbols) and modeling spectra $p(\omega)$ of absolute motion and $p(\omega, L)/2$ spectra of relative motion for the 2 AM SLAC site ground motion model.

We believe that the frequency dependence of the measured phase velocity $v(f)$ is explained by the geological structure of the SLAC site where, as is typical, the ground rigidity and the density increase with depth. The surface motion primarily consists of transverse waves whose phase velocity is given by $v_s \approx \sqrt{E/(2\rho)}$ and which are localized within one wavelength of the surface. If one plots the quantity v^2/λ versus wavelength λ, we see that this value is almost constant, varying from 3000m/s^2 at $\lambda = 100$m to 2000m/s^2 at $\lambda = 1000$m. This is consistent with a ground density at the SLAC site that ranges from $1.6 \cdot 10^3$ within the upper 100 m to $2.5 \cdot 10^3$kg/m^3 at a kilometer depth and a Young's modulus E which increases from 10^9Pa at 100 m to 10^{10} Pa at 1000 m. These results seem to be quite reasonable for the SLAC geology, and, as we will see below, they also agree with explanations of the observed slow motion.

* Work supported by the U.S. Department of Energy, Contact Number DE-AC03-76SF00515.

3 SLOW GROUND MOTION

Based on the arguments above, the wavelength at frequencies below 0.1 Hz quickly becomes much larger than the accelerator and eventually exceed the earth's size. In this case, the motion has little effect on the accelerator and at some point the notion of waves is not really applicable. Causes other than the wave mechanism must be responsible for producing relative misalignments that are important at low frequencies. Such sources include the variation of temperature in the tunnel, underground water flow, spatial variation of ground properties combined with some external driving force, etc. These causes can produce misalignments with rather short wavelength in spite of their low frequencies.

The ATL model of diffusive ground motion [7] is an attempt to describe all these complex effects with a simple rule which states that the variance of the relative misalignment ΔX^2 is proportional to a coefficient A, the time T and the separation L: $\Delta X^2 = ATL$. In the spectral representation this rule can be written as $P(\omega, k) = A/(\omega^2 k^2)$. It has been shown [10] that this rule adequately describes available measured data in many cases, however, typically only spatial or temporal information, but not both, was taken for a particular data set. Measurements where good statistics were collected, both in time and space and in a relevant region of parameter space, are sparse and difficult to perform. Thus, detailed investigation of slow motion is an urgent issue for future studies.

The diffusive component of the ground motion model considered is based on measurements of slow motion performed at SLAC. First, measurements performed in the FFTB tunnel using the stretched wire alignment system over a baselength of 30 m give the value of $A \approx 3 \cdot 10^{-7} \mu$m^2/(m·s) on a time scale of hours [3]. Second, a 48 hour measurement of the linac tunnel motion performed with the linac laser alignment system over a baselength of 1500 m gave $A \approx 2 \cdot 10^{-6} \mu$m^2/(m·s) [4]. Finally, recent measurements using a similar technique were made over a period of one month and show that $A \approx 10^{-7}$–$2 \cdot 10^{-6} \mu$m^2/(m·s) for a wide frequency band of 0.01–10^{-6}Hz [5]. In the latter case, the major source of the slow $1/\omega^2$ motion was identified to be the temporal variations of atmospheric pressure coupled to spatial variations of ground properties [5]. The atmospheric pressure was also thought to be responsible for a slow variation of the parameter A.

The clear correlation of atmospheric pressure variation with deformation of the linac tunnel, observed in [5], can only be explained if one assumes some variation of the ground properties along the linac. This variation can be due to changes in the Young's modulus E, changes in the topology such that the normal angle to the surface changes by $\Delta\alpha$, or changes in the characteristic depth h of the softer surface layers. A rough estimate of the tunnel deformation due to variation of atmospheric pressure ΔP can be expressed as

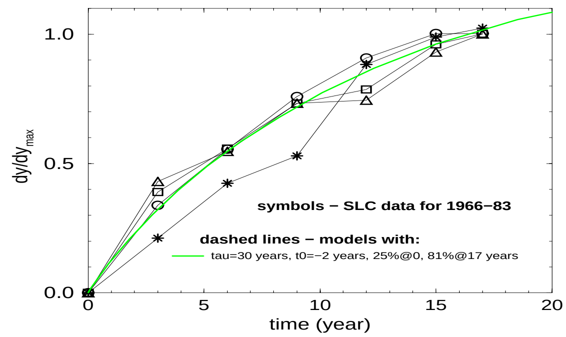

Figure 2: Displacement of some points of SLAC linac tunnel from 1966 through 1983 versus time and the approximation in Eq. (2) with $\tau = 30$ and $t_0 = 2$ years.

$$\Delta X, Y \sim \quad h\frac{\Delta P}{E} \cdot \left(\frac{\Delta E}{E} \quad \text{or} \quad \Delta\alpha \quad \text{or} \quad \frac{\Delta h}{h} \right) \quad (1)$$

The observed deformation of the tunnel $\Delta Y = 50\mu$m corresponding to $\Delta P = 1000$ Pa is consistent with this estimation if $\Delta E/E{\sim}0.5$, $\Delta\alpha \sim 0.5$ or $\Delta h/h{\sim}0.5$ and if one assumes $E/h \sim 10^7$Pa/m. The former assumption is consistent with the heterogeneous landscape and geology at SLAC while the latter appears to agree well with the properties of the ground determined in the previous SLAC correlation measurements, if one assumes that $h \sim \lambda$.

No direct conclusions can be drawn from the measurements [5] to determine the spatial behavior of the observed slow motion because the relative motion was only measured for one separation distance. However, the topology of many natural surfaces (including landscapes) exhibits a $1/k^2$ behavior of the power spectra [11]. Thus, it seems reasonable to expect that temporal pressure variation can also be a driving term of the spatial ATL-like motion. Furthermore, the measured parameter A can be extended from 1500 m to a shorter scale, without contradicting the very short baseline measurements [3] which produced a similar value of A.

It is also worth noting that the contribution to the parameter A driven by the atmosphere scales as $1/E^2$ or as v_s^4 and therefore strongly depends on geology. Thus, the parameter A, at a site with a much higher v_s, would not be dominated by atmospheric contributions, while a site with softer ground and a v_s half that at SLAC, may have a parameter A as high as $3 \cdot 10^{-5} \mu$m^2/(m·s).

Finally, very slow motion, observed on a year-to-year time scale at SLAC, LEP, and other places, appears to be

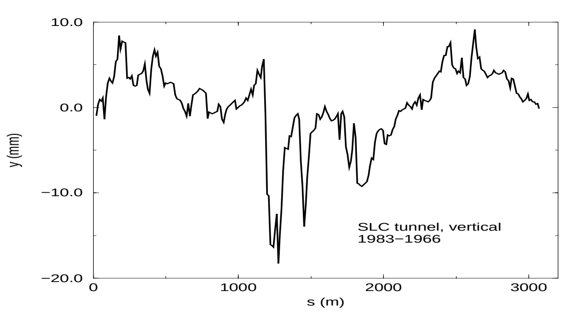

Figure 3: 17 year motion of the SLAC linac tunnel [1].

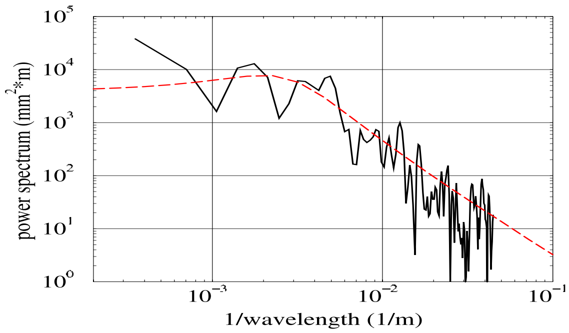

Figure 4: Spatial power spectrum of vertical displacements of the SLAC tunnel for 1966 to 1983.

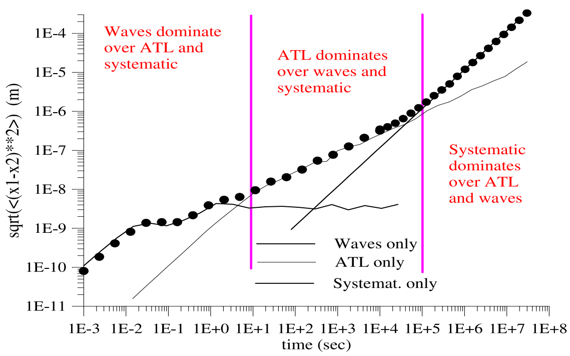

Figure 5: Rms relative motion versus time for $L = 30$ m for the 2 a.m. SLAC site ground motion model.

systematic in time, i.e. $\Delta X^2 \propto T^2$ [12]. For example, measurements of the SLAC linac tunnel between 1966 and 1983 [1] show roughly linear motion in time with rates up to 1mm/year in a few locations along the linac. Subsequent measurements indicate that the rate of this motion has decreased over time although the direction of motion is still similar as is illustrated in Fig. 2. In the case of SLAC, the motion may have been caused primarily by settling effects, while in LEP, the cause may more likely be something different such as underground water [12].

The temporal dependence of earth settlement problems typically are approximated as:

$$\frac{\Delta y}{\Delta y_{\max}} \approx 1 - \left(1 - \frac{\sqrt{t/\tau}}{(1+2\sqrt{t/\tau})}\right) \exp(-2.36\, t/\tau) \quad (2)$$

where the typical value of τ is years. This type of solution exhibits $\sqrt{t}$ motion at the beginning which then slows and exponentially approaches $\Delta y_{\max}$. An example of such a dependence is compared with the motion observed at SLAC in Fig. 2. One can see that the early SLAC systematic motion can be also described reasonably well by a linear in time motion, though nowadays the rate of the motion should be already much lower.

The spatial characteristics of this systematic motion also seem to follow the $1/k^2$ (or $\Delta X^2 \propto L$) behavior. This is evident in the displacements of the SLAC linac [1] after 17 years which is shown in Fig. 3. The corresponding spatial spectrum is shown in Fig. 4 and it follows $1/k^2$ in the range of λ from 20–500m. Although there is deviation from the $1/k^2$ behavior at long wavelengths where there is limited data, this spectrum can be characterized as $P_{\rm syst}(t,k) \approx A_{\rm syst} t^2/k^2$ with the parameter $A_{\rm syst} \approx 4 \cdot 10^{-12} \mu{\rm m}^2/({\rm m}\cdot{\rm s}^2)$ for early SLAC. An estimate of the rms misalignment due to this systematic motion is then $\Delta X^2 = A_{\rm syst} T^2 L$. One can see that the transition between diffusive and systematic motion would occur at $T_{\rm trans} = A/A_{\rm syst}$ which in our case, assuming the value $A = 5 \cdot 10^{-7} \mu{\rm m}^2/({\rm m}\cdot{\rm s})$ for the diffusive component of the SLAC ground motion model, would happen at about $T_{\rm trans} \approx 10^5$ s.

The SLAC ground motion model includes all of the features that we have described. The transition from the ‘fast’ to the ‘slow’ motion is handled in a manner described in Ref. [9]. The absolute spectrum $p(\omega)$ and the spectrum of relative motion $p(\omega, L)$ are shown in Fig. 1. The systematic motion is not seen in this figure as it corresponds to much lower frequencies. However, it is seen in Fig. 5 where the rms ΔX is calculated for $L = 30$ m by direct modeling of the ground motion using harmonic summation [15]. One can see that this curve can be divided into three regions: wave dominated ($T \lesssim 10$ s), ATL-dominated ($10 \lesssim T \lesssim 10^5$ s) and systematic motion dominated ($T \gtrsim T_{\rm trans} \sim 10^5$ s).

This ground motion model is included in the PWK module of the final focus design and analysis code FFADA [13] which can perform analytical evaluations using the model spectra. The model is also included in the linac simulation code LIAR [14] where the summation of harmonics is used for direct simulations of the ground motion.

4 CONCLUSION

We have presented a model of ground motion for the SLAC site. This model includes fast, diffusive and systematic motion with parameters that are consistent with the known geological structure of the SLAC site. It is being now used to study the performance of the various systems in the Next Linear Collider.

We would like to thank C.Adolphsen, G.Bowden, M.Mayoud, R.Pitthan, R.Ruland, V.Shiltsev, and S.Takeda for various discussions of ground motion issues.

5 REFERENCES

[1] G.Fischer, M.Mayoud, CERN-LEP-RF-SU-88-07, 1988.
[2] NLC ZDR Design Group, SLAC Report-474 (1996).
[3] R. Assmann, C. Salsberg, C. Montag, SLAC-PUB-7303, in Proceed. of Linac 96, Geneva, (1996).
[4] C. Adolphsen, G. Bowden, G. Mazaheri, in Proc. of LC97.
[5] A. Seryi, EPAC2000, also in this proceedings.
[6] V.M. Juravlev et al. CERN-SL-93-53.
[7] B.Baklakov, et al. Tech. Phys. **38**, 894 (1993).
[8] C.Montag, V. Shiltsev, et al., DESY HERA 95-06, 1995.
[9] A. Sery, O. Napoly, Phys.Rev. E **53**, 5323, (1996).
[10] V. Shiltsev, in Proc. IWAA95, KEK-95-12, 1995.
[11] R. Sayles, T. Thomas, Nature, **271**, February 2, (1978).
[12] R.Pitthan, SLAC-PUB-7043,8286, 1995,1999.
[13] O. Napoly, B. Dunham, in Proceed. of EPAC94, 1994.
[14] R. Assmann, et al., in Proceed. of PAC97, 1997.
[15] A. Sery, in Proceed. of Linac 1996.