LONG-PERIOD GROUND MOTIONS FROM DIGITAL ACCELERATION RECORDINGS: A NEW ERA IN ENGINEERING SEISMOLOGY

David M. Boore
U.S. Geological Survey, MS 977, 345 Middlefield Road, Menlo Park, CA 94025

Abstract: Digital strong-motion instruments allow routine recovery of ground motions at periods much longer than possible with older analog instruments, and under favorable conditions it may be possible to recover the residual displacements near earthquakes, particularly if both the rotational and translational components of motion are recorded (currently only the translational components are recorded). In practice, however, digital recordings are commonly plagued by drifts in the velocity and displacement traces obtained by integrating the recorded acceleration traces. Various baseline-correction schemes can be designed that give the appearance of removing these drifts. Although comparisons with independent measures of residual displacements, such as from GPS or InSAR measurements, show that such schemes can work, in general the sources of the drifts are such as to prevent routine corrections for the baseline problems; removal of low-frequencies by filtering is then required for many recordings. That is the bad news. The good news is that the filter corners can be so low that little of engineering interest is lost. Recent data from several earthquakes (e.g., 1999 Hector Mine and 2002 Denali) shows that for displacement response spectra, the transition from increasing to constant spectral levels occurs at significantly longer periods than in Eurocode 8; the transition period is in good agreement, however, with the recent 2003 NEHRP code.

Key words: `Long-period, displacements, displacement response spectra, digital accelerographs`

1.   INTRODUCTION

There are many benefits of digital recordings over the older analog recordings. The most obvious of these advantages is that the data are available for processing much more quickly than before. But another important advantage is that the resolution of the recordings is usually higher for digital than for analog recordings.   The typical digitization of an analog record has a maximum resolution of 2 cm/s^2, whereas digital instruments with ± 2g full scale recording have resolutions from about 1 cm/s^2 for 12-bit analog-to-digital conversion (ADC) to 0.0002 cm/s^2 for 24-bit ADC.   The Fourier acceleration spectrum decreases at long period, and thus the higher resolution should allow data at longer periods to be obtained than from analog recordings. These longer period data are useful in defining residual displacements, long-period site response and basin waves, as well as the long-period behavior of displacement response spectra and the strains within structures. An example of a digital recording of acceleration and the velocity and displacement obtained by straightforward integration of the acceleration (after filtering to remove long-period drifts) is given in Figure 1. Note the low amplitudes and the clear presence of basin waves (due to propagation across part of the Los Angeles basin).
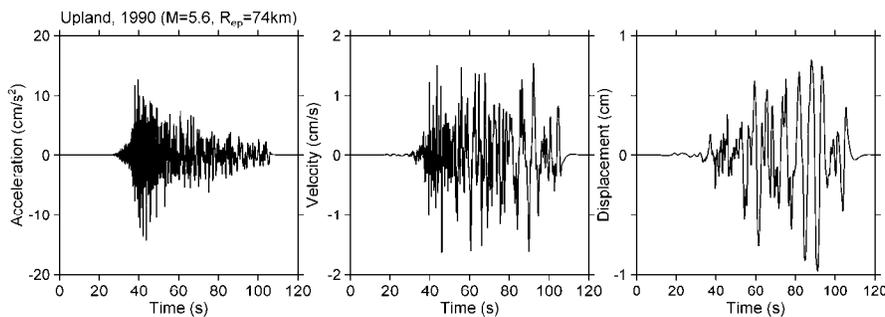

Figure 1. Acceleration, velocity, and displacement time series for one horizontal component of a 16-bit recording of the 1990 Upland earthquake, with a 0.1 Hz acausal low-cut filter. The waves traveling to the station have traversed part of the Los Angeles basin, and therefore large surface waves are present on the displacement time series. (From Boore, 2004a.)

2. POTENTIAL AND REALITY: LONG-PERIOD "NOISE"

Under the most ideal circumstances, with no instrumental or physical sources of long-period noise, the potential for obtaining long-period information is controlled by the number of bits used in the analog-to-digital converter (ADC) and the signal amplitude (assuming that the transducer is not the limiting factor). One measure of the potential is given by the accumulated error in the displacement trace from random digitizing errors in the acceleration trace. The expected error in the final displacement derived from double integration of a suite of digitizations will be zero, but as in a random-walk process, any single realization will show a drift in the displacement. The standard deviation of the final displacement after double integration for a length of time is a measure of the error in the displacement due to digitizing the acceleration time series. Using the equations in Boore et al. (2002), the standard deviation of the final displacement after double integration of a 200 sps acceleration time series for 100 s would be 11 cm, 1 cm, and 0.003 cm for 12-bit, 16-bit, and 24-bit ADC of recordings with a full scale of ±2g, respectively. The actual drifts in displacements obtained by double integration are often much larger than this (e.g., Boore, 2001, Boore et al., 2002, Wang et al., 2003). This indicates that the theoretical potential is usually not realized because a number of other sources of long-period noise may be present in digital recordings. By "noise" I mean undesired energy in the time series, whether it be due to instrumental instabilities, the effect of ADC on the baseline (Boore, 2003), or the effect of ground tilt and rotation (thereby putting a small component of gravitational acceleration onto the horizontal sensor, as discussed, for example, by Graizer, 1989, and Trifunac and Todorovska, 2001). Even with the presence of long-period noise, however, digital recordings are a significant improvement over analog recordings.

The long-period noise can be removed in several ways: making baseline corrections, filtering, or a combination of both.

2.1 Using Baseline Corrections to Remove Long-Period Noise

A number of methods for correcting for baseline variations have been used in the processing of strong-motion recordings. These usually have little physical basis and largely amount to fitting low-order polynomials to the velocity time series. Another method that is motivated by physical

causes for baseline offsets was proposed by Iwan et al. (1985), with modifications by Boore (2001). But as shown in Figure 2, the residual displacements can be sensitive to a parameter t_2 in the baseline correction (t_2 is the time at which any accumulated baseline shifts have ceased; see Boore, 2001, for details) . The displacement response spectrum, however, is relatively insensitive to the parameter t_2 at periods of usual engineering concern (Figure 3).
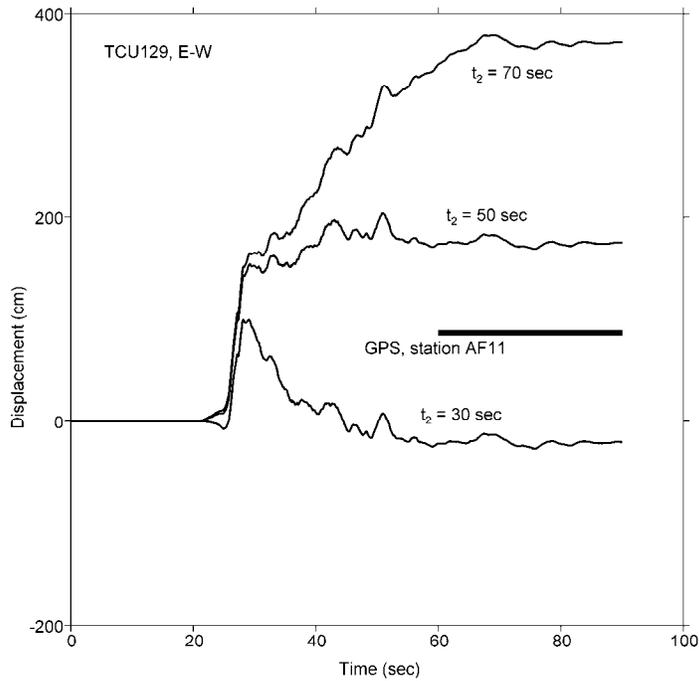

Figure 2. Displacements obtained by double integration of the EW component of acceleration recorded at TCU129 and modified using three values of t_2 to correct for baseline shifts. The GPS level was obtained at a station 2.3 km from TCU129, on the foot wall side of the fault (as is TCU129). (Modified from Boore, 2001.)
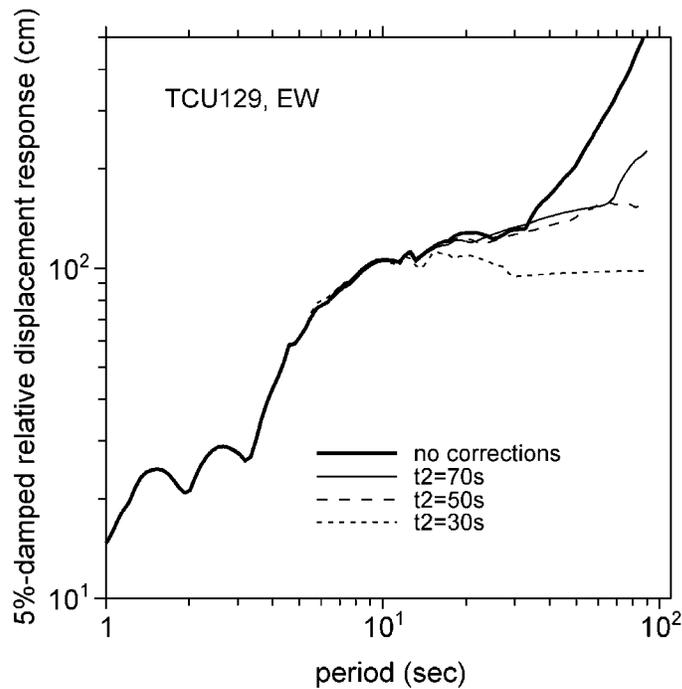
Figure 3. Displacement response spectra corresponding to processing shown in the previous figure.

2.2 Using Low-Cut (High-Pass) Filtering to Remove Long-Period Noise

Although baseline corrections result in removal of some long-period noise, often low-cut filtering is needed as well. In many cases, filtering is all that is needed, and filtering has the advantage that the effect in the frequency domain is more apparent than when baseline corrections are used.   As discussed by Boore and Akkar (2003), acausal (phaseless) filtering is preferred to causal filtering. An example of the velocity and displacement time series obtained by integration of an acceleration time series that was filtered using different filter corners is given in Figure 4.   The displacement waveforms and peak displacements are sensitive to the filter corners, but as shown in Figure 5, the displacement response spectrum is insensitive to the filter corners at periods of engineering interest when the amplitude of the

signal at long periods allows the use of relatively low-frequency filter cutoffs.

The increased resolution of digital instruments allows the low-cut filter corners to be chosen at lower frequencies, in general, than for analog recordings. This is shown in Figure 6 (plotted in terms of period rather than frequency).
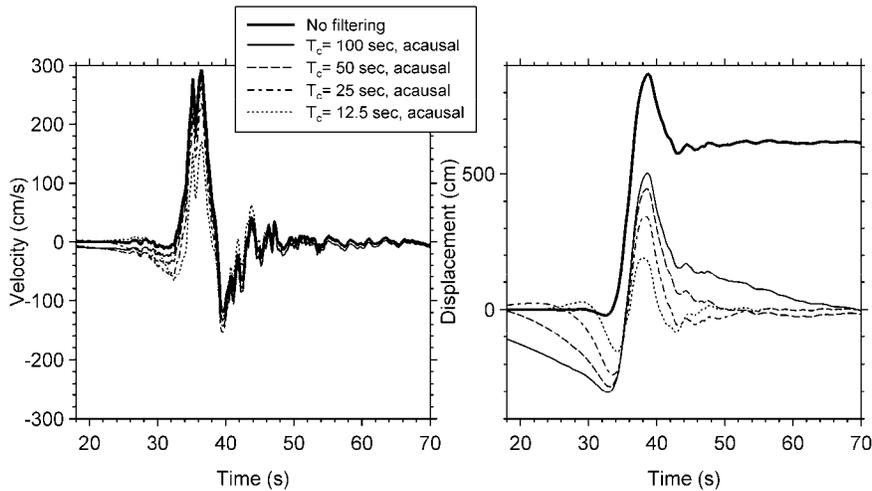

Figure 4. The velocity and displacement time series derived from the TCU068 recording. In all cases a simple baseline correction (the "v0" correction of Boore, 2001) was used, with and without filtering. The filters were low-cut acausal Butterworth filters having filter corner periods of 12.5, 25, 50, and 100 sec.
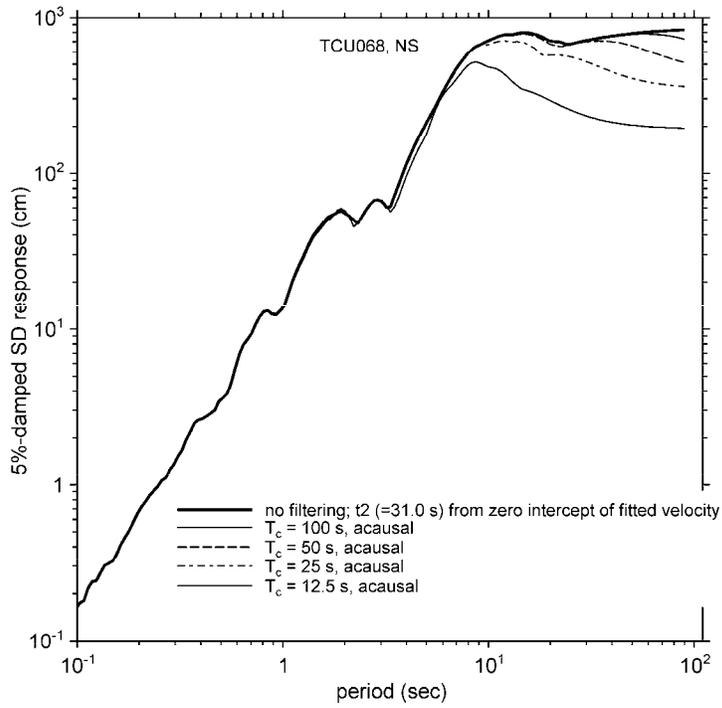
Figure 5. 5%-damped relative displacement response spectra for the time series processed using acausal filters.
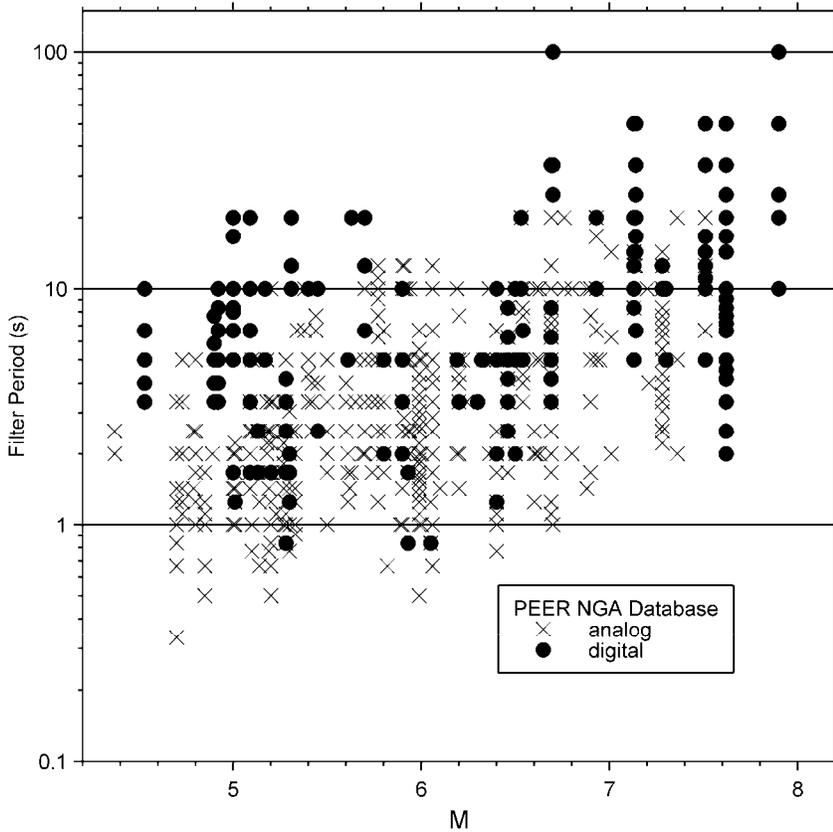
Figure 6. Filter period vs. moment magnitude, with data from analog and digital instruments indicated by the symbols. An effort has been made to determine whether each recording was obtained from an analog or a digital instrument, but there are undoubtedly a few errors. The filter for which the period is given removes long-period energy from the record, and the filter periods are those in a database being developed for use in the Pacific Earthquake Engineering Research Center (PEER) New Generation Attenuation (NGA) project. An attempt has been made in developing the PEER NGA database to apply uniform processing to all records. Some of the recordings, such as the analog recordings of the **M** 7.4 Tabas, Iran earthquake, may have had significant amounts of long-period noise removed by the use of baseline corrections, in which case the filter period is not a good measure of the long-period content of the record. For this reason the Tabas data are not shown here. In some other cases, such as the **M** 7.6 1999 Chi-Chi, Taiwan earthquake, longer filter periods could have been chosen.

3. SPATIAL SIMILARITY OF DISPLACEMENT WAVEFORMS: DEVELOPING CONFIDENCE IN LONG-PERIOD MOTIONS

As shown by Hanks (1975), a good way of judging the adequacy of the processing at long periods is to compare the displacement waveforms for stations within small distances of one another. The idea here is that long-period motions have wavelengths so large that the motions will be insensitive to site-to-site variations in geology (and thus site response). An example from the 1999 Hector Mine earthquake is shown in Figure 7. Note that the variations in the velocity waveforms are larger than in the displacement waveforms, as would be expected because the high frequencies in velocity waveforms are more sensitive to variations in near-surface geology.
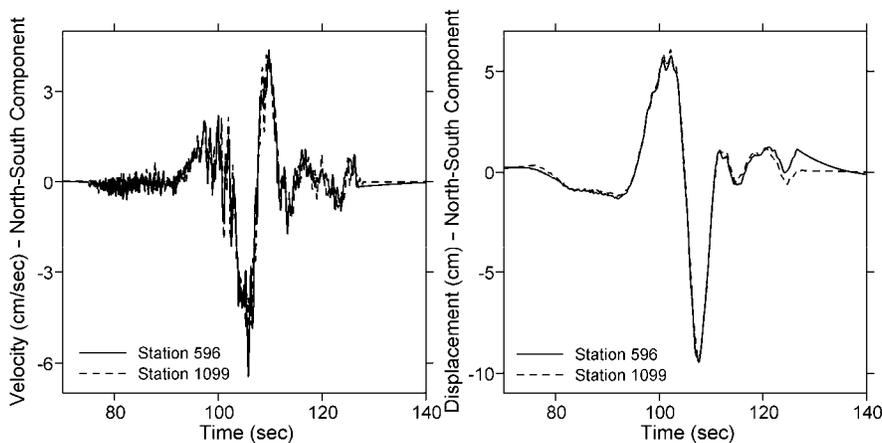

Figure 7. Comparison of velocities and displacements for two closely spaced (1.6 km) stations that recorded the 1999 Hector Mine, California, earthquake. The recorded accelerations from which the velocities and displacements are derived were processed using a constrained quadratic fit to velocity, followed by acausal filtering with a corner frequency of 0.02 Hz. The traces are aligned using time shifts derived by visually aligning the large pulse to the south on the

```
displacement trace.   (From Boore et al., 2002, but using
acausal rather than causal filtering.)
```

4.   DISPLACEMENT RESPONSE SPECTRA (SD) AND BUILDING CODES

The ability to determine motions at longer periods than before has an important application in displacement-based design (Bommer and Elnashai, 1999; Faccioli et al., 2004).   An important consideration in seismic design codes is the period at which the displacement response spectrum (SD) no longer increases. As seen in Figure 8, this period can exceed 10 seconds. Theoretical seismic source scaling can be used as a guide to the period at which SD flattens.   A single corner period model predicts the transition period as a function of moment magnitude shown in Figure 9, but Atkinson and Boore (1998) show that this model is not in agreement with the relation between surface wave magnitude and moment magnitude for large earthquakes. In better agreement with the magnitudes are two-corner-period models, such as the model of Atkinson and Silva (2000) shown in Figure 9. If the smaller of the two corner periods (corresponding to the line labeled f_b in Figure 9) is taken as the start of the transition of SD to a constant value, then Figure 9 shows that digitally-recorded data should be able to capture this transition period.

Figure 10 compares SD from several recent codes with that from the M 7.9 Denali Fault, Alaska, earthquake.   Clearly the comparison with the recent 2003 NEHRP code is much better than with either the 2000 NEHRP code, for which SD increases without limit, or Eurocode 8, for which the transition period to a constant SD is too short.   The transition period in the 2003 NEHRP code is taken from maps, and the values in the maps are based on the modal magnitude from disaggregation of 2%-in-50-year hazard maps. Given the modal magnitude, the transition corner period is based on a combination of theoretical and observational considerations (the Denali Fault earthquake data were not used in deriving the transition periods).
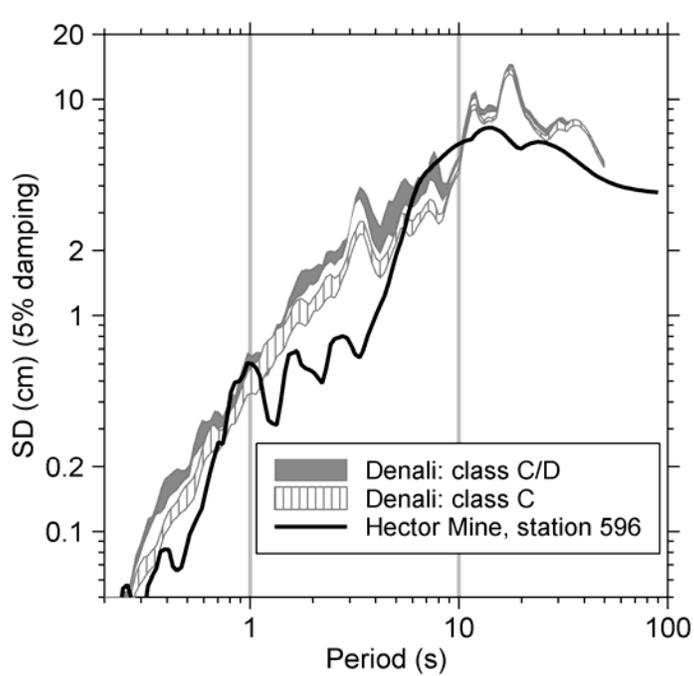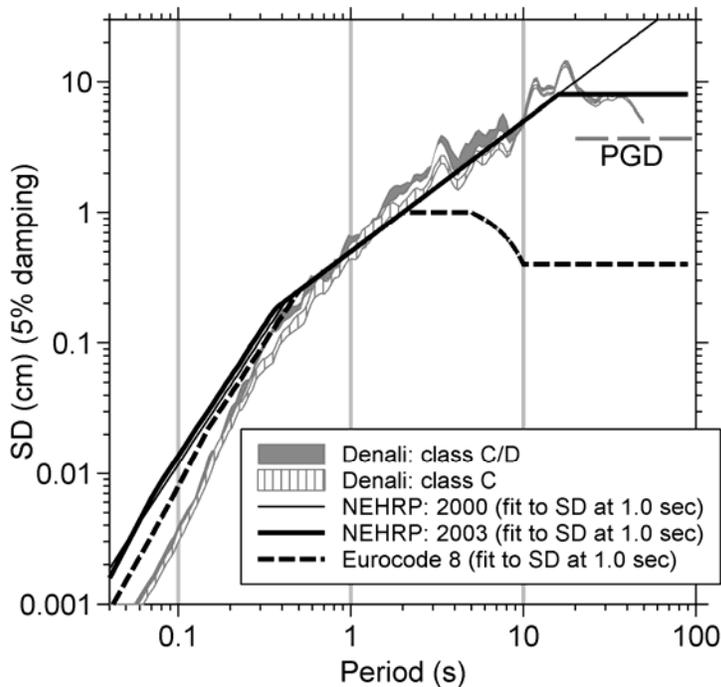
Figure 8. Displacement response spectrum (SD) for the 2002 Denali Fault, Alaska, earthquake recordings and for the transverse component of the 1999 Hector Mine, California, earthquake (after dividing the Hector Mine spectrum by 2.6 to correct for the different distances to the earthquakes). All records were low-cut filtered with a low-order acausal Butterworth filter with a corner at 0.02 Hz (the filter response goes as f^4 for low frequencies). (From Boore, 2004b).
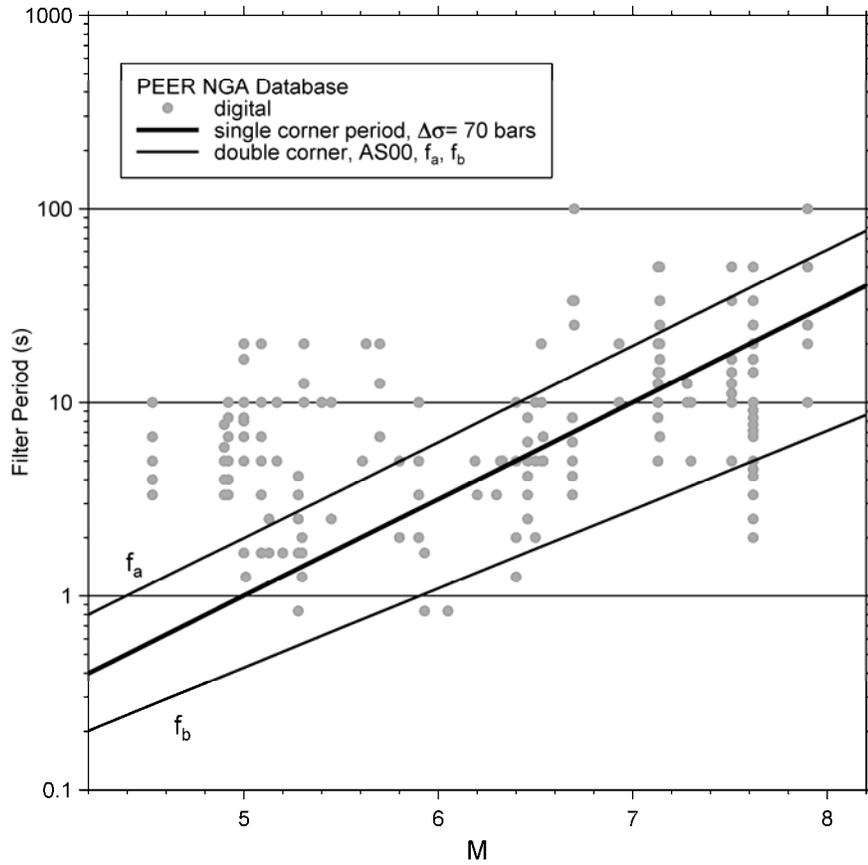
Figure 9. Corner periods from two source-scaling models, compared to the filter periods used in processing strong-motion data (AS00 = Atkinson and Silva, 2000). f_a and f_b are the corner frequencies for the 2-corner spectral model.

Figure 10. Comparison of observed displacement response
spectrum (SD) for class C/D and C sites in Anchorage to
the spectra constructed following the procedures for the
following building codes: 2000 NEHRP (BSSC, 2001), 2003
NEHRP (BSSC, 2004), and Eurocode 8 (CEN, 1998). Also
shown is the peak ground displacement (PGD) for the
Anchorage motions; the displacement response spectrum
will be asymptotic to this value at sufficiently long
periods. For NEHRP, the mapped values of spectral
response at 0.2 and 1 seconds were used, but to
emphasize the shape, the spectra for the three codes
have been normalized to a representative value of the
data at 1 second. (From Boore, 2004b.)

5.   SUMMARY

Digital strong-motion instruments allow routine recovery of ground
motions at periods much longer than possible with the older analog
instruments.

In spite of the theoretical possibility of recovering even the residual displacements in the vicinity of earthquakes, in practice digital recordings are often plagued by drifts in the velocity and displacement traces obtained by integrating the recorded acceleration traces. Baseline-correction schemes may not give stable results, and removal of low-frequencies by filtering is often required. The filter corners can be so low, however, that little of engineering interest is lost.

Recent data from several earthquakes (e. g. 1999 Hector Mine and 2002 Denali) shows that for displacement response spectra, the transition from increasing to constant spectral levels occurs at significantly longer periods than in Eurocode 8; the transition period is in good agreement, however, with the recent 2003 NEHRP code.

## 6.	ACKNOWLEDGMENTS

## 7.	REFERENCES

Atkinson, G. M. and Boore, D. M., 1998. Evaluation of models for earthquake source spectra in eastern North America, *Bull. Seism. Soc. Am.* **88:** 917—934.

Atkinson, G. M. and Silva, W., 2000, Stochastic modeling of California ground motions, *Bull. Seism. Soc. Am.* **90:** 255—274.

Bommer, J. J. and Elnashai, A. S., 1999, Displacement spectra for seismic design, *J. Earthquake Eng.* **3:** 1—32.

Boore, D. M., 2001, Effect of baseline corrections on displacements and response spectra for several recordings of the 1999 Chi-Chi, Taiwan, earthquake, *Bull. Seism. Soc. Am.* **91:** 1199—1211.

Boore, D. M., 2003, Analog-to-digital conversion as a source of drifts in displacements derived from digital recordings of ground acceleration, *Bull. Seism. Soc. Am.* **93**: 2017—2024.

Boore, D. M., 2004a, Can site response be predicted?, *J. Earthquake Eng.* **8:** Special Issue 1, 1-- 41.

Boore, D. M., 2004b, Ground motion in Anchorage, Alaska, from the 2002 Denali fault earthquake: Site response and displacement pulses, *Bull. Seism. Soc. Am.* **94:** (in press).

Boore, D. M. and Akkar S., 2003, Effect of causal and acausal filters on elastic and inelastic response spectra, *Earthq. Eng. And Struct. Dyn.*, **32:** 1729—1748.

Boore, D. M., Stephens, C. D., and Joyner, W. B., 2002, Comments on baseline correction of digital strong-motion data: Examples from the 1999 Hector Mine, California, earthquake , *Bull. Seism. Soc. Am.* **92：** 1543—1560.

BSSC, 2001, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, 2000 Edition, Part 1: Provisions, prepared by the Building Seismic Safety Council for the Federal Emergency Management Agency (Report No. FEMA 368), Washington, D.C. (available from http://www.bssconline.org/NEHRP2000/comments/provisions/).

BSSC, 2004, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, 2003 Edition, Part 1 - Provisions, Part 2 - Commentary, prepared by the Building Seismic Safety Council for the Federal Emergency Management Agency (Report No. FEMA 450), Washington, D.C. (available from http://www.bssconline.org/).

CEN, 2002, Eurocode 8: Design of structures for earthquake resistance, Draft No. 5, CEN (European Committee for Standardization) Doc CEN/TC250/SC8/N317 (prEN 1998-1:200X), Brussels.

Faccioli, E., Paolucci, R., and Rey, J., 2004, Displacement spectra for long periods, *Earthquake Spectra* **20:** 347--376.

Graizer, V. M., 1989, On inertial seismometry, Izvestiya, Physics of the Solid Earth **25:** 26--29.

Hanks, T. C., 1975, Strong ground motion of the San Fernando, California, earthquake: ground displacements, *Bull. Seism. Soc. Am.* **65:** 193—225.

Iwan, W. D., Moser, M. A., and Peng, C.-Y., 1985, Some observations on strong-motion earthquake measurement using a digital accelerograph, *Bull. Seism. Soc. Am.* 75: 1225--1246.

Trifunac, M. D. and Todorovska, M. I., 2001, A note on the useable dynamic range of accelerographs recording translation, *Soil Dynamics and Structural Eng.* **21:** 275—286.

Wang, G.-Q., Boore, D. M., Igel, H., and Zhou, X.-Y., 2003, Some observations on colocated and closely-spaced strong ground motion records of the 1999, Chi-Chi, Taiwan earthquake, *Bull. Seism. Soc. Am.* **93:** 674—693.